CELLO MAP:

A HANDBOOK OF CELLO TECHNIQUE FOR PERFORMERS AND COMPOSERS

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Abstract

Many new sounds and new instrumental techniques have been introduced into music literature since 1950. The popular approach to support developments in modern instrumental technique is the catalogue or notation guide, which has led to isolated special effects. Several authors of handbooks of technique have pointed to an alternative, strategic, scientific approach to technique as an ideological ideal. I have adopted this approach more fully than before and applied it to the cello for the first time. This handbook provides a structure for further research. In this handbook, new techniques are presented alongside traditional methods and a ‘global technique’ is defined, within which every possible sound-modifying action is considered as a continuous scale, upon which as yet undiscovered techniques can also be slotted. The ‘map’ of the title is meant in the scientific sense of the word; connections are made between: ‘actions that a cellist makes’ and ‘sounds that a cello can produce’. In some cases, where existing scientific theory is insufficient to back up these connections, original empirical research has been undertaken and areas for further research have been suggested. Within this system there are no special effects, rather a continuum of actions with a clear relationship to sound.

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Contents

Context and Methodology

In the past fifty years a new genre of musical literature has developed: the handbook of modern instrumental technique. It is the first body of texts regarding instrumental technique to be aimed at a mixed composer-performer readership, being an amalgamation of composers' instrumentation books and instrumentalists' methods and studies, which were previously separate. In this introduction I will outline the historical provision of texts regarding cello technique; review the literature of modern handbooks on instrumental technique; and consider the ideological inconsistencies in the way technique has been discussed and the vocabulary that has developed around changes in technique. Finally, I will present my methodology in the context of these issues.

Technique is not fixed. Musicians usually use the word technique as a measure of their playing ability; it is not fixed because it can be improved upon. More generally, technique, in the sense of what playing a particular instrument physically involves, has changed considerably through time: technique has a history. Cello technique developed, throughout the mid to late eighteenth and nineteenth centuries to include, for example thumb position, *spiccato* bowing, vibrato, use of an end pin. So, despite the surge of additions made in the twentieth century, the idea of developing technique is itself not new or surprising. There is a body of literature that documents technical development, and there are study or exercise books that support instrumentalists. Valerie Walden provides a list of these texts.[1] Walden cites the first example of a text describing the method of cello playing, written in Paris in 1741, which, along with other early examples of cello methods, compared cello technique to that of the viola da gamba. As cello technique evolved in parallel with developments in

[1] See Valerie Walden, 'Technique, style and performing practice to c.1900', in Robin Stowell (ed.), *The Cambridge Companion to the Cello* (Cambridge: Cambridge University Press, 2000) 178-94 and Valerie Walden, *One Hundred Years of Violincello: A History of Technique and Performance Practice, 1740-1840* (Cambridge: Cambridge University Press, 1998).

the instrument (primarily the use of the endpin c.1845[2] and the use of the Tourte bow c.1800[3]) and the rise in solo repertoire, several pedagogical texts were published with the aim of updating the method of cello playing. Walden notes in particular the development of fingering patterns by Salvatore Lanzetti (Amsterdam, c.1756-67),[4] the new bowing method devised by Jean-Louis Duport (Paris, 1806) and systematic approaches to fingering and bowing by Joseph Fröhlich (Cologne, 1808)[5] and Johann Schetky (London, 1811).[6] Some studies from this period are still in use today, notably those by Jean-Louis Duport.[7] Walden describes the development of a Romantic cello technique in the first half of the nineteenth century, during which cello technique and cello pedagogy, as we understand them today, were established. Since 1850, the texts that describe the method of cello playing have mostly had a pedagogic focus, particularly describing methods of teaching.[8] The studies that were published in this period build towards the virtuoso cello technique still widely aspired to today. Many of these studies are still in widespread use, notably those by Grüzmacher,[9] Popper[10] and Feuillard.[11] To summarise: throughout the instrument's history, there exist texts, which have described the method of cello playing, often from a pedagogic approach, and study/exercise books, which present musical scores and exercises for developing technical skill.

Woodwind players have an excellent resource that compares early sources describing articulation in early wind music.[12] The sources themselves are presented in such a way that the reader is able to see directly the words and

[2] John Dilworth, 'The cello: origins and evolution', in Robin Stowell (ed.), *The Cambridge Companion to the Cello* (Cambridge: Cambridge University Press, 2000) 14.
[3] John Dilworth, 'The bow: its history and development', in Robin Stowell (ed.), *The Cambridge Companion to the Cello* (Cambridge: Cambridge University Press, 2000) 32.
[4] Salvatore Lanzetti, *Principes ou l'Application de Violoncelle, par tous les tons de la manière la plus facile* (Amsterdam, c.1756-67).
[5] Joseph Fröhlich, *Violoncelloschule* (Cologne, 1808).
[6] Johann Schetky, *Practical and Progressive Lessons for the Violincello* (London, 1811)
[7] Jean-Louis Duport, *21 Etudes for Solo Cello* (Paris, c.1813).
[8] Titles include: Hermann Hemberlein, *Violoncelloschule, neuste, praktischste und leicht verständliche Method für Schul- und Selbstunterricht, Op.7* (Leipzig, 1887).
Otto Langey, *Practical Tutor for the Violincello* (London, 1909).
Paul Bazelaire, *Pédagogie du Violoncelle* (Paris: Durand, 1952).
Paul Tortellier, *How I Play, How I Teach* (London: Chester Music, 1975).
[9] Friedrich Grüzmacher, *Hohe Schule des Violincellospiels* (Leipzig, 1891).
[10] David Popper, *Hohe Schule des Violincellospiels,* Op. 72, 2 Vols. (Leipzig, 1901-5).
[11] Louis Feuillard, *Excercises Journaliers pour Violoncelle* (Paris: Schott, 1919).
[12] Edward H. Tarr and Bruce Dickey, *Articulation in Early Wind Music: a Source Book with Commentary* (Winterthur: Amadeus, 2007).

exercises used to illustrate technique. Tarr and Dickey include an extract from Francesco Rognoni's *Forest of Assorted Passages. Part two in which are treated difficult passages, how to bow and tongue and make divisions from one step to the next on instruments.* Printed in 1620, the part relating to stringed instruments refers to the viol rather than the violin family. Nonetheless, it is interesting to see how an aspect of technique that is now fundamental to string players, *legato* bowing, was defined and illustrated as a new method for the first time. The following example precedes a short musical study for practice purposes.

> By legato bowing we mean playing two, three, or more notes in a single bow stroke…It is necessary for the wrist of the bow hand, almost jumping, to beat each note, one at a time…You should be careful not to make more noise with the bow than with the sound.[13]

In the case of the cello, the provision of texts and study/exercise books since 1950 has mostly focussed on traditional technique. There are two notable exceptions however: Caroline Bosanquet's book dedicated to harmonics, which combines written explanation with short exercises,[14] and a collection of extracts to be used as studies to modern cello playing compiled by Siegfried Palm.[15] The Palm studies are part of a series, *Pro Musica Nova,* by Breitkopf und Härtel that includes similar books for flute, piano, oboe, violin, viola, guitar and clarinet. In general, however, newly published studies focus on traditional technique and there are very few that attempt to incorporate even well established 'new' methods of playing. A study book for viola by Garth Knox is a recently published exception to this. Knox has written studies on eight particular aspects of technique often found in contemporary scores (*Sul ponticello, Sul tasto, Glissando, Pizzicato, Tremolo, Harmonics, Quartertones* and *Bow directions*).[16] The studies are a good resource for training elements of

[13] Tarr and Dickey, *Articulation in Early Wind Music,* 84.
[14] R. Caroline Bosanquet, *The Secret Life of Cello Strings (Harmonics for Cellists)* (Cambridge: SJ Music, 1996).
[15] Siegfried Palm (ed.), *Pro musica nova: Studien zum Spielen neuer Musik: für Violoncello* (Wiesbaden: Breitkopf und Härtel, 1985).
[16] Garth Knox, *Viola Spaces: Contemporary Viola Studies* (Mainz: Schott, 2009).

technique that are otherwise often only rehearsed in the context of a score.[17] In general, however, there are more handbooks to modern instrumental technique than there are etudes. Despite this, given the scale of development in instrumental technique over the past sixty years, their number is strikingly few. Wind instruments are the most well represented. There are no such handbooks for the cello. Why is this the case? The cello has been popular with avant-garde composers. The particular efforts of Mstislav Rostropovich and Siegfried Palm resulted in hundreds of commissions in which composers were encouraged to stretch cellists' traditional technical boundaries. In fact, technique was being expanded in more than one sense. Alongside the introduction of new techniques, the idea of the Romantic virtuoso was still strong; the rise in historically-informed practice was changing the performance of early music, but Romantic interpretations of early music were still viable. Has the idea of 'a technically accomplished cellist' ever been as broad as it was in the mid twentieth century? Naturally, some aspects of this diversification were controversial.

To some avant-garde compositional schools, new sounds and new techniques became the drive behind new writing. This stretches from the importance that timbre held in the compositions of Schönberg and Webern, to the experimentalism of Kagel and Lachenmann, and beyond. Experimenting with technique, if not the basis of some works, was certainly an axis around which pieces were structured. The bringing of technique to the foreground in certain compositional schools, and the diversification of compositional style in general meant that technique became a contentious issue. It is perhaps not surprising therefore, that many handbooks on instrumental technique should be found to have an aesthetic or compositional bias. Handbooks on instrumental technique were influenced by the ideas and vocabulary surrounding technique, and vice versa. The handbooks and the broader idea of technique are both discussed here.

[17] There are some misconceptions concerning acoustics in the accompanying text, which will be discussed later.

LITERATURE REVIEW

As mentioned above, a new body of texts in the second half of the twentieth century addressed questions of instrumental technique to a performer-composer readership for the first time. The literature described above (studies and methods for cello playing), which serves performers' interests, has historically been separate from composer-focussed texts. The latter body of texts consists mostly of orchestration and instrumentation guides, most famously those by Berlioz (republished with notes by Strauss)[18] and Rimsky Korsakov.[19] More recently, notation guides have been written for composers, attempting to standardise the vastly differing notation of contemporary techniques. The most well known notation guides are by Gardner Read (first published in 1969),[20] Erhard Karkoschka[21] and Kurt Stone, [22] the last deriving from the International Conference on New Musical Notation in Ghent in 1974.[23] There follows an outline of the development of the literature and a literature review, which analyses the main themes and approaches of handbooks for modern instrumental technique.

The early twentieth century handbook on modern technique by the harpist Carlos Salzedo combines a text on methods and notation with five studies to practise the newly described techniques.[24] The pioneering nature of his ideas is astounding given the early date of publication. Techniques discussed include: plucking the strings so forcefully that they strike one another, sliding the hand vertically up and down the strings to create 'whistling sounds', striking the sound board, sliding the tuning key along a vibrating string to change its pitch, preparing the harp with paper, and developing a notation for continuous contact points along the upper half of the string. Writing thirty years before the surge in experimentation with technique, Salzedo seems an anomaly in terms

[18] Hector Berlioz and Richard Strauss, *Treatise on Instrumentation,* trans. Theodore Front (New York: Dover, 1991).
[19] Nikolay Rimsky Korsakov, *Principles of Orchestration* New edn., ed. Maximilian Steinberg, trans. Edward Agate (New York: Dover, 1964).
[20] Gardner Read, *Music Notation: A Manual of Modern Practice* (London: Gollancz, 1978).
[21] Erhard Karkoschka, *Notation in New Music: A Critical Guide to Interpretation and Realisation,* trans. Ruth Koenig (New York: Praeger, 1972).
[22] Kurt Stone, *Music Notation in the Twentieth Century: a Practical Guidebook* (New York: Norton, 1980).
[23] Herman Sabbe, Kurt Stone and Gerald Warfield (eds.), *International Conference on New Music Notation Report* (Amsterdam: Swets and Zeitlinger, 1975).
[24] Carlos Salzedo, *Modern Study of the Harp* (Milwaukee: Schirmer, 1921).

of his instrumentalist contemporaries, although he did find solidarity in composer Edgard Varèse, another Paris-based pioneer (with whom he jointly founded the International Composers' Guild).[25] Salzedo's techniques and studies are integral to modern harpists' repertoire, his etudes are widely used by harp students and his influence on contemporary composers is strong. Certain similarities between Salzedo's notation and that of Helmut Lachenmann, Pierre Boulez and George Crumb suggest that they were influenced by him. Luciano Berio also acknowledges Salzedo as a strong influence on his *Sequenza II* for harp (written in 1962).[26]

Another pioneering figure in writing handbooks on instrumental technique is Bruno Bartolozzi, whose influential *New Sounds for Woodwind* was first published in 1967.[27] Bartolozzi was the first to write in detail about multiphonics and microtonal playing in woodwind instruments. In addition to the originality of the content, another significant aspect of Bartolozzi's handbook is his approach. Bartolozzi carries out research on the instruments in a systematic and rigorous way and is the first to mention the importance of acoustical understanding in developing technique. Writing about the contemporary state of research concerning multiphonic and microtonal possibilities, Bartolozzi comments:

> Results of investigations have been arrived at only by practical experiment and not through scientific research. This is inevitable [because] scientific research lags very much behind the practice which this thesis proposes…It is to be hoped that science will furnish explanations for many perplexing phenomena.[28]

By the time Bartolozzi printed a second edition of *New Sounds for Woodwind* in 1982, his call for scientific research had been answered. Acoustician Arthur

[25] Shelley Batt Archambo Wiest, 'Salzédo, Carlos' in *Grove Music Online*. *Oxford Music Online*, http://www.oxfordmusiconline.com/subscriber/article/grove/music/24438, accessed August 30, 2009.
[26] Rosanna Dalmonte and Bálint Andreas Varga, *Luciano Berio: Two Interviews* (London: Boyars, 1985), 99.
[27] Bruno Bartolozzi, *New Sounds for Woodwind,* trans. Reginald Smith Brindle (London: Oxford University Press, 1967).
[28] Bartolozzi, *New Sounds for Woodwind,* 6.

Benade researched multiphonics extensively and, crediting Bartolozzi, was able to provide an acoustical explanation of multiphonics in his widely read *Fundamentals of Musical Acoustics.* [29] Benade documents the growing interest related to multiphonics in the 1960s, and observes that this occurred 'particularly after the publication of Bruno Bartolozzi's *New Sounds for Woodwind.'*[30]

The research element of Bartolozzi's text and the call for strategic experimentation extends to performers and composers as well as acousticians:

> How it is that… possibilities which have always existed, have been so long ignored? How is it that instrumental techniques have become fixed in a pattern which does not allow any results except those actually in conventional use?[31]

Bartolozzi puts particular emphasis on timbral variation, microtonal playing and multiphonic playing, describing these three elements as 'the most fruitful field for research'.[32] This research has been taken up and developed in many subsequent texts for woodwind instruments. The ideas and themes recur: Bartolozzi is personally thanked by Robert Dick in the introduction to *The Other Flute*,[33] and appears in almost all of the bibliographies of the handbooks for woodwind instruments that are discussed below. Another central aspect of *New Sounds for Woodwind* is Bartolozzi's requirement that performers rehearse new techniques to the same level of accuracy as traditional technique.

The importance Bartolozzi places upon finding a method of practising new techniques is confirmed by his provision of short exercises throughout *New Sounds for Woodwind*, which enable performers to practise new techniques in this traditional format.

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[29] Arthur Benade, *The Fundamentals of Musical Acoustics* (2nd edn., New York: Dover, 1990). The first edition was published in 1976.
[30] Benade, *The Fundamentals of Musical Acoustics*, 559.
[31] Bartolozzi, *New Sounds for Woodwind,* 2-3.
[32] Bartolozzi, *New Sounds for Woodwind,* 2nd edn., 2.
[33] Robert Dick, *The Other Flute, a Performance Manual of Contemporary Techniques* (New York: Oxford University Press, 1975), v.

Another important figure in the literature is Bertram Turetzky, who published *The Contemporary Contrabass* in 1974,[34] the first in the New Instrumentation series of handbooks on modern instrumental technique by University of California Press. He continues to commission and oversee the series, taken over by Scarecrow Press in 2004, which currently numbers nine volumes.[35] Like Bartolozzi, Turetzky begins with a call for experimentation and an expansion of sound materials:

> The starting point of this work is a re-evaluation of *pizzicato* technique, until recently a barren wasteland…Apparently little…heed was paid to [Berlioz' comments on *pizzicato* in his *Treatise on Instrumentation*][36]

The passage from Berlioz' *Treatise on Instrumentation* referred to by Turetzky is as follows:

> In the future the *pizzicato* will doubtless be used in even more original and attractive effects than here to fore. Violinists, not considering the *pizzicato* an integral part of violin technique, have given it hardly any serious attention…players will doubtless become familiar with [a wider range of] techniques in the course of time. Then composers will be able to take full advantage of them.[37]

[34] A new edition was published in 1989.
[35] The titles are as follows, in order of first publication:
Bertram Turetzky, *The Contemporary Contrabass* (Berkley: University of California Press, 1974). This title was republished in 1982.
Thomas Howell, *The Avant-Garde Flute: A Handbook for Composers and Flautists* (Berkley: University of California Press, 1974).
Stuart Dempster, *The Modern Trombone: a Definition of its Idioms* (Berkley: University of California Press, 1979).
Philip Rehfeldt, *New Directions for Clarinet,* (Berkley: University of California Press, 1977). This title was republished in 1994.
John Schneider, *The Contemporary Guitar* (Berkley: University of California Press, 1985).
Ruth Inglefield and Lou Anne Neill, *Writing for the Pedal Harp: a Standardised manual for Composers and Performers* (Berkley: University of California Press, 1985).
Patricia and Allen Strange, *The Contemporary Violin: Extended Performance Techniques* (Berkley: University of California Press, 2001).
Libby Van Cleve, *Oboe Unbound: Contemporary Techniques* (Lanham Maryland: The Scarecrow Press, 2004).
Michael Edward Edgerton, *The 21st-Century Voice: Contemporary and Traditional Extra-normal Voice* (Lanham Maryland: The Scarecrow Press, 2005).
[36] Turetzky, *The Contemporary Contrabass*, 1.
[37] Hector Berlioz, *Treatise on Instrumentation,* 35-6.

Turetzky believes that Berlioz' expectations of 1844 (when his *Treatise* was first published) have not been realised. He goes on to argue that Classical *pizzicato* technique is limited compared to the wide range of *pizzicato* possibilities in Jazz, and cites the first composer to differentiate between *pizzicato esspressivo* and *non espressivo* in the double bass literature, Barry Childs in 1960.[38] Turetzky and Bartolozzi have in common a certain experimental drive behind the writing of their handbooks, but, rather than a scientific call for research, Turetzky's book returns throughout the text to the idea of composer-performer collaboration, the production of new compositions for the instrument and joint exploration of sound.

Another influential figure in the establishing of a field of research in instrumental technique is Robert Dick, whose handbook *The Other Flute* was first published a year after *The Contemporary Contrabass*.[39] Like Turetzky, Dick is motivated to explore the capabilities of the instrument and widen the traditional idea of the flute.[40] However, the style of the book has much in common with Bartolozzi. Dick developed Bartolozzi's important ideas about microtonal and multiphonic playing, and was the first to try to establish a strategic and comprehensive approach to fingering charts to describe these. Moreover, Dick develops Bartolozzi's method of categorising timbre and particular quality of microtones and multiphonics for each of the thousands of fingerings represented. Reprinted in 1989, the book is still widely used. Its exponents include John Cage, who credits Dick, alongside Rehfeld in the preface of *Music for*.[41]

Another series, more recently established and especially important to woodwind instruments, is Bärenreiter's series on the techniques of playing instruments. Handbooks currently exist for the oboe,[42] flute[43] and saxophone[44]

[38] Barney Childs, *Sonata for Bass Alone* (Unpublished, 1960).
[39] Robert Dick, *The Other Flute*.
[40] Robert Dick, *The Other Flute,* v.
[41] John Cage, *Music for* (New York: Henmar Press, 1984).
[42] Peter Veale and Claus-Steffen Mahnkopf, *The Techniques of Oboe Playing* (Kassel: Bärenreiter, 1998).
[43] Carin Levine and Christina Mitropoulos-Bott, *The Techniques of Flute Playing,* (Kassel: Bärenreiter, 2002).
[44] Marcus Weiss and Giorgio Netti, *The Techniques of Saxophone Playing* (Kassel: Bärenreiter, 2010). Since the book has not yet been published, I was kindly allowed an electronic copy for

and there is an impending text for bassoon.[45] Like *The Other Flute*, these texts seem to be extensions of the Bartolozzi school. Timbral variation, microtones and multiphonics are described and categorised with even greater accuracy. Veale and Mahnkopf present a thorough list of multiphonic fingerings in order of decreasing overtone content and 'diffusity' (noise level) of sound. Their aim for 'thoroughness' and 'technical certainty' is notable throughout the book.[46] Levine and Mitropoulos-Bott are less accurate in their categorisation of multiphonics, giving a three-level stability gradation and dynamic range for hundreds of multiphonic fingerings but indicating only the frequency of microtonal fingerings. *The Technique of Flute Playing* takes up Bartolozzi's pedagogic line in including 'Practice Tips' at the end of each section. Weiss and Netti do the same in *The Techniques of Saxophone Playing*, and extend the idea by also including advice for composers. Weiss and Netti make a particularly important contribution to the degree of accuracy and predictability of multiphonic production and the ability to depend on particular fingerings. They organise multiphonics into families according to the pitch components, and break these down into sub categories according to the stability of the sound, the number of contributing partials, sound quality etc. Moreover, these are cross categorised by dynamic markings, which show how the pitch content and quality of sound change according to the dynamics at which the multiphonic is performed. Particularly in the case of woodwind instruments, a clear trajectory of research is perceivable from the 1960s to the present day.

Books that have an exploratory remit, that focus on empirical exploration of an instrument's sound possibilities can be placed easily in the historical line of development of the genre of handbooks of instrumental technique. If the research aims are clearly stated, as is the case with Bartolozzi, they can easily be taken up and extended by subsequent authors. Consequently, there is a continual path of research into woodwind multiphonics from Bartolozzi to today. The opposite approach – a documentation of previous uses of technique, a list of effects, or a sporadic, non-strategic approach – has a static effect on

research purposes. The page numbers have not yet been fixed. Therefore, when quoting from the book in this introduction I refer to the chapter headings where the information can be found.

[45] Pascal Gallois, *The Techniques of Bassoon Playing* (Kassel: Bärenreiter, 2010).

[46] Veale and Mahnkopf, *The Techniques of Oboe Playing,* 8.

research. This can be seen in several of the handbooks reviewed below. The remit of handbooks for new instrumental technique does not always come across clearly from the text. What can we expect from such books? The varying approaches brief us on history, notation, acoustics and relevant contemporary scores and composers. In the following review of existing handbooks I discuss the main themes and approaches under the following three headings: Purpose, Structure and Content.

Purpose

In general there is a shared purpose of clarifying confusion about newly-developed techniques and showing new possibilities. Inciting new works is also a common theme. Several books set out to challenge preconceptions about the instrument in question:

> Throughout its history, the guitar has been treated as a second-class instrument.[47]

> Composers are afraid to write for the horn, that most treacherous of instruments[48]

> [Percussionists have been] given the short shrift[49]

Robert Dick also sets out to challenge preconceptions but in a more measured way:

> I have dropped the following preconceptions…:
> 1. The flute has only one basic tone quality…
> 2. The flute can only produce one note at a time
> 3. The …flute allows the production of only a few microtones[50]

[47] Schneider, *The Contemporary Guitar,* vii.
[48] Douglass Hill, *Extended Techniques for the Horn,* 2nd edn. (Van Nuys California: Warner Bros Publications, 1996), 7.
[49] Reginald Smith Brindle, *Contemporary Percussion* (London: Oxford University Press, 1970), 1.
[50] Dick, *The Other Flute,* v.

A few authors address what I consider to be the real challenge to technique in contemporary music. Recognising confusion and inconsistency in the use of new techniques for their instrument (on the part of composers and performers), they state the aim of describing new techniques in a comprehensive way rather than as special effects, and particularly of considering new techniques in the same detailed way as traditional techniques. This can be observed in the following quotations by Dick, Veale and Mankopf, and Weiss and Netti:

> I set out to remove the non-traditional aspects [of technique] from the category of special effects and into the realm of valid musical materials.[51]

> [We aim to] present recent innovations of the oboe with a thoroughness and technical certainty[52]

> Once the first fascinating experiences with multiphonics (as *objet trouvé*) were done with, it became possible to describe the differences and similarities between different multiphonics…more precisely.[53]

Structure

Handbooks on instrumental technique vary greatly in how the authors decide to present the information, that is the structure of the book. In the most successful books the structure allows an efficiency in sorting through information.

Information in the existing literature for stringed instruments is almost always grouped by methods, which are usually defined by sound, for example common chapter headings are: glissando, the prepared instrument, percussive sounds, harmonics etc. The woodwind books tend to follow Bartolozzi's structure: two large chapters, one for monophonic sounds, one for multiphonic sounds, and a shorter chapter for combinations of these and other techniques.

John Schneider's guitar manual is an exception. He follows a premise of exploring timbre variation in his instrument, and structures the technical part of

[51] Dick, *The Other Flute,* v.
[52] Veale and Mahnkopf, *The Techniques of Oboe Playing,* 8.
[53] Weiss and Netti, *The Techniques of Saxophone Playing,* Chapter 3.

his handbook around five elements of timbre.[54] These are: transient, time envelope, prefix, spectral envelope and formant glide. The ideas in themselves might be interesting, but faced with the above subheadings it is almost impossible for the reader to dip in and out of the book in pursuit of particular information.

Michael Edgerton on the voice and Allen and Patricia Strange on the violin exemplify the negative effect of unclear contents pages. The following, by Edgerton is almost impossible to navigate around because the reader cannot associate the chosen chapter headings clearly with particular actions or sounds made by a singer. The headings lack key words that might relate to a particular question regarding technique.

Part I Airflow	1. Airflow
Part II Source	2. Vocal fields
	3. Laryngeal semi-periodic source
	4. Registral
Part III Resonance and Articulation	5. Filtering
	6. Turbulent to absolute airflow modification
Part IV Heightened Potentials	7. Combinational, multiphonic principles
	8. Extremes
	9. Interface
Part V Context	10. Context[55]

Patricia and Allen Strange do not give the headings and subheadings in *The Contemporary Violin* relative weight.[56] Furthermore, the same aspects of technique appear more than once in the contents page, leading the reader to several passages in pursuit of a single piece of information. For example, seeking information about *col legno battuto,* the reader will find, under the first

[54] Schneider, *The Contemporary Guitar,* 29-45.
[55] Edgerton, *The 21st-Century Voice.*
[56] Strange, *The Contemporary Violin.*

chapter heading: ‘Bowing Technique’, the subheading ‘*Col legno battuto’.* Later, chapter three: ‘Percussion Techniques’ includes the subheading ‘The Bow’, in which *col legno battuto* is described again. Similarly, *pizzicato* is found in chapter two: ‘The Fingers’ as a sub-subheading under ‘The Right Hand’ and it appears again shortly afterwards, next to ‘Slurs’ ‘Vibrato’ and ‘Trills’ as a sub-subheading under ‘The Left Hand’. A second problem, perceivable from this example, is that technique has been divided in a non-strategic way under different terms, leading to overlaps in content. This is clear from the titles of the first three chapters: ‘Bowing’, ‘The Fingers’ and ‘Percussion Techniques’. If ‘Bowing’ and ‘The fingers’ cover every method and sound producible with the bow and the fingers, and ‘Percussion Techniques’ covers every method in which the violin is struck, then there will necessarily be huge overlaps (not least, using the right hand fingers to strike the bow against the string).

Almost all handbooks have a chapter of extra techniques (labelled ‘Miscellanea’ by Turetzky, ‘Special Techniques’ by Veale and Mahnkopf, ‘Other Resources’ by Van Cleave and Dick and ‘Special Effects’ by Howell). In other words, when technique has been separated into chapters, there are almost always some methods that remain uncategorized.

Content:

Information usually consists of a description of the instrumentalist’s actions (method of sound production). In many cases, notations are suggested and/or the name of a composer or an illustrative extract from a composition are given.

Various depths of explanation behind principles of technique can be successful, from experience-based theory (tips and observations ‘proven’ through experience) to deeper, research-based acoustics (the physical reason why a fact is true). Consider the following examples:

> [To produce a multiphonic] it often helps to abandon normal embouchure position, to take (much) less mouthpiece and…reduce the embouchure pressure.[57]

> [The angle of the flute] primarily affects pitch; as the angle of the flute is turned inwards towards the player, the pitch is lowered…Turning the flute in tends to increase the strength of the higher partials in the tone and weaken the fundamental.[58]

> When a soft beater strikes an instrument, its head 'gives', spreading momentarily, but just long enough to impede vibrations of short wavelength.[59]

Despite the difference in depth of reasoning, all of the above examples are useful in clearly showing how an instrumentalist can influence sound. Problems of clarity occur when a proper connection between theory (on any level) and sound is not made clear. Compare the following examples with those above. The reader is left asking: Why? How? What does that sound like?

> Right hand plucking technique can alter the tone quality of harmonics.[60]

> [Overblowing] has the greatest effect on low notes.[61]

> Many differences of production and expression exist between egressive and ingressive airflow, and depending on context, both are equally effective in performance.[62]

An insufficient connection to sound is apparent in the literature in another sense. This can be summarised as a lack of continuity or 'the catalogue

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[57] Weiss and Netti, *The Techniques of Saxophone Playing,* Chapter 3b.
[58] Dick, *The Other Flute,* 46.
[59] Smith Brindle, *Contemporary Percussion,* 22.
[60] Schneider, *The Contemporary Guitar,* 135.
[61] Van Cleve, *Oboe Unbound,* 75.
[62] Edgerton, *The 21st-Century Voice,* 3.

problem' of listing techniques without making comparisons or connections between them or their resulting sounds. This can be well illustrated with the following example from Gardner Read's *Compendium of Instrumental Techniques.* Read is listing percussive devices in the violin family. Under each entry he gives the names of several composers who have used the technique.

> 1. Slap/strike the strings with the flat left-hand fingers over the fingerboard…
> 2. Same, with the fingers over the bridge…
> 3. Tap the strings with the fingers…
> 4. Trill on the strings with the left-hand fingers (no bow)…
> 5. Tap on the string with a left-hand fingernail…
> 6. Tap on the string with two right-hand fingers (quasi trill)…

There are twenty-two entries in this list. Read then moves on to 'devices mainly applicable to violoncello and/or contrabass':

> 1. Slap the four strings with the left-hand fingers near to or on the instrument neck
>
> …
>
> 11. With a large wooden salad-tossing spoon in the left hand, strike the strings behind the bridge…
> 12. Same, with a tablespoon…
>
> …
>
> 16. Same with a chopstick…[63]

Despite the length of the list, the information that the reader takes away from this passage is extremely limited, Read gives an idea of what has been done, without consequence in terms of sound or possible variations on technique outside this list (how much simpler and more informative is the statement: the denser the object with which the string is struck, the more overtone-rich the sound?). A further problem in listing technique is when illogical subdivisions are

[63] Gardner Read, *Compendium of Modern Techniques* (Westport: Greenwood Press, 1993), 92-100.

made. In the following example, Allen and Patricia Strange are summarising point of contact on a violin string:

> The points of generation are:
>
> 1. Bow placed more or less half way between the bridge and the fingerboard, or position *normale*.
> 2. Bow placed near or on the bridge: *sul ponticello*.
> 3. Bow placed between the bridge and the tailpiece: *sub ponticello*.
> 4. Bow placed under the strings.
> 5. Bow placed over the fingerboard: or *sul tasto*.
> 6. Bow placed on the non-resonating part of the strings, between left hand fingers and nut.
> 7. Bow placed in the peg box or on the body.[64]

This is misleading in several ways. Firstly it suggests that there are seven clean-cut points of contact on a violin string. Secondly, the authors group bowing on a string and bowing on wood in numbers two and seven (they would have done better to at least mention the different sound outcomes in this case). Thirdly, the length of string between the fingers and the nut is described as non-resonating: if they are bowed, they are resonating. Fourthly, point of contact is not considered when referring to the plucked or struck string later in the book. Lastly, points one, two and five are unnecessarily separated: since contact can take place at any point on the string length, suggesting that three discrete points exist is breaking up a continuous scale. A more useful explanation of point of contact describes the way that overtone content changes as contact point moves along the whole string length, not simply at three discrete points on that length.

The catalogue problem can be summarised as over-dividing technique and under-supplying information. An extension of this problem is an illustrative approach to technique. By this I mean something that comes too close to what might appear in a score. For example Turetzky writes about *glissandi:*

[64] Strange, *The Contemporary Violin,* 41.

A *glissando* can consist of:

1. One note, stopped or a harmonic, played *ordinario* or with a trill.
2. A double stop, stopped or harmonics, played *ordinario* or with trills.
3. Three or four notes if it is a strum (*pizzicato tremolo) glissando.*[65]

In this instance the author is over-informing the reader. If the handbook is consistent, this implies that every element of technique will be expanded upon in this way, that every combination of every sound will be described, which is too huge a task for any such resource. Weiss and Netti describe their deliberate avoidance of mixing techniques for this reason:

> While the performance or composition of music is…much more complicated…than a simple ordering of building blocks, [our division of material into separate sections is practical]…It might indeed be conceivable to compile a multi-dimensional "Encyclopaedia of Saxophone Playing" [however] the demands on presentation and readability would be so complex as to make such a text impractical.[66]

Gunther Schuller writes in the forward to Gardner Read's Compendium:

> The author of a compendium on modern instrumental technique faces the disconcerting prospect that as soon as his tabulation is published, it is likely to be considered incomplete.[67]

In other words, catalogue-style information is disposable; it can be used once to recreate a technique but is not sustainable as new techniques are developed. The short-term usability of such information is not inevitable, as Schuller suggests.[68] It is possible to provide sustainable, continuous information regarding technique. By 'continuous' I mean presenting information in a continuous way, showing how, for each step along a scale of actions, a

[65] Bertram Turetzky, *The Contemporary Contrabass,* (2nd edn., Berkley: University of California Press, 1982), 142.
[66] Weiss and Netti, *The Techniques of Saxophone Playing,* Introduction.
[67] Read, *Compendium of Modern Techniques,* vii.
[68] There could be a role for catalogue-type texts as a historical resource to document the development and use of technique over time.

musician can change sound, control fine detail and understand the possible sonic variation within a wider categorisation of technique. This approach avoids the disposability of information, providing a basis for personal experimentation on the part of the performer and for further research. Examples of a continuous approach can be found throughout *The Other Flute – for* example, when describing jet whistles, Dick summarises the 'parameters' of the technique, describes how each parameter influences sound and explains the interdependency of these parameters.[69] Similarly, Veale and Mahnkopf's presentation of all possible fingerings for each microtonal pitch in order of decreasing overtone content and 'diffusity' (noise level), and Weiss and Netti's demonstration of how dynamics change the outcome of each harmonic fingering can also be described as continuous and strategic.[70]

Another issue that runs through the literature is finding an appropriate level of detail and necessary subjectivity in describing technique and sound. In this case, woodwind instruments often have the advantage over strings because information is presented in finger charts, which are largely unambiguous (although they are not always reliable across various makes of instruments). Finger charts for microtonal scales and multiphonics often make up more than half of the books' content. Dick, Levine, Artaud and Geay, Rehfeldt, Veale and Mahnkopf, and Weiss and Netti give thousands of examples of multiphonic and microtonal fingerings.[71] The more subjective aspect of this is when slight differences in technique can make slight alterations in sound. To accommodate this in a fingering chart, several systems of categorising sound (noise level, ease of response, dynamic range etc) and technique (lip opening, tension etc) are in place. This usually involves three or four classes or categories for each element of sound and technique, proposed originally by Bartolozzi and expanded upon by Dick, Artaud and Geay, Rehfeldt, Veale and Mahnkopf and particularly Weiss and Netti. Although 'categorising' might appear to point to a

[69] Dick, *The Other Flute,* 133-4.
[70] Weiss and Netti, *The Techniques of Saxophone Playing,* Chapter 3.
[71] Dick, *The Other Flute.*
Levine and Mitropoulos-Bott, *The Techniques of Flute Playing.*
Pierre-Yves Artaud and Gérard Geay, *Present Day Flutes* (Paris: Jobert, 1980).
Rehfeldt, *New Directions for Clarinet.*
Veale and Mahnkopf, *The Techniques of Oboe Playing.*
Weiss and Netti, *The Techniques of Saxophone Playing.*

catalogue approach, it is perhaps the only solution to organising thousands of examples in a concise and practicable way and, in considering the examples relative to one another, and, as is the case with the authors above, linking the techniques clearly to the possibilities of controlling sound avoids a restrictive catalogue-like approach. Stringed instruments do not lend themselves to charts in the same way, but Turetzky provides a pullout scaled double bass fingerboard in the appendix to *The Contemporary Contrabass* that shows the position of harmonics two to nineteen.[72] A similar chart could be produced showing positions of multiphonics in stringed instruments, perhaps with a scale for finger pressure and bow speed/pressure or plucking/striking force similar to the woodwind model. Such a project would, especially in combination with acoustical research, be a valuable research tool in an area that has been little investigated. Multiphonics could become as important to the development of new string technique as they have been to woodwind but are currently barely represented in handbooks of instrumental technique for string instruments. The only author to mention them is Turetzky, who, like Bartolozzi calls for further experimentation (albeit not in the acoustical field as in the latter's case):

> I know of no music employing string multiphonics…this is entirely new ground, it remains for composers and performers to build the usable technique.[73]

Turetzky intuits some relationship between finger position, bow pressure and point of contact, but, because of the lack of research, is unable to make a more detailed comment:

> [If] the finger is between the nodes of the seventh and eleventh partials but…the bow pressure corresponds to the third partial and the bow placement corresponds to the tenth. The result: some multiphonic.[74]

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[72] Turetzky, *The Contemporary Contrabass,* 2nd edn.. (Lose sheet in back of book).
[73] Turetzky, *The Contemporary Contrabass,* 2nd edn., 138.
[74] Turetzky, *The Contemporary Contrabass,* 2nd edn., 138-9.

Bartolozzi's call for acoustical research was taken up by Benade but, although multiphonics have been used in scores since Turetzky's comments, an acoustical explanation of their effect is still lacking.

An aspect that divides the literature is the inclusion of notation, composer citation or illustrative musical examples. This historiographical approach to technique can lead to 'the catalogue effect', list-making without consolidation, repeating rather than building on ideas, and can express partiality and bias in terms of musical taste. Robert Dick shares this view, presenting purely technique 'from an aesthetic point of view' and 'without stylistic or aesthetic bias'.[75] There are many existing reference materials that attempt to standardise notation (particularly useful are those by Stone and Karkoschka),[76] most of which are directed at composers. It is not necessary to duplicate these in handbooks to instrumental technique and moreover, since it can lead to a catalogue-like approach, it is not desirable. Problems posed by lack of clarity in notation, such as weak understanding of sound possibilities, lack of clarity regarding the scope of a particular notation etc, can be resolved without referring to the notation: a handbook that approaches technique in a continuous, strategic way will support such problems.

In some cases there is a sense that such citations endorse the inclusion of certain techniques, for example in his discussion about multiphonics, Rehfeldt lists forty-two composers 'and many others' whose pieces include the technique.[77] Without reference to exact pieces, even the historiographical interest of this list must be questioned. Schneider, who approaches microtones, body percussion, *glissandi* and preparation all in the context of extracts from scores, writes in the conclusion to *The Contemporary Guitar:*

> Many of the pieces which have been chosen to illustrate the techniques of sound production discussed here are simply not good music; but…

[75] Dick, *The Other Flute,* v.
[76] Stone, *Music Notation in the Twentieth Century.*
Karkoschka, *Notation in New Music.*
[77] Rehfeldt, *New Directions for Clarinet,* 2nd edn., 39.

> have been included because they have introduced new techniques and sounds into the repertoire.[78]

A technique simply being possible gives it a valid place in such a text without a supporting citation and certainly without comment regarding the author's view of success on the part of the composer. Verification of a technique by citing music of any taste is not necessary. Moreover, the assumption inherent in the above quotation, that methods need to be verified by musical examples, disregards the possibility of including methods in a handbook that have not yet been used in a score, which is extremely limiting.

The inclusion of extracts from scores seems to have the added purpose of pointing performers to new repertoire. Indeed, repertoire recommendations are popular, particularly in the most recently written handbooks. In the second edition of his book, Rehfeldt includes a fifty-page compilation of repertoire lists of various specialist performers.[79] Sharon Mabry goes a step further by including recommended concert programmes.[80] Both Sharon Mabry and Allen and Patricia Strange include a long list of unpublished works in their bibliographies, which, being largely unobtainable can't possibly be thought of as supporting a musical point. Creating an unbiased list of contemporary scores is a daunting task and cellists are fortunate to have two books (by Homuth and Markevitch)[81] and several websites dedicated to this purpose (such as the online database compiled by Matthias Lorenz).[82]

Musical examples that do work well in such books are exercises and short studies written for the purpose of technical training. Bartolozzi considers those in his book as 'illustrations of all the technical possibilities discussed to allow the immediate use of the resulting new sounds'.[83] Douglass Hill also includes

[78] Schneider, *The Contemporary Guitar,* 208.
[79] Rehfeldt, *New Directions for Clarinet,* 2nd edn., 145-94.
[80] Sharon Mabry, *Exploring Twentieth-Century Vocal Music: A Practical Guide to Innovations in Performance and Repertoire* (New York: Oxford University Press, 2002), 141-80.
[81] Donald Homuth, *Cello Music Since 1960: A Biography of Solo, Chamber and Orchestral Works for the Solo Cellist* (Berkeley: Fallen Leaf Press, 1994).
Dimitry Markevitch, *The Solo Cello: A Biography of the Unaccompanied Violincello literature* (Berkeley: Fallen Leaf Press, 1989).
[82] <http://www.matlorenz.de/Datenbank/index.htm> (accessed 1st October, 2009).
[83] Bartolozzi, *New Sounds for Woodwind,* 5-6.

several such exercises and an accompanying CD of him performing them.[84] Short extracts from existing scores, used for the purpose of training rather than having a historiographic purpose, can provide a useful tool for studies. Levine and Mitroloulos-Bott use short extracts effectively in such a way.[85]

Several authors include practice tips for performers. These are at their most useful when a practical tip is given alongside a clear reason for its application, for example:

> Using the fourth finger of the left hand [when producing key clicks] is…helpful for…achieving a high degree of resonance.[86]

> Keep the embouchure very loose [to produce a] *secco* slap; this mutes the resonance of the instrument.[87]

The above quotations are both taken from the Bärenreiter series, the joint composer-performer authorship of which, in reflecting the similar joint readership might account for a perceivably more balanced tone. Mabry, who claims to: 'present practical ideas concerning the…preparation [of contemporary scores]…from a pedagogical point of view',[88] often uses expansive descriptions of technique and practice methods without the sense of reliable, practical, consequential information seen above. This is perceivable in the following description of preparing scores that use microtones:

> The original tone should be raised or lowered slightly…The microtonal indication does not affect tone quality…If accompanying instruments are also playing microtones, make a tape of their accompaniment.[89]

Finally, there is certain content regularly found in the literature that focuses on external elements. This is information on vocal sounds for instrumentalists,

[84] Douglass Hill, *Extended Techniques for the Horn,* 2nd edn..
[85] Levine and Mitropoulos-Bott, *The Techniques of Flute Playing.*
[86] Levine and Mitropoulos-Bott, *The Techniques of Flute Playing,* 26*.*
[87] Weiss and Netti, *The Techniques of Saxophone Playing,* Chapter 4a.
[88] Mabry, *Exploring Twentieth-Century Vocal Music,* vii.
[89] Mabry, *Exploring Twentieth-Century Vocal Music,* 75-6.

theatrical movements, amplification and electronics. Both Turetzky, and Inglefeld and Neill dedicate a chapter to vocal sounds and theatrical movements. In both cases the authors review examples from the literature and give little information other than notation possibilities. Given the difficulty of supplying interesting and concrete information, and the pre-existence of relevant notation in notation guides, the information appears superfluous. In the following two examples there is a lack of practical information:

> Twenty-two compositions that were studied by the authors…incorporate the use of extra-musical activities…[including 'Walk around the stage']. Use the words 'walk around the stage' or use even more specific words to describe the activity.[90]

> Vocal sounds can be used to add weight, density, and other sounds to those played by the contrabass [two examples follow]…Speech sounds can accent, color, or articulate instrumental sounds in a most marked and/or theatrical manner [two examples follow].[91]

Information regarding electronics, which appears in almost every title reviewed, is equally vague. More practical information, such as techniques of amplification is occasionally given, which, despite its practicality, doubles information in the pre-existing literature in the field of sound design, often explaining particular information less clearly than the specialist literature.

IDEOLOGICAL CONTRADICTIONS AND INCONSISTENCIES

An extension of the argument relating to tone is the use of certain words and definitions to describe technique. Inconsistencies exist in the vocabulary surrounding new instrumental techniques that have, in some cases been influenced by inconsistencies in the handbooks to modern technique and in some cases caused them.

[90] Inglefield and Neill, *Writing for the Pedal Harp,* 60.
[91] Turetzky, *The Contemporary Contrabass,* 2nd edn., 73-4.

Because of technique's newfound compositional importance in the last sixty years, and because of developments in historically-informed practice, technique has been discussed in a more self-conscious way than before. Terms like 'Baroque/Classical technique', 'modern/contemporary technique(s)' and 'extended technique(s)' were introduced; the idea of performance practice was born.

The entry 'Instrumental and vocal resources', in the *Dictionary of Contemporary Music* of 1974 is an early discussion of modern developments to technique.[92] William Brooks recognises an 'increased expansion of sound materials' that, in the case of stringed instruments, have 'usually been based on techniques known in the nineteenth century'. He suggests an emphasis on a more explicit notation of old techniques rather than the invention of new ones, for example notating point of contact more precisely than *sul ponticello* or *sul tasto.* He mentions techniques such as *snap* (*Bartók*) *pizzicato,* plucking with the fingernail, *col legno battuto, col legno tratto* and tapping on the instrument body. There is a clear idea of expanding existing sound resources. At the same time, Bartolozzi, Turetzky and Dick published the first edition of their handbooks to instrumental technique, with the theme of exploration and research as seen in the literature review above.

Contemporary to this there was a broadening of discussion regarding technique, especially terminology, which influenced the technical and practical challenges addressed in the handbooks. Recently, discussion has particularly focussed on the term 'extended technique' or synonyms such as 'modern/contemporary performance techniques'. A clear definition of 'extended technique' and its synonyms must be twofold; firstly an explanation of the idea, and secondly a list of techniques considered to be extended. A consistent definition in either sense is still lacking in the main musicological texts, despite the term being well established in the vernacular of contemporary music specialists.[93]

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[92] "Instrumental and vocal resources" by William Brooks in John Vinton ed. *Dictionary of Contemporary Music* (New York: EP Dutton, 1974).
[93] A google search for 'extended cello technique' produces 96,600 hits.

Grove includes the entry: ‘Instrument modifications and extended performance techniques’. Strikingly, the term is never explicitly defined here, and the resistance to accept non-standard techniques is lightly overlooked:

> This flood of new instruments has been supplemented by many modifications…of standard instruments in ways that go far beyond the intentions of the manufacturer…Composers have also called for extended performance techniques on traditional instruments.

Regarding stringed instruments:

> Adaptations to the instruments themselves, such as scordatura tunings and the use of the mute, and non-standard performance techniques – for example, playing *col legno*, making percussive effects on the body and producing harmonics – have long since been accepted.[94]

The term does not appear in the other major music dictionaries or encyclopaedias.

The most unequivocal definition of extended technique is in the consumer-edited online encyclopaedia, Wikipedia. Although it cannot be held up as a measure of accuracy, Wikipedia is a measure of popularity and public and industry debate regarding a topic.

The Wikipedia entry ‘Extended Technique’ states that:

> Extended technique is a term used in music to describe unconventional, unorthodox or "improper" techniques of singing, or of playing musical instruments.[95]

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[94] Hugh Davies. "Instrument modifications & extended performing techniques." In *Grove Music Online*. *Oxford Music Online*, <http://www.oxfordmusiconline.com/subscriber/article/grove/music/47629> (accessed 13th August, 2009).

[95] <http://en.wikipedia.org/wiki/Extended_technique> page last modified 1st August 2009 (accessed 13th August, 2009).

The article outlines extended techniques for string instruments under the following headings:

1 Bowing techniques
    1.1 Bowing on the body of the instrument
    1.2 Bowing on the bridge
    1.3 Bowing the tailpiece
    1.4 Scratch tone
    1.5 Bowing behind the bridge
2 Plucking techniques
    2.1 Buzz pizzicato
    2.2 Snap pizzicato
    2.3 Nail pizzicato
3 Tapping techniques
    3.1 “Silent” fingering
    3.2 Striking the strings
    3.3 Tapping on the instrument
4 Miscellaneous effects
    4.1 “Chewing”
    4.2 Bow screw glissando[96]

Although the Wikipedia contributors make a more direct attempt at defining extended technique than found in Grove, there are some ambiguities here, not least the unusual choice of names for certain individual techniques (for example ‘nail’ *pizzicato* and ‘chewing’). The definition is in flux because the idea of what is unconventional, unorthodox and improper changes with time and with practice. In a sense a technical canon exists: there is a common awareness, notation and use of certain techniques at a point in time and a sense of certain techniques being conventional, orthodox and proper. Before techniques are standardised as part of this canon they could be described as ‘extended’.

[96] <http://en.wikipedia.org/wiki/String_instrument_extended_technique> last modified 28th June 2009 (accessed 13th August, 2009).

However this line is very difficult to draw. For example *col legno battuto* and *snap pizzicato* are considered extended by Grove and Wikipedia's definition respectively. However, both are certainly commonplace and, in not requiring extra performance notes in the score, conventional.

Describing some techniques as 'extended' or 'modern' implies being able to distinguish them clearly from 'non-extended' or 'standard'. Such a task is difficult as it is often impossible to draw an unambiguous line between the two, especially where new techniques are a development of well-established technical practice. For example when does decreased bow pressure go beyond *flautando?* When does 'fast *vibrato'* become 'exaggerated *vibrato'*? How precise a sub-categorisation of *sul ponticello* or *sul tasto* can be labelled extended (e.g. 'extreme *sul tasto',* 'one centimetre from the bridge' or 'on the bridge')?

It is possible to conceive of something that might be labelled 'extended' although it doesn't sound 'extended'. For example, one could build a plectrum that is exactly the same shape and density as a finger. It would produce exactly the same sound as *pizzicato normale*; there would be no audibly recognisable extension to technique although the excitation method uses resources outside the norm. Should an 'extension' to technique be audible? Surely categorising a method as 'extended' is misleading if the resulting sound can also be produced within non-extended technique.

Another difficulty is that, although the term 'extended technique' was introduced in the twentieth century, such experimentation cannot be said to belong to a single period in time; 'extended' techniques are also present within Renaissance, Baroque, Classical and Romantic technique. Examples from composers as diverse as Biber (who prepared a double bass string with paper), Monteverdi (who probably invented *tremolo* on stringed instruments), Pagannini (who wrote high harmonics) and Mahler (who used *col legno*) demonstrate an 'extension' of contemporarily conventional playing that predates the terminology. In other words, categorising techniques as outside the canon also creates contradictions in a historical sense. The terminology was developed after the techniques themselves; it was conscious and deliberate. Salzedo, in his early example of a handbook to modern instrumental technique, shows no desire to separate techniques by language, despite the pioneering nature of his methods. He writes of technique in general: ‘There is nothing difficult. There are only NEW things, *unaccustomed* things.’[97]

More important than proving inconsistencies in definition of ‘extended technique’ is to consider the effect of the word, its synonyms and the atmosphere that created them. I believe that the use of new terminology has been fractious. Separating extended technique from traditional technique, without being able to define the difference, causes problems. This fracturing of technique is closely linked to the catalogue problem defined above: techniques have been divided and organised into catalogues under frameworks that do not exist. The context of newly developed techniques is obscured. The extent to which performers can apply traditional technical practice to new methods is unclear.

MY APPROACH

I propose joining the separate ideas of technique (extended, unconventional, traditional, etc) and viewing cello technique as a flexible whole that can be developed. Where links exist between catalogued techniques they should be acknowledged and described as aspects of a single method or family of methods. The theoretical importance of my proposal is: if it is possible to imagine a hypothetically complete space of ‘every sound that can be produced on the cello’, then outside the techniques of the past and past musics (overlapping and constantly shifting with time) and present (whether labelled conventional and/or extended) are ‘undiscovered’ techniques, or ‘improper’ playing that are yet to be treated musically. In reality, all technique is bounded by the physical abilities of the performer and the instrument, and this is the ‘true’ limit on technique. Technical development (historical and personal) then can be understood as taking place within a whole potential space.

[97] Carlos Salzedo, *Modern Study of the Harp,* 6.

To move from this theoretical ideal to a practical approach I asked myself the following key research questions:

> Can cello technique as a whole be reduced to a minimum number of actions?
>
> Is it possible to organise the variation of these actions upon a continuum (a set of continuous ‘scales’) and link this to scales of sound (increasing and decreasing magnitudes of pitch, loudness, and overtone content)?
>
> If so, can we define the parameters and suggest the limits of these scales, i.e. explore the scope of an action (the range in loudness, pitch and overtone content that are available to the cellist)?

This approach views unusual techniques in the same (essentially musical) way that we view traditional techniques asking, for example: how loudly can I play this? What happens if I increase bow pressure? What are the differences in high and low positions? Regarding traditional techniques this might seem overly analytical, it might seem to make a process of something which is natural/instinctive (for example: I can increase the loudness of a *pizzicato* tone by increasing the force of my plucking finger, or: I can increase the overtones in the timbre of a bowed tone by moving the point of contact towards the bridge). Technique is discussed in this way in the early stages of learning an instrument. For new techniques such an application seems appropriate, because we are also learning them for the first time.

The key to realising the proposed continuity is firstly, the ‘reduction’ of technique. Here I mean to imply that technique is a group of parameterised actions and that, since the parameters of action are continuous, they can be organised on scales, which have natural limits. Any part of technique that can be assigned to the same scale is part of the same particular parameter of action. For example the action of exciting a string (by bowing, plucking of striking it) is parameterised by point of contact, bounded by the limits of the bridge and the nut. Similarly, the parameter of excitation force is bound by the minimum and maximum force a particular arm can apply.

The second process in the organisation of technique is mapping instrumentalists' actions to sound. Here I mean mapping in the mathematical sense: relating two sets (in this case the theoretically complete spaces: 'actions possible on the cello' and 'sound that a cello can produce') by linking the objects (actions and sounds) within them. This is the key idea of my research: to create a cello 'map'. Since each parameter of action is continuous, the relation action-sound can be described on a scale. For example: point of contact is proportional to the number of overtones present in the resulting sound; excitation force is proportional to loudness. While the parameters of the actions, the inputs, are continuous, the resulting sound, the outputs, need not be. For example: as contact point moves towards the bridge (continuously), overtone content becomes richer, then at a certain point lower partials begin to drop out of the sound. Or: as excitation force increases (continuously), loudness increases, then these increases tail off and eventually the sound becomes distorted.

My reduction of cello technique in terms of actions, associated parameters and sound is as follows:

Input: actions and their parameters

Actions that generate vibration:

- Plucking (with a plectrum, traditionally the right-hand fingers)
- Striking (with a hammer, usually the wood of the bow)
- Bowing or stroking (with any bowing object, traditionally the bow)[98]

Actions that interfere with the vibration (before/after it has been generated):

[98] The neutral terms 'plectrum', 'hammer' and 'bowing object' open the possibilities of each action. They are wider, 'families' of technique. For example, the plectra 'family' includes the traditional finger, guitar plectrum etc. The principles of controlling sound are applicable to each member of the family.

- Stopping/touching the strings (shortening the string or harmonics)
- Allowing external elements to absorb vibration (mutes, preparations, rattles)

Parameters:

- Point of excitation/interference:
    - The cello strings between nut and bridge, between bridge and tailpiece (including the wrapped part of the string) and in the peg box
    - The cello body/bridge/tailpiece/pegs/fingerboard (without touching the strings)/end pin
- Force of excitation:
- Distance of ‘pull’ of pluck
- Speed of attack of strike
- Pressure and speed of bow (or alternative object)
- Direction of excitation:
- Angle of pluck/strike/stroke
- Quality of object which initiates excitation:
    - Width/density of plectrum
    - Width/density of hammer
    - Width/density/tilt/material (i.e. bow hair, wood of bow, fingers) of bowing object
- Length and tension of strings
    - Position of stopping finger
    - Amount by which the string is ‘stretched’ by peg (or other object)
- Nature of interference
    - Pressure and material of stopping finger (or alternative stopping object)
    - Quality of mute/other external object: width/density and pressure/angle at which it is applied

Musical Output:

- Pitch

- Loudness
- Timbre
- Duration

Viewing technique in such a way shows the simplicity of the idea behind a reduction of technique. The musical output seems especially simple. Of course, using technique in such a way that pitch, loudness, timbre and duration are musically interesting is not simple, but this is not my task. In my opinion, the most useful handbooks separate technique from musical taste. My aim is to demystify technique: to put taste to one side and to explain methods, previously discussed only in an opinion-based, or mystical way, that are in fact technical. To show, simply, how a player/composer can influence sound.

The process of connecting parameters of action to parameters of sound is fundamental to realising the proposed cello 'map'. It required background reading and empirical research in acoustics. Stating the importance of linking action and sound seems so obvious as to be banal; of course an instrumentalist should always be aware of his/her influence over sound. An insufficient link between action and sound is a most basic and serious problem, but it is widespread and occurs especially in the case of new techniques described above in the literature review and below in the discussion regarding notation. The link between actions and sound is acoustics. A basic acoustical understanding is often incorporated in the teaching of a musical instrument. This understanding need not be as deep as a scientist's but is nonetheless clear and conscious.[99] In fact, there is a propagation of false information that is remarkably widespread, and part of the problem of an insufficient link between action and sound. For example, Garth Knox, in his recent book of viola studies, mentioned above, gives a short introduction to each of the technical themes around which the studies are centred. He uses acoustics to help the player understand the sound but presents frequent misunderstandings:

[99] It is not unusual for instrumentalists to have some scientific training as part of their studies. Physiological understanding is also necessary to instrumentalists, and, unlike acoustics, often taught at conservatoires.

> The closer the bow plays to the bridge [in *sul ponticello*], the more the high harmonics of the note being played become audible.[100]

> [In *sul tasto*] the bow is actually preventing the string from vibrating freely, reducing the high harmonics.[101]

> By touching the string lightly with the left hand at strategic points on the string, we can obtain single partials, and these are called harmonics.[102]

PRACTICAL APPLICATIONS

Naturally, under my method, traditional and new techniques are treated in the same way; they are both part of the global view: 'everything that is possible on the cello'. In this sense I am working outside music history, not prioritising, for example, bowed sound because it has been used most often.[103] The strength of fitting new and old techniques into a global technique is the enabling of application of information. I use the terms 'plectrum', 'hammer' and 'bowing object' in a neutral way to open possibilities. The knowledge we have relating to plucking with the finger can also be applied to plucking with a guitar plectrum (e.g. moving towards the middle of the string reduces overtone content); the knowledge we have relating to *col legno battuto* can be applied to *Fingerschlag,*[104] (e.g. the duration of hammer-to-bridge tone is maximised when the hammer is held to the string); the knowledge we have about bowing can be applied to stroking the cello strings with the hands (e.g. the faster the stroke, the louder the resulting tone). In other words this global view exposes ways of influencing sound that might not otherwise have been obvious.

The idea of a global technique also impacts upon the debate about notation. Notation has been the source of much contentious and divisive debate since

[100] Knox, *Viola Spaces,* Supplementary booklet, 1.
[101] Knox, *Viola Spaces,* Supplementary booklet, 1.
[102] Knox, *Viola Spaces,* Supplementary booklet, 4.
[103] This is in line with Lachenmann's comment: 'the clean, nice, full cello sound is a special case in the various possibilities of bow pressure, bow speed and point of contact' (trans. author).
Helmut Lachenmann, ed. Joseph Häusler, *Musik als Existentielle Erfahrung* (Kassel: Bärenreiter, 2004), 381.
[104] *Fingerschlag* is tapping the strings against the fingerboard with the fingers.

the middle of the twentieth century. The main perceived problem is that multiple notations exist for similar techniques, or the same notations are used for different techniques and sounds. There are two main roots to this problem, each of which as a consequence tends to consider technique in a fractured, 'discontinuous' way. Firstly, many timbre-based techniques have been devised which cannot be represented on a stave-like system; timbre is incommensurable. Therefore composers have used prescriptive notation, describing instrumentalists' actions rather than the desired sound. Where performers focus on reproducing actions rather than reproducing a stipulated sound, there is a danger that the listening and refining part of the rehearsal process can become marginalized, particularly when working with unfamiliar sounds. The link between the notated action and a particular sound is not clear. Secondly, a personal/school-based nomenclature has developed in line with experimentation as composers have developed techniques form individual perspectives. Techniques have been 'discovered', labelled, notated and catalogued without being linked to other (new or traditional) methods (perhaps in some cases, in the spirit of pioneering new sound or being loyal to a particular compositional school, it was even seen as desirable to disconnect them from traditional practice). The context of a technique becomes obscure and, in bearing no relation to known technique, and therefore having no application to known sound, possibilities for variation are obscured. In the most extreme sense this creates an atmosphere of special effects that are reproduced without variation by composers and performers. How much musical variation would an instrumentalist consider possible in a *Bartók pizzicato,* a tone bowed with overpressure or tapping the instrument body? Or, as an instrumentalist, how would you comply if a *Bartók pizzicato* were marked *sostenuto?* If a tone bowed with overpressure were marked *piano?* If tapping the instrument body were marked *overtone-rich*?[105]

Notation is an important issue: prescriptive notation is necessary and multiple notations are inevitable. Notational issues can, to an extent, be dealt with by standardisation but, ultimately, technical understanding, particularly the relationship between instrumentalists' actions and sound, is the only way of

[105] This is linked to the 'catalogue problem' observed in the literature review.

overcoming notation-related problems. The musical, interpretive part of the process of reading from a score is asking: which elements of sound are not notated? What spectrum/degree of flexibility is available to me within a particular notation? How can I change the sound within this? This involves establishing a sphere of the possible variations within an adherence to the notation and choosing from this sphere. Knowledge and clarity maximise the scope of this choice; technical knowledge increases interpretive freedom. If the link between sound and action is unclear, interpretive boundaries are set which are different from the composer's intentions. A notation-based or a catalogue approach to technique can lead to the unintentional restriction of interpretive and compositional freedom. A continuous approach to technique facilitates individuality of expression and makes a performance more informed. It gives the instrumentalist the resources to be musical, which is, in fact, a good definition for technique in general.

METHODOLOGY

The key steps in my methodology were:

1. Reducing cello technique into actions and developing continuous scales for parameters of these actions
2. Linking action and sound
3. Structuring the information in a consistent and logical way

The reduction of cello technique is described above. The second step, linking these scales of parameters of action to sound, involved a considerable amount of background reading in acoustics. Where relevant acoustical information was lacking I undertook empirical research (see Appendix) or proposed areas for further study. Thirdly, I divided the information into four sections with minimum overlaps: Excitation of the string; Harmonics;[106] The Prepared Cello and Excitation of the Body, Bridge, Tailpiece and Bow Hair. The parameters of action set the titles of the subheadings ('Point of contact', 'Force of excitation'

[106] Harmonics are presented separately to 'excitation of the string'. Many of the acoustic principles regarding harmonics require further explanation, and are sometimes considerably different to *ordinario* stopped string vibration. Were the two to be presented alongside one another the text would be very fragmented.

etc.) and these are discussed in relation to sound. The actions ‘plucking’, ‘striking’ and ‘bowing’ are referred to specifically as subheadings if additional information is required. Where extra scientific information exists and might be useful to the understanding of the parameters, an Explicatio subheading is included.

MY OBJECTIVES

Finally, the objectives of this handbook, presented under the same terms as I used to review the literature above, are as follows:

Purpose: I aim to present a global cello technique (incorporating new and old methods) in a clear and continuous way.

Structure: The text is structured according to the cellist’s actions, in a logical order. It is not narrative, to be read from beginning through to end. It is not intended as a catalogue; it provides an explorative answer rather than a direct answer to a question regarding technique. Rather than referring to a traditional word-by-word index, the reader navigates her/his way around the research by the means of either an Actions Index which lists the headings and subheadings as they appear in the text, or a Parameters of Sounds Index which lists description of the sound outcome in terms of pitch, loudness, overtone content and duration and refers the reader to the relevant section of text.

Content: The information links actions and sound with a basis in acoustics. It is a step back from the score and needs application. The information will be neutral, outside of historical context and, as such, without composer references, citations of scores and notation examples. There is no section for miscellaneous or extra techniques; every aspect of sound discussed has a logical place in the global framework. Information regarding theatrical aspects, movement, singing and speaking, amplification and electronics is not included because it does not relate to the technique of playing the cello and, especially in the case of amplification and electronics, is well researched and explained in the specialist literature.

This is the first time that instrumental technique has been treated as a continuum. An investment is required to obtain the acoustical understanding implicit in this approach. However, the idea itself provides a simple solution to the problems presented in this text, observed both in the literature and the ideas surrounding technique. These problems (insufficient connection between action and sound, one-off catalogued special effects, notational issues, misconceptions concerning acoustics, and contradictions in the debate regarding new instrumental techniques) restrict interpretive freedom. The continuum presents a way of tackling these problems directly, by reopening interpretive freedom. Naturally, organising the actions of a cellist on continuous scales exposes the means of modifying sound by degrees. In so doing, it rejects special effects and expands the possibilities of musical expression. This way of presenting technique provides a framework for further research, which can be taken up and expanded upon by instrumentalists, composers and acousticians.

How to use this resource

This resource is not intended as a catalogue to look up specific effects by name or notation. Neither is it a historical document, referencing certain composers' usage of technique. Rather, information is given about cello technique that is as broad as possible, with the aim that the reader expands upon this to find a solution to fit their specific purpose. The resource addresses technique in its broadest sense, therefore information is relevant to both traditional and new methods. The parameters of the cellist's actions are outlined and are always connected to the control the cellist has over sound. The simplest and most efficient way to use the resource is with a cello to hand to work through the described actions and sounds.

I have structured the resource around the cellist's actions because it is possible to organise them on a continuous scale. For example, bow pressure can be described on a scale from low to high; contact point, from bridge to nut etc. These scales of actions are linked to scales of 'output', i.e. sound, which are not necessarily continuous, for example: an increase in loudness, which, at a certain point is overtaken by noise. Information is ordered starting with the movements of the right hand and followed by the movements of the left. The resource is split into four sections: 'Section A: Excitation of the string', 'Section B: Harmonics', 'Section C: The Prepared Cello' and 'Section D: Excitation of the Body, Bridge, Tailpiece and Bow Hair'. The structure follows a logical pattern but the information does not have to be read in the order in which it is presented. Cross-referencing is provided at every stage of the resource to refer the reader to other relevant sections. The reader should therefore be able to dip into the resource at any point and use it to look up information related to a specific question. In order to find the required information, two indices are available to the reader: the Actions Index and the Parameters of Sounds Index. The Actions Index lists all of the headings and subheadings in the order in which they appear in the text. The reader can follow this extended list of actions to find the required information. Alternatively, the Parameters of Sounds Index lists the possible sound outcomes under the headings Pitch, Loudness, Decay Duration and Overtone Content. These are subcategorised into: ‘String vibration, clearly pitched sound’, ‘Harmonics’ and ‘Semi-clear pitches and/or noise-like sounds, vibration of the cello body’. The reader can use this index to sort through information from the perspective of sound. The Action and Parameters of Sounds Indices are duplicated in loose pages in the back of this thesis for the convenience of the reader.

In approaching the Actions Index, the reader will have to ‘generalise’ the particular action. For example: if the reader wants to know what happens when bow pressure is increased s/he starts at ‘Excitation of the string’ (rather than ‘bowing the string’), scans the actions index to find the entry ‘String displacement and excitation force’ (rather than ‘bow pressure’), reads the following subheadings to search for entries relating specifically to bowing, and refers to the relevant part of the text. On the other hand, if the reader wants to know how to maximise the decay of plucked harmonics s/he refers to the Parameters of Sounds Index, starts at ‘Decay Duration’, scans down to find ‘Decay duration of plucked and struck tones’ under ‘String vibration, clearly pitched sound’ and ‘Decay duration of harmonics’ under ‘Harmonics’ and follows the references to the relevant text.

The information in the text is given in the following form: the aspect of technique in question; the parameters within which the cellist can control this; and the aural effect of changing these parameters. These facts are given as concisely as possible. An Explicatio section might follow the main section with the purpose of giving more in-depth scientific information that could be of interest to the reader. In general, the explicatio sections explain why the facts in the main section are true. That is to say that the explicatio sections give a wider background to the facts but do not contain any new information relating to the particular technique in practice. Therefore these sections are more abstract and contain more acoustics. Since they often cover the same ground, albeit in more detail, there is a certain amount of repetition, which I have tried to minimise. At the end of each section there is a summary of the information included in the main and explicatio subsections. This will help the reader to extract the key points for each subsection and browse through the main points in search of a particular piece of information.

In trying to be as efficient as possible with information, plucking, striking and bowing are grouped into the more general ‘excitation’ of the string/cello body etc. If further information, specific to plucking/striking/bowing is required it follows this section, sub-headed: ‘Applications specific to plucking/striking/bowing’.

Before using this resource

A certain amount of acoustical knowledge on the part of the reader is assumed. A number of key words are used throughout: amplitude, antinode, cent, coupling, damping, decay, density, excitation, frequency, masking, node, partial, period, and wavelength. If these words are new to the reader, s/he is advised to refer to an introductory acoustics textbook such as Benade's *The Fundamentals of Musical Acoustics*.[107] I have invented certain terms: piano- and clavichord-type battuto (defined in A0), overtone-takeover (defined in A1.2), horizontal and vertical *pizzicato* (defined in A3), harmonic cluster (defined in A5.2), touch point (defined in B1), touching finger (defined in B1) and double-touching (defined in B12.1). These are explained as they are introduced into the text. A general introduction to the terminology used when discussing plucking, striking and bowing a string is given in subsection A0.

To indicate pitch, C4 is described as middle C (i.e. B4 is one seventh above middle C, C5 is one octave above middle C and C2 is the lowest cello string).

[107] Arthur Benade, *The Fundamentals of Musical Acoustics* (2nd edn., New york: Dover Publications, 1990).

Actions Index

Parameters of Sounds Index

Pitch

STRING VIBRATION, CLEARLY PITCHED SOUND

- Pitch of a string excited ‘above’ the stopping finger **A1.1**
- Pitch bends
    - by increasing excitation force **A2**
    - by changing the tension of the string **A6.2, A6.1**
- Pitch of Bartók *pizzicato* **C2**
- Pitch of the various components of *battuto* tones **A0, A1.2, A5.2**
- Pitch content of striking the strings from side to side **A3**
- Pitch when slide (quasi guitar slide) is used **A7**
- Pitch of strings between bridge and tailpiece **A8**
- Pitch of strings in peg box **A8**

HARMONICS

- Pitch of harmonics **B2, B14**
- Pitch components of harmonics **A5.2, B6**
- Pitch content of multiphonics **A5.2, A5.3, B13**
- Pitch of artificial harmonics **B10**
    - Pitch of harmonics when more than one node is touched simultaneously **B11**
- Pitch bends and vibrato in harmonics **B12.2**
    - Pitch *glissandi* of harmonics and artificial harmonics **B12.5**
- Pitch of harmonic trills **B12.3**
- Pitch content of harmonic *bisbigliando* effect **B12.4**

- Pitch of double-touched harmonics **B12.1**

SEMI-CLEAR PITCHES AND/OR NOISE-LIKE SOUNDS, VIBRATION OF THE CELLO BODY

- Pitch content of overpressure bowed sound **A2**
- Pitch content of noisy, vertical square circular bowing **A3**
- Pitch of *col legno tratto* with the bow stick or another object **A4**
- Pitch content when object is used to rattle against the string **C2**
- Pitch of strings prepared with fixed objects **C3**
- Pitch of strings which are linked together in some way **C4**
- Pitch content when the body, bridge, tailpiece of the cello is plucked, struck or bowed/stroked **D1**

Loudness

STRING VIBRATION, CLEARLY PITCHED SOUND

- Loudness of a plucked, struck bowed tone **A2, A3**

HARMONICS

- Loudness of harmonics **B1**
- Loudness of harmonics by changing excitation force **B4**

SEMI-CLEAR PITCHES AND/OR NOISE-LIKE SOUNDS, VIBRATION OF THE CELLO BODY

- Loudness of noise if an object is allowed to rattle against the string **C2**
- Loudness of Bartók *pizzicato* **C2**
- Loudness of noise when strings are prepared with fixed objects **C3**
- Loudness when other objects are pressed against the body of the cello **D3**

Decay Duration

STRING VIBRATION, CLEARLY PITCHED SOUND

- Decay duration of plucked and struck tones **A3**
- Decay duration of plucked, struck and bowed tones **A5.2, A5.3**
- Decay duration of *fingerschlag*, (finger slaps/taps, hammer on) **A4**

HARMONICS

- Decay duration of harmonics **A5.3, B8**

SEMI-CLEAR PITCHES AND/OR NOISE-LIKE SOUNDS, VIBRATION OF THE CELLO BODY

- Decay duration of normal tone and noisy tone as an object is allowed to rattle against the string **C2**
- Decay duration of Bartók *pizzicato* **C2**
- Decay duration of strings prepared with fixed objects **C3**
- Decay duration when the body, bridge, tailpiece of the cello is plucked, struck or bowed/stroked **D1**

Overtone Content

STRING VIBRATION, CLEARLY PITCHED SOUND

- Overtone content of plucked, struck and bowed tones **A1.2, A2, A4, A5.1, A5.2**
- Overtone content of *flautando,* weak-sounding tones **A2**
- Overtone content of strings tuned *scordatura* **A6.3**
- Overtone content of tones muted by damping the string **C1**
- Overtone content of a string muted at the bridge **C5**
- Overtone content of left hand *pizzicato* **A1.2**
- Overtone content of *fingerschlag*, (finger slaps/taps, hammer on) **A4**

HARMONICS

- Overtone content of harmonics **A5.2, A5.3, B1, B3, B4, B5, B8**
- Overtone content of artificial harmonics **B10**
- Overtone content of harmonics when more than one node is touched simultaneously **B11**

SEMI-CLEAR PITCHES AND/OR NOISE-LIKE SOUNDS, VIBRATION OF THE CELLO BODY

- Overtone content of normal tone and noisy tone as an object is allowed to rattle against the string **C2**
- Overtone content of Bartók *pizzicato* **C2**
- Overtone content of noise when strings are prepared with fixed objects **C3**
- Overtone content of a string muted at the bridge **C5**
- Overtone content when the body, bridge, tailpiece of the cello is plucked, struck or bowed/stroked **D1**
- Overtone content of a string muted at the bridge **C5**
- Overtone content when other objects are pressed against the body of the cello **D3**

Index of figures

The Resource

Section A Excitation of the string

The vibrating string is discussed. Ways of influencing the overtone content, loudness and duration of string excitation are explained.

A0 Definitions of plucking, striking, and bowing a string

For a thorough description of the mechanisms of plucking, striking and bowing the string, the reader is advised to refer to a musicians' guide to acoustics. I particularly recommend that by Arthur Benade.[108] For the purposes of the terminology used in this resource they will be defined in the following way. As mentioned in the introduction to this resource, I try to be as broad as possible in describing aspects of technique. Therefore, the term 'exciter' is the general term used to refer to any object that excites vibration and, more specifically, the terms 'plectrum', 'hammer' and 'bow' are used as general terms within each method of excitation. These terms are collective descriptions for all potential excitation objects e.g. plectrum, finger, bow stick, bow hair etc.

PLUCKING

A plectrum (traditionally the finger) pulls the string, and, upon releasing it sends two kinks of vibration from the contact point, one in the direction of the bridge and the other in the direction of the nut. The kinks are reflected at the bridge/nut or, in the case of a stopped string, at the stopping finger. This process continues until the excitation energy has been expended.[109]

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[108] Arthur H. Benade, *The Fundamentals of Musical Acoustics* (2nd edn., New york: Dover Publications, 1990).

[109] Carleen M. Hutchens, 'How the violin works' in *Sound Generation in Winds, Strings, Computers* (Stockholm: Royal Swedish Academy of Music, no. 29, 1980), 154-5.

STRIKING

A hammer (traditionally the wood of the bow) strikes the string. Two systems of vibration take place:

- Firstly, kinks of vibration are sent from the hammer to the bridge and the nut, one kink in each direction. This vibration is reflected at the bridge/nut and returns to the hammer where it is reflected again. This process continues as long as the hammer is in contact with the string (or until the excitation energy is expended). Two pitches are heard, those associated with the lengths of string between hammer and bridge and hammer and nut. I will refer to this as 'clavichord-type' vibration.[110]
- Secondly, as the hammer leaves the string, the vibration is able to pass its impact point and the kinks of vibration are reflected between the bridge and nut or stopping finger. Vibration continues until the excitation energy is expended. The resulting pitch is that associated with the length of string from nut/stopping finger to bridge. I will refer to this as 'piano-type' vibration.[111] This tone is usually the most prominent within the sound and is traditionally the notated pitch.

The vibrating string lengths are measured from the bridge-/nut-*edges* of the hammer and the stopping finger. This is clear from the figure below. *Two* clavichord-type pitches only sound simultaneously in the special case of an open string. For a stopped string, clavichord-type vibration is present between hammer and stopping finger but it is inaudible because it cannot be transmitted to the cello body.

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[110] This is because the physical process is similar to the system inside a clavichord, where a hammer is thrown onto the string by the action of the keys and *remains* on the string during vibration. The string vibrates on both sides of the hammer but only one of these vibrations is heard in the case of the clavichord, the other is damped. See: Charles Taylor, *The Science and Technology of Tones and Tunes* (Bristol: Institute of Physics Publishing, 1994), 124.

[111] In this case, the process of exciting vibration upon release of a hammer is similar to the mechanical action of a piano's hammers as the keys are depressed. See: Donald E. Hall, 'Piano string excitation in the case of a small hammer mass', *Journal of the Acoustical Society of America*, Vol. 79 (1986), 141-7.

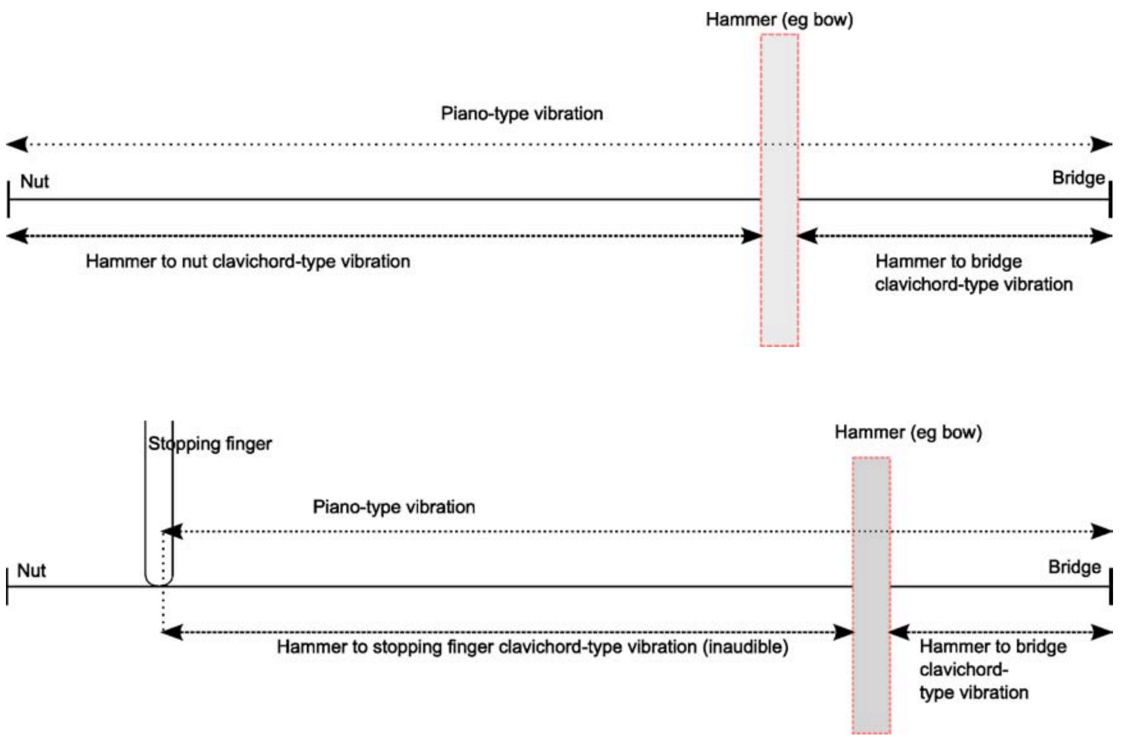

Figure A0 Clavichord- and piano-type vibration for an open and stopped string.

BOWING

The bow is drawn across the string. Vibration is caused by a repeating cycle of excitation: initially the string 'sticks' to the bow and moves with it, sending a kink of vibration to the bridge, where it is reflected. The tension of the stretched string increases and as the kink of the displaced string returns to the bow, the string breaks free from the bow and 'slips' back to its rest position. This is known as the 'stick-slip' process.[112]

When the bow is used in the traditional way, a cellist can influence the sound by changing three elements: bow speed, point of contact and bow pressure. These three properties are dependent upon one another (i.e. the limits of bow pressure vary for different bow speeds and contact points). The simplest way to view this relationship is that the 'optimum' and maximal/minimal bow speed and pressure vary for each contact point. In other words, for every contact

[112] Hutchens, 'How the violin works', 154-155.

point there is a band of values within which a ‘normal’ arco sound can be produced. Furthermore, for every fixed point of contact, a change in bow speed is also a relative change in bow pressure.

Vibration continues as long as the bow draws the string. When the bow is removed from the string, the string vibration decays until the excitation energy is expended.

A1 Point of contact

A1.1 ‘Ordinario’ and ‘behind’ the stopping finger

The stopped string can be excited ‘ordinario’, between finger and bridge, or ‘behind’ the stopping finger, between finger and nut. The string vibrates between the *bridge-edge* (rather than the middle) of the stopping finger and bridge (‘finger-to-bridge’) or between the *nut-edge* of the stopping finger and nut (‘finger-to-nut’).[113] The respective string lengths are shown in the following figure.

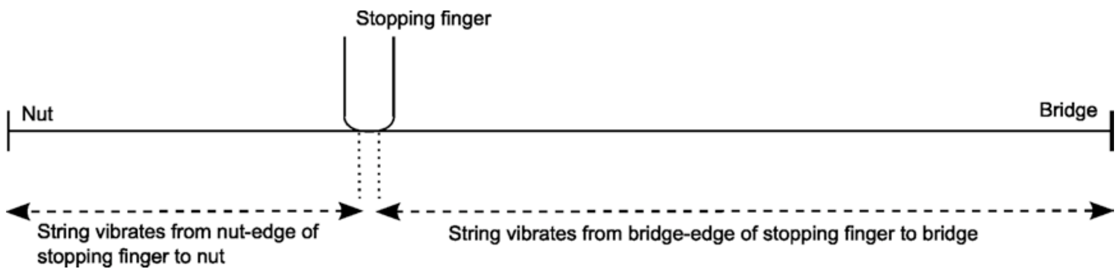

Figure A1.1a The two lengths of string either side of the stopping finger.

[113] For coherence and to avoid overuse of long-winded terminology, when ‘finger-nut’ or ‘finger-bridge’ occurs in this thesis, it can be assumed to mean ‘nut-edge of finger to nut’ or ‘bridge-edge of finger to bridge’, with the exception of harmonics.

For similar string lengths, finger-to-nut vibration is slightly less overtone rich, quieter and faster to decay than finger-to-bridge vibration.

Explicatio A1.1

The distinctions ‘nut-’ and ‘bridge-edge’ are important in defining the corresponding pitches. The bridge edge of the finger is at the centre of the fundamental’s node.[114] Because the portion of string under the stopping finger does not vibrate (this is clear in the above figure), the string length ‘finger-to-bridge’ added to ‘finger-to-nut’ is the total string length minus finger width. If this is not considered when calculating the finger-to-nut pitch, it will sound slightly sharper than expected.

For example: In the figure below, the A string is stopped at 2/3 of its length, producing an E4. The remaining portion of string is 1/3 of the total length, which corresponds to an E5 one octave higher, since it is half of the stopped length. However, keeping the stopping finger in the same position and exciting the string behind it produces a sharp E5 because, taking finger width into account, the string length is slightly less than half of the stopped string length. Clearly this sharpness varies from cellist to cellist, from finger to finger (the degree of sharpness increases with finger width).

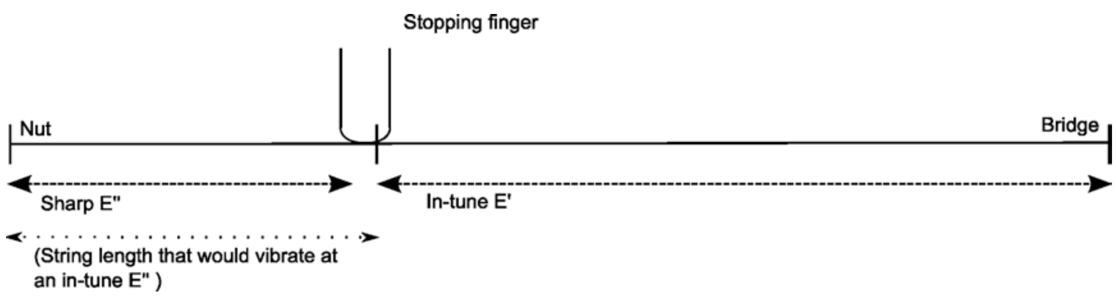

Figure A1.1b Two lengths of string either side of the stopping finger. The actual vibrating string lengths are shown alongside the hypothetical length if finger width is not taken into account.

[114] This is in contrast to harmonics, in which case the *middle* of the finger is at the centre of the node.

Vibration between stopping finger and nut is quieter and decays faster than stopping finger-to-bridge excitation because the nut is less efficient than the bridge at transferring energy to the cello body; relatively more energy is lost through damping in the air or non-amplifying parts of the body (e.g. the fingerboard). In general, energy that is lost through damping inhibits the amplitude and decay-duration of higher partials more than those of lower partials.[115] Consequently, for fixed contact points,[116] stopping finger-nut excitation has a more *sul tasto* quality than stopping finger-bridge. The amplitude of finger-nut excitation is also restricted for a practical reason: the shallow angle between the string and the fingerboard in the region of the nut inhibits large movements in the plucking/striking/bowing action.[117]

A1.2 Proximity to the string's mid point

If a string is excited at its mid point, the contribution from overtones is minimised, producing the most extreme *sul tasto* timbre. The mid point is half way between bridge and nut for an open string and half way between finger and bridge for a stopped string. As the contact point moves away from the middle of the string, towards the bridge or the nut, sound becomes increasingly overtone-rich.[118] Overtone content is maximal for contact points close to the bridge or the nut/stopping finger. The change in timbre as contact moves from the mid point is symmetrical, i.e. excitations at a fixed distance from the bridge or nut/stopping finger are equivalent in tone colour.

As contact point moves very close to the bridge/nut/stopping finger, higher partials become more present in the sound than the fundamental. Eventually the fundamental is barely present or excluded completely. More precisely, there is a contact area close to the bridge/nut/stopping finger, where pitch is

[115] Benade, *The Fundamentals of Musical Acoustics*, 355.
[116] All other excitation conditions are also fixed (bow speed, plucking force etc.).
[117] Amplitude is proportional to string displacement (plucking/striking force and bow speed). This will be discussed in A2 String displacement and excitation force.
[118] This increase is uneven, see Explicatio below for more information.

dominated by the first overtone and a point closer still where the second and then the third overtone dominates. This effect, which I will call 'overtone-takeover', is difficult to control but can be heard up to the seventh or eighth overtone. The point at which this effect begins to take place, the 'overtone-takeover point', is variable. The proximity of the overtone-takeover point to the bridge/nut/stopping finger depends on:

- String length
- Excitation force (plucking/striking force, bow speed and bow pressure) and
- Exciter material/size.

The overtone-takeover point moves towards the middle of the string as:

- String length increases
- Excitation force decreases,
- Exciter density increases

and/or

- Exciter width decreases.

In other words the cellist can more easily find areas of overtone takeover and 'fine tune' playing to pick out particular overtones if the string is long, excited with low force (or in the case of the bowed string, low bow pressure, high bow speed) and a small, dense plectrum/hammer/bow (in the latter case, tilting the bow is equivalent to reducing width).[119] This 'filtering' of the lower overtones is more easily controlled when bowing the string because, unlike plucking or striking, excitation is continuous; the cellist can make small changes in contact point during excitation to find a particular overtone.

An approximation of the string's response to various contact points is summarised in the following figure:

[119] In fact, tilting the bow is not exactly equivalent to reducing bow width since the distribution of pressure is slightly different. However, the effect is very similar.

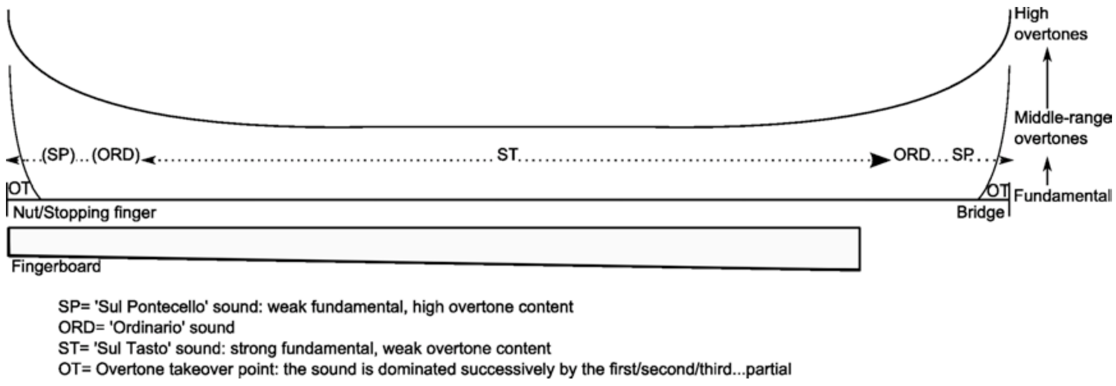

Figure A1.2a The overtone content for contact points along the whole string length.

Some obvious physical considerations restrict the extent of changes in contact point. In general, the exciter's manoeuvrability over the fingerboard is limited; the closeness of the string to the fingerboard restricts plucking/striking force and bow pressure, especially in the region of the nut/stopping finger. Therefore loud tones are more difficult to produce. The plectrum is more manoeuvrable than the hammer or the bow. However, some areas of the string over the fingerboard are more liable to produce unwanted *Bartók pizzicati* than others.[120] Striking and bowing are especially restricted if a long hammer/bow is used, particularly on the outer two strings, as the cello body/fingerboard obstructs the movement of the hammer/bow. The cellist has more freedom when hammering/bowing on the neck part of the fingerboard than over the body, although the shallow angle between the strings in this region makes unintended double stops likely. Controlling long bow strokes is especially difficult.

APPLICATIONS SPECIFIC TO PLUCKING

LEFT-HAND PIZZICATO

Left hand *pizzicato* is used to facilitate rapid changes between plucking and bowing, striking and/or plucking with a different timbre. If the left hand is also stopping the string, the pluck necessarily takes place close to the stopping finger, i.e. timbre is restricted to '*sul ponticello*'. The extent of this restriction

[120] For more information see C2 Dense objects or mutes as 'rattles'.

depends on the length of the vibrating portion of string. For shorter lengths of vibrating string, the cellist is able to pluck relatively further from the stopping finger.

APPLICATIONS SPECIFIC TO STRIKING

The point of contact decides the timbre of the piano-type tones and the pitch of the clavichord-type tones. In one sense the effect of changing contact point is reduced and in another sense the possibilities are increased compared to plucking and bowing:

The overtone content of piano-type tones broadly follows the above pattern with changing point of contact. However, for a particular change in contact point, the change in timbre is less extreme compared with plucking or bowing the string; the cellist’s control over timbre is relatively limited.

More significantly audible is the influence of point of contact on clavichord-type tones, primarily in controlling pitch:

The pitches of clavichord-type vibration are dependent only on the position and the width of the hammer;[121] they are equal when the string is struck at its mid point (i.e. when the mid point of the string coincides with the mid point of the hammer). As the contact point moves towards the bridge, the pitch of the hammer-to-bridge clavichord-type vibration is raised and the pitch of the hammer-to-nut clavichord-type vibration is lowered. This raising/lowering is heard as two pitches moving in contrary motion. If the string is stopped/dampened on one side of the hammer, only one pitch is heard. Figure A1.2b shows clavichord pitches for two different hammer positions.

[121] See A4 Choice of exciter width and density.

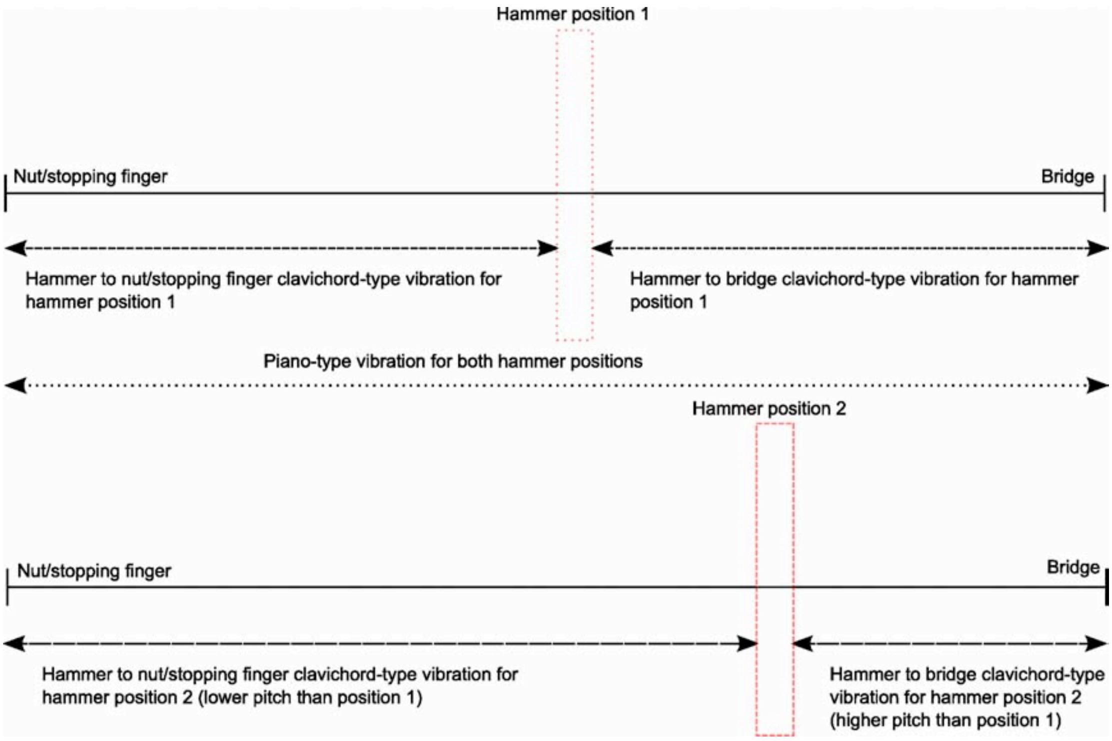

Figure A1.2b String lengths of piano- and clavichord-type vibration for two hammer positions.

In general the loudness of clavichord-type tones is proportional to string length, i.e. the lower clavichord tone is almost always louder than the upper. However, for fixed string lengths, hammer-to-bridge tones are slightly louder than hammer-to-nut. Therefore their amplitudes are not equal at the mid point, rather at a short distance from the mid point, towards the bridge. However, masking can play a significant role in the perception of clavichord-type tones, often concealing the lower pitch completely (especially if it is close to the piano-type pitch).

In addition, contact point indirectly affects the timbre of clavichord-type vibration. As the clavichord pitches become higher (i.e. the length of vibrating string becomes shorter), fewer overtones are present in the sound. The thinness of the harmonic spectrum is particularly noticeable at high pitches.

Very short lengths of string (excitation almost at the bridge/nut/stopping fingers) produce overtone-weak and quiet upper clavichord-type tones. In this case, the lower clavichord-type tone is necessarily close in pitch to the piano-type tone (being a bit less than the total vibrating string length), and therefore is often masked by it; the piano-type pitch is almost isolated in the sound.[122] This can be an effective way of filtering the clavichord pitches from the sound so that only the piano-type pitch is heard. The most effective way to exclude both clavichord tones (for a stopped string) is to strike very close to the stopping fingers. In this case the upper clavichord-type pitch (hammer to fingers) is not transmitted to the cello body and the lower clavichord-type pitch is usually well masked.[123]

The masking effect that piano-type tones have on clavichord-type is demonstrable by comparing an un-dampened struck tone to a tone struck with the same force, at the same contact point but isolated by damping between hammer and bridge. The hammer-to-nut pitch, which is clearly audible in the latter case, is usually inaudible in the former case, especially when the hammer is close to the bridge.

Another psychoacoustic factor is the ear's favouring of piano-type pitch over both clavichord-type pitches, probably because of the extremely short duration of the latter under 'normal' *battuto* conditions. The clavichord-type pitches are probably analysed by the ear as a transient part of the piano-type vibration rather than individually.[124] This effect is clear when comparing repeated *battuto* tones with a constant point of contact to repeated *battuto* tones with slight changes in point of contact. The wandering pitch of the clavichord-type tones in the latter case is tracked by the ear and makes clavichord-type *battuto* much more easily identifiable than in the former.

[122] For a stopped string, the clavichord-tone 'hammer-to-stopping finger' is in any case inaudible.
[123] This is physically restricted, but easier on the outer strings, especially for high left hand positions or if a short hammer is used.
[124] This is in a sense accurate, since they occur just before piano-type tones and stop as soon as the piano-type tone sounds.

APPLICATIONS SPECIFIC TO BOWING

For excitation exactly at its mid point, the bowed string deviates from the general pattern described above. Bowing at the mid point of a string produces a throaty, restricted and inconsistent sound with faintly recognisable pitch content.[125] If the string is stopped in a higher position and/or when very light bow pressure and a fast *flautando*-like stroke are used at the point exactly between stopping finger and bridge, a thin-sounding tone with reduced harmonic spectrum is heard. This can sound similar to clarinet or flute timbre.[126] The noise of the bow hairs moving across the string is very present in the sound.

Explicatio A1.2

For any point of contact, the player will always 'block' or restrict a number of overtones. Depending on which/how many, this can have a significant influence on timbre.[127]

In the plucked and struck string this 'blocking' occurs because the process of excitation necessarily fixes the portion of string under the exciter (in contact with the plectrum or hammer) as an antinode, since it is exactly this portion that is being maximally displaced. Partials with antinodes at or close to the excitation point will contribute to the sound. However, partials with a node at the excitation point, where the ideal value is zero, will have reduced amplitudes or be excluded from the sound.

For example in the following figure, the plectrum/hammer displace the string at its mid point. This is ideal for the fundamental (first partial), which has an

[125] In theory bowing in the middle of the string will produce no sound because the mid point is the only point on the string that is either an antinode or a node for all partials. Partials with both nodes *and* antinodes (in this case *all* partials) are subdued because bowing simultaneously enforces movement at a particular point and restricts it, since the string must move at the bow's pace. In practice, however, some sound is heard.

[126] This is because of the breath-like quality of the *flautando* bow stroke and because, like the clarinet, only odd-ordered overtones are present.

[127] Authur Benade refers to the mix of overtones for certain excitation conditions as the 'excitation recipe'. For a more detailed analysis of the effect of changing point of contact on the excitation recipe see: Benade, *The Fundamentals of Musical Acoustics*, 91-103.

antinode at this point, and restrictive for the second partial, which would ideally have zero amplitude at this point.

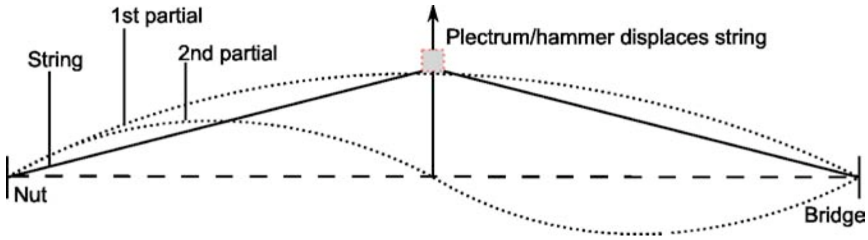

Figure A1.2c The shape of a string displaced at its mid point alongside the shape of the first two partials.

Excitation at the above point affects more than just these two partials; in fact excitation at any point affects every partial by either enabling or restricting its vibration. The pattern of the timbral response to each excitation point changes significantly throughout the string length. Below are some examples:

If the point of contact is one fifth of the way along the string, the fifth partial is removed from the sound, as are the tenth, fifteenth, twentieth, twenty-fifth… 5nth.[128]

[128] 5n is the multiple of 5 nearest to the total number of partials in which a string can vibrate.

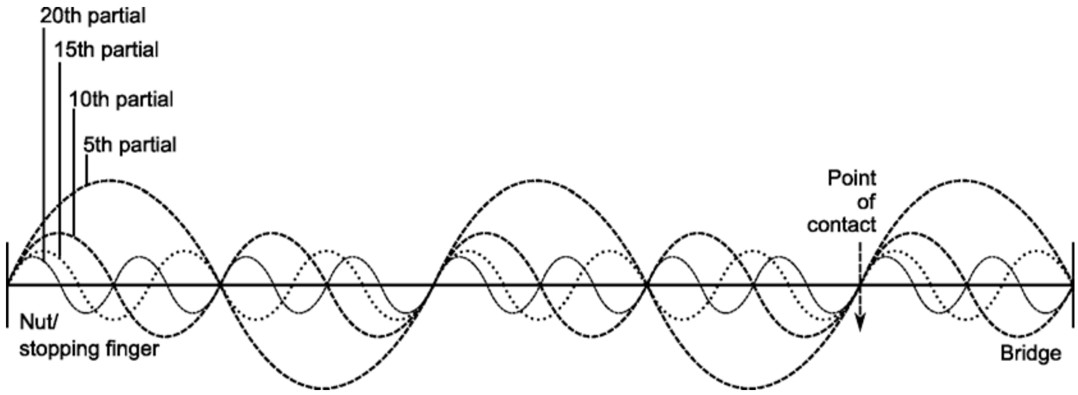

Figure A1.2d A contact point at a node of the 5th, 10th, 15th and 20th partials.

Since there are a finite number of partials in which a string can vibrate,[129] a fifth of the string's potential partials are excluded from the sound.

The number of higher partials in a tone is minimal when the point of excitation is at the middle of the vibrating length of string. The string vibrates with half of its potential overtone content, i.e. every other partial is excluded from vibration. This is the most extreme *sul tasto* timbre.

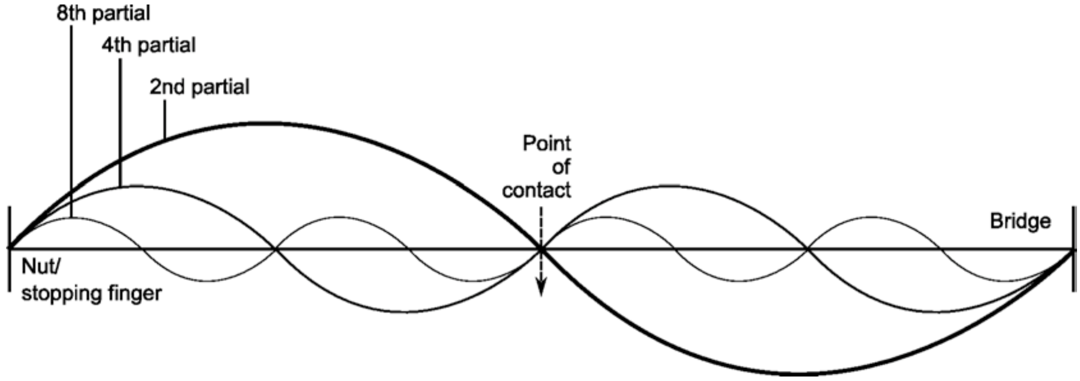

Figure A1.2e A contact point at a node of the 2nd, 4th and 8th partials.

[129] This value is set by several factors, including string width/thickness, stiffness, damping etc.

The second, fourth, sixth, eighth, tenth, twelfth…2nth partials are excluded from the timbre. Similarly, exciting a string at a quarter of its length removes a quarter of the potential overtones from the sound and at a third of its length removes a third of the string's potential overtones from the sound etc.

The situation in reality is less clear cut than the above examples suggest; sometimes extra partials are removed from vibration because of damping, string thickness etc and sometimes partials are re-added to the sound because of cello body responses, room acoustics, psychoacoustic effects etc. However the above pattern is broadly perceivable as the contact point changes.

The situation for the bowed string is more complicated. Partials with nodes *and* antinodes at particular contact points are restricted by excitation since the bowing action, in constantly inputting energy into the system,[130] both fixes the portion of string under the bow *and* forces it to move (consider the bowing mechanism: the string is 'pulled' at the speed of the bow and springs back to its rest position at a speed determined primarily by string stiffness). However, this process does not restrict partials with antinodes *close to* the bowing point. Consequently the relationship between timbre and contact point is not significantly different from that of the plucked or struck string except that, as mentioned above, a string bowed at its mid point (either an antinode or a node for all partials) produces almost no sound.

In reality, many partials can have a significant involvement in cello sound,[131] but to see the emerging of a general pattern I will consider a string that can only vibrate in partials 1- 13. In the following figure, possible contact points on the string are shown alongside the number of partials excluded at that contact point:

[130] This is in contrast with the single attack of a pluck/strike.
[131] There are 40 or more significant partials in a bowed open C-string. Colin Gough, 'Musical Acoustics', in Thomas D. Rossing (ed.), *Springer Handbook of Acoustics* (New York: Springer, 2007), 560.

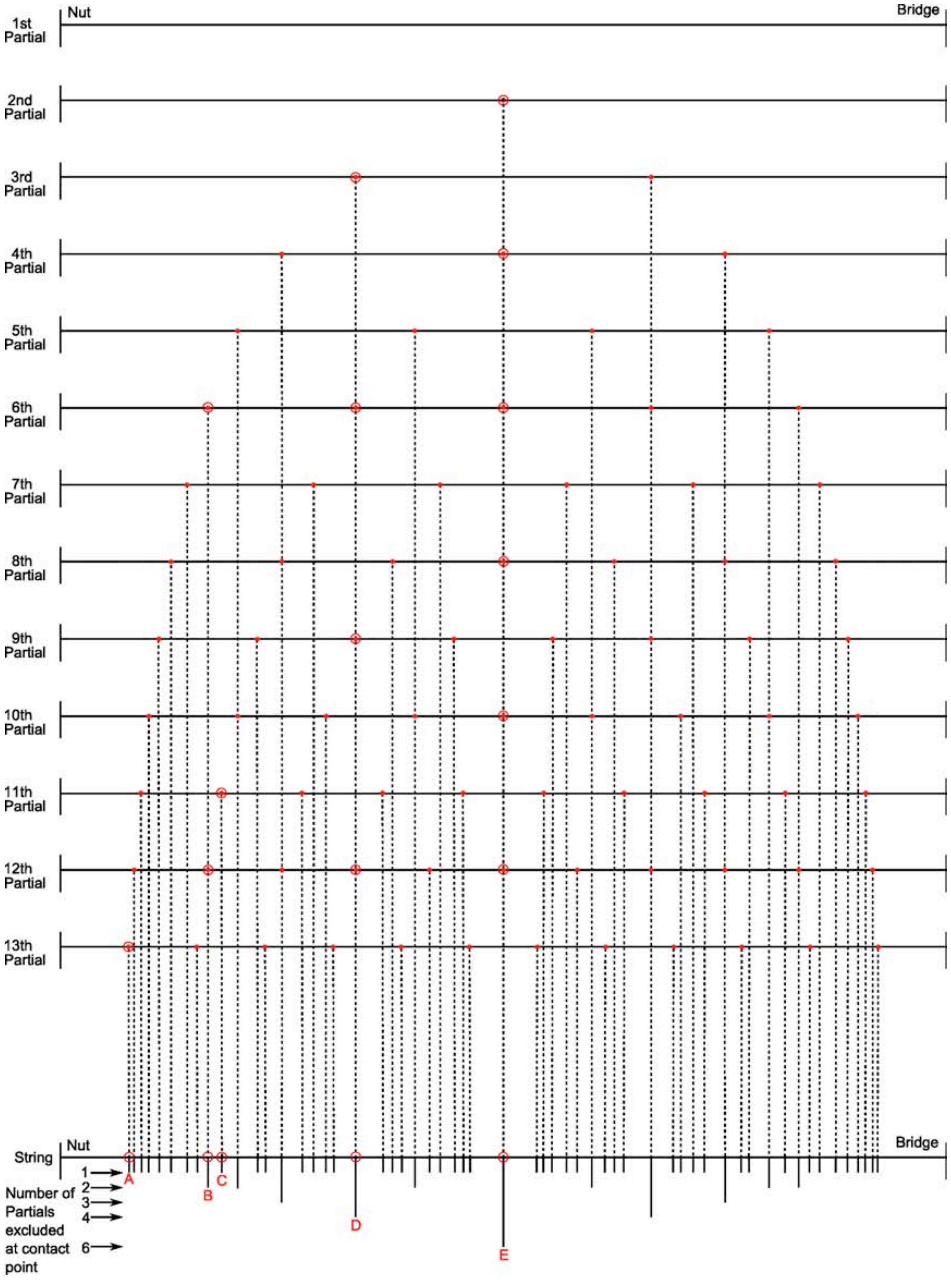

Figure A1.2f The distribution of nodes for the first thirteen partials and the pattern of the exclusion of these partials by excitation at contact points along the string length.

For example if the string is excited close to the nut, at the node for the thirteenth partial (contact point A on the diagram), one partial (the thirteenth) is excluded from the sound. As contact point moves towards the middle of the string the timbre remains similar until the first node of the sixth partial (contact point B on the diagram), where two partials are excluded from the sound (the sixth and the twelfth). Moving towards the mid-point the spectrum becomes richer; only one partial is excluded (contact point C on the diagram). Approaching the mid point the spectrum then changes as three, one, four (contact point D on the diagram), one, two, one and eventually six partials (contact point E on the diagram) are excluded respectively. The pattern is then mirrored in the upper half of the string (where ordinario playing normally takes place). In other words, on this very reduced model, there are areas of string close to the mid point that are as overtone-rich as those close to the nut/bridge.

Of course, the above diagram is a very over-simplified model for a cello string, where the number of overtones is higher (probably three or four times the above) and where other effects can influence sound significantly (for example, consider the possibility of covering more than one nodal point with the plectrum/hammer/bow).[132] However, the general pattern of distribution is applicable and the following general points are true to both the model and the real cello string:

- The contact point that excites minimal overtone content is at the mid point of the string.
- As the contact point moves away from the mid point of the string, the overtone content of a sound increases nonlinearly with some fluctuations.
- The pattern of variation in overtone content is symmetrical about the string's mid point, i.e. a fixed distance from the bridge is equivalent in overtone content to the point the same distance from the nut/stopping finger.

[132] In addition, exciter width/material, excitation force, damping, cello body responses etc also influence timbre.

- There is a point near to the end of the string where overtone content increases at a faster rate without fluctuation (but still non-linearly).

When the contact point is very close to the extremities of the bridge or the nut/stopping finger, the fundamental is weak in relation to its overtones and the overtones dominate the timbre, ‘overtone takeover’. In this case, the excitation energy is inputted too close to a node of the fundamental to incite vibration. The partials drop out in ascending order (fundamental, second, third, fourth…) because contact point is relative to wavelength: any fixed contact point is closer to the bridge/nut/stopping finger in relative terms i.e. closer for the fundamental than the second harmonic, which is closer than the third harmonic etc. Therefore there is an excitation point close to the bridge at which the fundamental is excluded from the sound and the second partial dominates the timbre and, as this point moves further towards the bridge/nut/stopping finger, where the second partial can no longer be sustained and the third overtakes the timbre etc. The longer the string is and quieter the sound is (i.e. the lower the excitation force), the further from the bridge this effect takes place.

Point of contact is relative to string length: i.e. a fixed excitation point (e.g. 3cm from the bridge) for stopped strings is relatively further from the bridge than for (longer) open strings. This implies:

- To maintain a consistent tone when shifting with the left hand towards the bridge, the point of excitation must move correspondingly (this movement becomes natural to cellists).

In other words, this implies that the *sul ponticello* effect will be more extreme when a string stopped in first position is excited a centimetre from the bridge than when the same string, excited at the same point is stopped in fourth position. In addition to this: increased string width in relation to string length limits higher partials. This is because the string can only vibrate at partials with wavelength greater than string width. Some important implications of this are:

- At any fixed stopping position, a progressively less extreme *sul ponticello* sound is producible on the (thicker) D, (even thicker) G or (thickest) C strings than on the A string.
- For a fixed string length and a fixed point of excitation, the number of higher partials in a sound diminishes from A to D to G to C string.

A2 String displacement and excitation force

In general, as string displacement and excitation force increase, amplitude increases and overtone content becomes richer.

For the plucked/struck/bowed string, string displacement and excitation force are equivalent to:

- The distance that (and force with which) the string is pulled from its resting position
- The speed at which the hammer hits the string[133]
- Bow speed and bow pressure.[134]

This implies that amplitude is high and overtone content is rich for strings that are:

- Pulled far (/hard) from their rest position
- Hit with a fast hammer stroke
- Bowed under high pressure with a fast stroke

and vice versa for low amplitude and weak overtone content.

At the upper end of excitation force, increases in loudness begin to plateau and increases in overtone content become less apparent; eventually higher partials become *weaker*. For very large excitation forces a detuning effect is heard; the

[133] This is also the 'dropping distance' that the hammer travels freely between its release point and its contact with the string.

[134] Bow speed and pressure are equivalent to string displacement and excitation force respectively. As a consequence the former primarily influences loudness and the latter overtone content. See Explicatio 2.1 for more information.

string vibrates at a slightly higher frequency and falls to its normal frequency as the sound decays. This effect is most noticeable for the plucked string, where the decay is usually relatively long. For the bowed string, a pitch bend is produced by gradually increasing bow pressure. And, because it is possible to change bow pressure during a stroke, a detuning followed by a return to normal pitch is possible within a single stroke. This shifting in pitch, usually narrower than a quartertone, is relatively easy to control.

For very low excitation forces, higher partials are more present than the fundamental; the first few overtones dominate the sound. In this case, the excitation force is so low that the overtone-takeover point is moved into the region of the 'normal' contact point.[135]

APPLICATIONS SPECIFIC TO PLUCKING

Large plucking forces are often associated with (intended or unintended) *Bartók pizzicati,* the 'snap' component of which can be restricted/encouraged by particular contact points and plucking directions.[136]

APPLICATIONS SPECIFIC TO STRIKING

The loudness of piano- and clavichord-type vibration do not increase and decrease at equal rates with striking force; clavichord-type vibration is less susceptible to increases/decreases in striking force than the piano-type. Under a light striking force, clavichord-type can be as loud as piano-type pitches; however, with increasing force the loudness of the latter quickly overtakes the former. Under moderate striking forces, piano-type vibrations are usually louder than the clavichord-type. The only case in which this is not true is for short lengths of string, where damping effects at the stopping finger reduce the amplitude of the piano-type tone significantly and the hammer-to-bridge clavichord-type tone can be well heard.

The duration of contact between string and hammer is an important factor in *battuto* sound and it increases with excitation force. As contact time between

[135] See 'A1.2 Proximity to the string's mid point' for an explanation of overtone-takeover.
[136] See 'C2 Dense objects/mutes as 'rattles''.

hammer and string increases, the amplitude and duration of clavichord-type *battuto* increase and those of piano-type *battuto* decrease.[137] As a result of this relationship, under high striking forces, the loudness of clavichord-type *battuti* begin to increase at a faster rate than the piano-type *battuti* and gradually overtake them in loudness, reversing the effect described in the above paragraph. The effect of changing contact time, particularly of gradually increasing contact time, is not easily controlled by excitation force because of the muscle control required to hold a hammer to the string for a particular length of time. The bow rebounds off string before the cellist can react. Contact time can be better controlled independently of striking force by other means, chiefly by striking the string with different points of the hammer (the middle of the bow to minimise contact time, the frog of the bow to maximise) or simply holding the hammer down after striking (in this case there is no/almost no output from piano-type vibration).

To summarise: a general increase in loudness is heard for all types of *battuto* as striking force increases. At first amplitude increases in piano-type vibrations are more apparent, however, as force becomes larger still, increases in clavichord-type vibration overtake them.

The pitch bends associated with increased striking force can be controlled for clavichord-type pitches to produce a '*vibrato*' effect (quasi *vibrato* in a clavichord) by applying a pulsating force with the hammer after it has struck the string (maintaining contact between hammer and string). This is more effective when a denser object replaces the bow as hammer (e.g. a blunt knife).

APPLICATIONS SPECIFIC TO BOWING

Bow Speed

The amplitude of a tone increases with bow speed. However this relationship is not simple because bow speed is relative to bow pressure and point of contact. Bow speed is important factor in overpressure techniques (see below).

[137] They are inversely proportional to one another. This is clear because the more excitation energy 'spent' on clavichord vibration while the hammer is in contact with the string, the less energy remains for the piano type tones, which begin as the hammer leaves the string.

Bow pressure

Overtone-content and perceived amplitude increase with bow pressure. The latter 'perceived' increase in loudness is an effect of the increase in overtone content.

The interdependency between contact point, bow pressure and bow speed means that an increase in bow pressure without changing speed or point of contact is necessarily a relative increase in bow speed and vice versa.[138] In other words, when increasing bow pressure, a constant sound quality and loudness is only maintained by reducing bow speed and/or by moving contact point away from the string's mid point. A high level of control over relative bow pressure, speed and point of contact becomes natural to cellists and there are many studies and exercises that work on refining it. Since, within 'normal' cello sound most of these actions and relationships are so well practised that they are automatic to a cellist, distinguishing between speed and pressure can be difficult. For example, maintaining a constant bow speed while altering bow pressure or point of contact (required for some of the bow pressure-related techniques) is unusual for a cellist but becomes less awkward with practice.

VERY LOW BOW PRESSURE

At very low pressures, timbre has a particular thin quality: *flautando* or *flautato*. The 'thin-sounding' spectrum is caused by the strength of the mid range partials in relation to the weakness of the fundamental *and* the upper partials. The fundamental is weakened in the overtone-takeover process[139] and the upper partials are restricted by low bow pressure.

VERY HIGH BOW PRESSURE

Extreme increases in bowing pressure can be controlled to produce various sounds. The controlling factor of these sounds is the relationship between bow pressure and bow speed:

Distorted noise

[138] This assumes a fixed point of contact.
[139] See 'A1.2 Proximity to the string's mid point'.

Encouraging the ‘noise’ element of the bow against the string under high bow pressure produces distortion-like sounds. These are produced by ‘desynchronising’ bow speed and pressure (i.e. by using bow speeds above or below the *normal* range for a particular high bow pressure). High-pitched squeaking sounds might also be present. Loudness is controlled by speed; relatively quiet distortion sounds are easily producible under slow bow strokes.

Undertones

Undertones (or subharmonics) are pitches *below* the fundamental frequency of a string. They require high bow pressure and a very consistent bow speed at the lower end of ‘normal’ playing. In general the effect is more readily achieved when the point of contact is not close to the bridge. It is very difficult to sustain the tone, which often has a high noise component. Moving the point of contact towards the bridge sharpens the pitch slightly but also makes the tone less stable.

Nageln (clicking sounds)

Under very high pressure and very slow bow strokes, the bow produces a ‘clicking’ sound with (either one or two) clear pitches. The speed of the individual components (or ‘clicks’) is controlled by bow speed. Long pauses between the clicks can be controlled more easily when the right hand thumb presses against the fingerboard as a pivot. The two possible pitches are dependent on point of contact, being determined by the length of string between bridge-edge of bow and bridge and between nut-edge of bow and nut. Damping or stopping the string on either side of the bow isolates one of these pitches. It is easier to produce a consistent effect when the bow is held in the fist of the right hand or if the first finger of the right hand is extended along the length of the bow. The technique is stabilised when the cellist pulls the string upwards, towards the bow with the left hand. This necessarily dampens one of the component pitches.

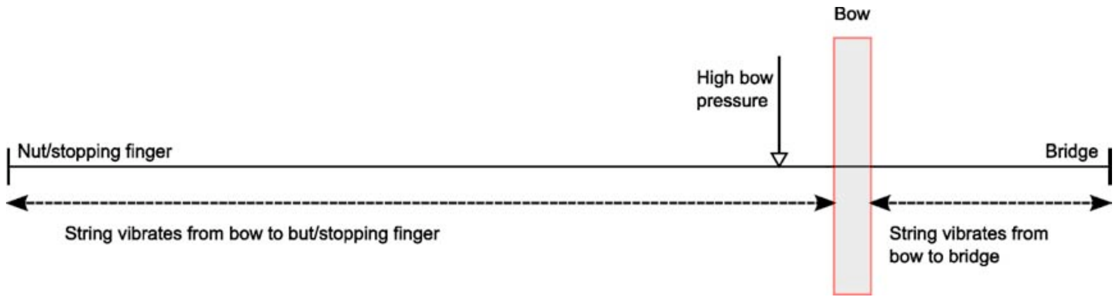

Figure A2a The lengths of string that vibrate under very high bow pressure.

Variations in volume for the latter two techniques are restricted because the bow pressure and speed are fixed within a narrow range. For undertones, where the technique is most dependent on the relationship between bow pressure and speed, volume is virtually fixed and uncontrollable.

All overpressure effects except undertones are easier to produce (i.e. the effects of overpressure are more extreme) on shorter, thicker vibrating strings. In other words, overpressure effects take place for lower values of pressure as string length decreases and/or as width increases; they are most easily attainable for high positions on the C string. Undertones are an exception to this; they are most stable on upper strings and are easiest to produce if the string is relatively long, e.g. stopped in first position.

Explicatio A2

String displacement is the distance by which a string is moved (pulled by a plectrum, struck by a hammer or drawn by a bow) from its resting position. Excitation force is the energy with which the string is displaced.

If the string is plucked or struck, string displacement is equivalent to excitation force; the amount by which a string is pulled by a plectrum/moved by a hammer is necessarily equivalent to the energy of the pluck/strike. In the case of the bowed string, *bow speed* is the displacement force since it controls the width of the string's lateral movement.[140] *Bow pressure* is the excitation force, the perpendicular force (towards the cello body) that the bow exerts on the string.

String displacement causes a rocking motion at the bridge which incites vibration of the cello body. Large displacements incite large movements at the bridge and body; therefore amplitude is proportional to string displacement. In other words, amplitude is proportional to plucking/striking force and bow speed.

Excitation force decides the shape of the kink in the vibrating string. High excitation forces shape the corner of the kink into sharper angles, allowing the string to vibrate in smaller sections, which facilitates the inclusion of higher partials. Lowering excitation force decreases tension, softens the angles of the vibrating string and gradually excludes higher partials.[141] Therefore overtone content is proportional to excitation force, which is: 'amount of displacement' in the plucked and struck string and 'bow pressure' in the bowed string.

In fact, separating bow pressure and bow speed as respectively controlling amplitude and overtone content is not as simple as this theoretical model suggests. Some psychoacoustic effects counteract this, the most significant of these being that increases in bow pressure, in increasing the 'brightness' of a tone, also increase its perceived loudness.[142] The ear's receptiveness to a certain pitch band explains this psychoacoustic effect. The fundamentals of cello tones in the common playing range are usually well below the band to which humans are most sensitive. However, the mid-range partials of these fundamentals are within this band. If their amplitudes are increased by increased bow pressure, a disproportionately significant increase in loudness is perceived by the ear.[143]

[140] Unlike plucking or striking, the bowing angle is more or less fixed to a lateral movement.
[141] Anders Askenfelt, 'Measurement of bow motion and bow force in violin playing', *Journal of the Acoustical Society of America,* 80 (1986), 1007-15.
Norman C. Pickering, *The Bowed String* (New York: Ameron Ltd., 1991), 82.
[142] Anders Askenfelt, 'Measurement of bow motion and bow force in violin playing', 1007-1
[143] This psychoacoustic effect is defined by 'Fletcher Manson curves'. See David Howell and James Angus, *Acoustics and Psychoacoustics* (2nd edn., Oxford: Focal Press, 2007), 82-4.

The general rules above operate within limits of maximum and minimum plucking, striking and bowing forces, between which a 'normal' sound is produced. The value of these limits is not fixed, nor is the distance between them. The limits change according to: contact point, vibrating string length, string thickness and, in the case of the bowed string, the relationship between bow speed and bow pressure.[144]

The minimum excitation force is defined as the minimal value required for 'normal' sound, i.e. when it is high, larger excitation forces are required to produce a 'normal' tone and 'underpressure' effects (*flautando, flautato*) are more readily produced; and when it is low, the tone is stable under low excitation forces and very low forces are required to produce 'underpressure' effects.

The maximum excitation force is defined as the maximal value under which a 'normal' sound can be produced. When it is high, the string can sustain 'normal' sound under high excitation forces and 'overpressure' effects require very high excitation forces. When it is low, the string is less able to sustain high excitation forces and 'overpressure' effects are more readily produced.

The minimal and maximal excitation forces:

- Increase as the contact point moves from the middle of the string towards the bridge or nut/stopping finger[145]
- Increase as string width increases relative to length (that is as a string is made shorter by stopping or, for a fixed stopping position, moving from a thinner, higher string to a thicker, lower string)
- In the particular case of the bowed string, increase with bow speed.[146]

[144] John C Schelleng, 'The bowed string and the player', in Carleen M. Hutchens (ed.), *Musical Acoustics Part I: Violin Family Components* (New York: Halsted Press, 1975), 225-35.
[145] In fact, the value for minimum bow pressure falls by a quarter for every doubling of the distance between bridge and bowing point. See: Arthur H. Benade, *The Fundamentals of Musical Acoustics,* 520.
[146] Benade, *The Fundamentals of Musical Acoustics*, 519-21.

For example, if the bow stroke is fast and/or close to the bridge/nut/stopping finger, low pressures are not sustainable (the overtone-takeover effect begins)[147] and higher than 'normal' pressures are possible.

Furthermore, increases and decreases in minimal and maximal excitation forces occur at different rates; the difference between them is not constant. The limits of maximal and minimal string displacement are narrower at the bridge/nut/stopping finger and become broader at the mid point of the string. In other words, there is more scope for varying excitation force within 'normal' sound near the middle of the string and progressively less as the contact point moves towards the bridge/nut/stopping finger.[148]

Various effects are possible beyond the limits of minimal and maximal excitation force:

Below minimal excitation force, the mid-range overtones dominate the timbre. Again, this is a special case of overtone-takeover; the fundamental is excluded from the sound and, in addition, the reduced excitation force weakens higher partials. In other words, timbre is 'filtered' at both ends, the tone is dominated by the mid-range overtones. The overtone most present in the sound depends on contact point and excitation force. The reason for this is as follows. Each overtone requires a minimum excitation force at a particular contact point in order to sound. This value increases as the contact point moves towards the bridge/nut/stopping finger.[149] Contact point is relative to the wavelength of a particular overtone, for example contact point is measured as '1/10 of a wavelength from the bridge' not '3cm from the bridge'. A fixed point on the string is always, relative to wavelength, closer to the bridge for the first overtone than the fundamental. Similarly, a fixed contact point is relatively closer to the bridge for the second overtone than the first, etc. Therefore, at a fixed contact point, minimal excitation force becomes increasingly lower for ascending

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[147] See 'A1.2 Proximity to the string's mid point' for an explanation of the overtone-takeover effect.

[148] Neville H. Fletcher and Thomas D. Rossing, *The Physics of Musical instruments* (2nd edn., New York: Springer), 279.

[149] As described above, in general, minimal excitation force increases as point of contact moves from the string's towards the bridge/nut/stopping finger

partials. If excitation force is reduced, the string is not supplied with enough energy to sustain each successive overtone; one-by-one the fundamental and then the first, second, third… overtones 'drop out' of the sound. It is difficult for the performer to control which overtone dominates the sound, but a progressive increase in order from the lower overtones is possible by gradually reducing excitation force.

Very high excitation forces increase the tension of the string. At first this restricts overtone content and then it begins to force the pitch of the string upwards. The string is relatively unstable under these conditions, producing pitch fluctuations and 'noisy' distortion sounds. A downward *glissando* is heard as the elasticity of the string returns it to its original tension as the sound decays.

APPLICATIONS SPECIFIC TO BOWING

More effects are possible on the bowed than the plucked or struck string at high excitation forces because of the relationship between bow speed and pressure,[150] and the sustained nature of the technique:

Distorted noise

The roughness of tone associated with high excitation force occurs when the bow is unable to grip the string to incite regular vibration, i.e. when the relationship between bow speed and pressure is 'wrong', just above the maximum pressure associated with 'normal' vibration for a particular speed. Torsion and longitudinal vibration are often present under these conditions. The former encourages the 'noisiness' of the tone as it restricts the string from being gripped by the bow. The latter is heard as high-pitched, irregular squeaks and is particularly present at high bow speeds.

Undertones

Under consistent high bow pressure and at speeds slightly lower than 'normal', undertones are produced. These are tones lower than the fundamental frequency of a vibrating string. There has been no conclusive study that

[150] Although there are interdependent, these factors can be controlled separately.

explains the production of undertones but Mari Kimura, composer and violinist credited with discovering the effect, has undertaken some research in this area in the form of recordings, performers' guides, notation and collaborative research with acousticians.[151] Kimura's proposed explanation is as follows. If the bow exerts high downward pressure on the string, the kink of vibration in the string is unable to pass the bow in the usual way. If this restriction is controlled such that the kink passes the bow at a frequency that is lower than the 'normal' frequency but nonetheless regular, the pitch of the vibrating string is lowered.[152] This effect is very difficult to control (more so on the longer cello strings than on the violin); it is more easily sustained with very regular, quite slow bow speeds on short, thick strings. Several undertones are producible: a semitone 7th and minor 3rd below 'normal' pitch (and perhaps more, Neville Fletcher suggests that intervals of a third, seventh, octave, ninth, twelfth and possibly lower are possible on the violin).[153] These pitches are rarely 'in tune' with the fundamental pitch and intonation varies with contact point: the pitch is sharpened as contact point moves towards the bridge. A high component is also present in the sound. This is possibly vibration between bow and bridge.

Nageln (clicking sounds)

Bowed under very high bow pressure, the string produces resonant 'clicking' sounds.[154] Similarly to above, there has been little research into the mechanics of this technique. However a summary of the likely process is as follows: the bow force is such that the kink of displacement in the string is prevented from passing the bow altogether. Instead it is reflected at the bow back to the bridge. In addition, a second kink passes between the bow and the nut (or stopping finger), also unable to pass the bow. The string then vibrates in two

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[151] See <http://www.marikimura.com> (accessed 1st October, 2009). The first piece in which Kimura first notated violin subharmonics, 'ALT', was written and first performed by her in New York in 1994. Some exploration of undertones has been done by Michael Maierhof whose 2004/5 solo piece *Splitting 14* (unpublished) is based almost entirely on the method of undertones. See <http://joomla.stock11.de/> (accessed 1st October, 2009). Double bassist and colleague of Kimura, Mark Dresser <http://www.mark-dresser.com> (accessed 1st October, 2009) has undertaken some research on his instrument.

[152] Roger J. Hanson and Andrew J. Schneider, 'Anomalous low-pitched tones from a bowed violin string', *Catgut Acoustical Society,* Vol.2 No. 6 Series II (Nov. 1994), 1-7.

[153] Neville Fletcher and Thomas Rossing, *The Physics of Musical instruments* (New York: Springer, 1991), 285.

[154] 'Nageln' comes from the German verb 'to nail/knock'

systems simultaneously: from the bridge-edge of the bow to the bridge and nut-edge of bow to nut (or the stopping finger, in which case the corresponding pitch is inaudible since the vibration has no means of coupling with the body of the instrument). Pulling the string upwards with the left hand increases the pressure between string and bow, and can enable better control of the speed of the clicking components.

The relationship between bow speed and pressure

The interdependency of bow speed and bow pressure is inherently so well understood by cellists that ‘speed-pressure’ is perceived as a single force. To maintain a consistent rich/bright/full cello sound, certain adjustments in pressure need to be made for an increase in speed (or vice versa). These adjustments are so well practised that they are automatic to cellists. The overpressure techniques above require new technical coordination. The possibilities of speed and pressure combinations can be well represented on a speed-pressure vector. From the figure below it is clear that there is a band of speed and pressure variation within which ‘normal’ cello sound is produced, where speed and pressure are coordinated in the way well practised by cellists. At one edge of this band, the maximum bowing pressure for each particular speed, the sound becomes distorted and noise-based. At specific areas in this region, overpressure techniques are produced. It is clear that, since there is a continuous transition from the pressures and speeds required to produce noise-based sounds to those required to produce *nageln* and/or subharmonics/undertones, that a transition in sound also exists. This is heard as a mixture between noise and *nageln* and/or undertone pitches. At the other edge of the band of ‘normal’ sound, the minimum bow pressure for each particular speed, overtone takeover begins. The control of the dominance of specific partials in overtone takeover takes place at specific speeds and pressures in this region.

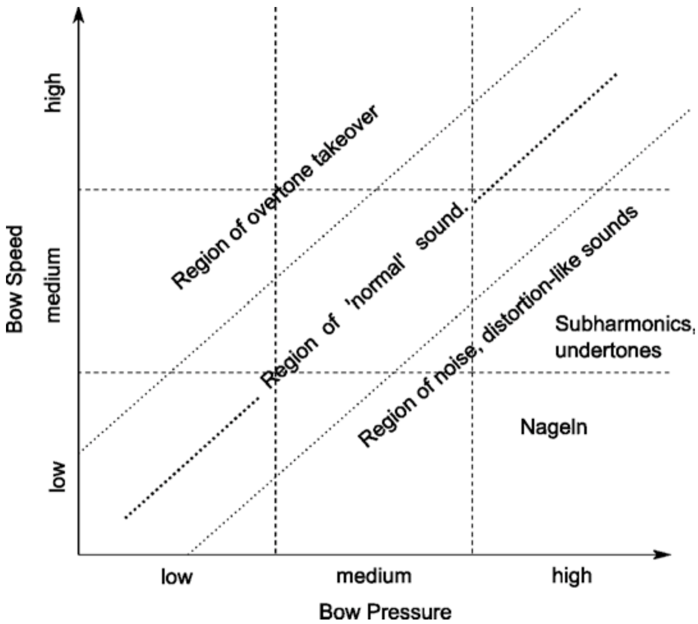

Figure A2b The bow speed-pressure vector

A3 Direction of excitation/displacement

In general, excitation force takes place at an angle parallel to the cello body surface (left↔right across the body). It is possible that this type of excitation maximises loudness and limits decay-duration and that, as excitation moves towards a perpendicular angle (towards-away from the cello body) loudness decreases and duration increases.[155]

APPLICATIONS SPECIFIC TO PLUCKING

The plucking angle that a cellist normally chooses is diagonally about half way between a lateral movement left↔right across the cello body and a perpendicular movement towards/away from the cello body.[156] A cellist can fairly accurately pluck at a chosen angle anywhere between these extremes (there is more flexibility when playing between the end of the fingerboard and

[155] I applied this theory from a study into plucking direction in guitars. An experiment recorded in the appendix implies that the above general statement holds in the case of the plucked cello string. See 'Excplicatio A3' for more information.
[156] Actually, undertaking an experiment on plucking angle, see appendix, I found that plucking technique in cellists is much less easily generalised than bowing technique. Since it is rarely taught, methods tend to be individually developed.

the bridge than over the fingerboard, especially at higher dynamics). Changing the plucking angle can affect sound significantly.

I use the terms ‘horizontal’ *pizzicato* and ‘vertical’ *pizzicato* to describe the lateral and perpendicular plucking of the string respectively. For diagonal *pizzicati*, where the angle is between these two extremes, the output is mixed: an angle closer to the lateral plane favours amplitude at the expense of duration and moving towards the perpendicular plane, the duration of a tone increases at the expense of initial amplitude. These differences are subtle but perceivable, especially in moderate and loud dynamics.[157] A soft, deep thudding sound is also present in *horizontal pizzicato*. It can be interesting to experiment with the possibilities of variation in plucking by moving between these two extremes.

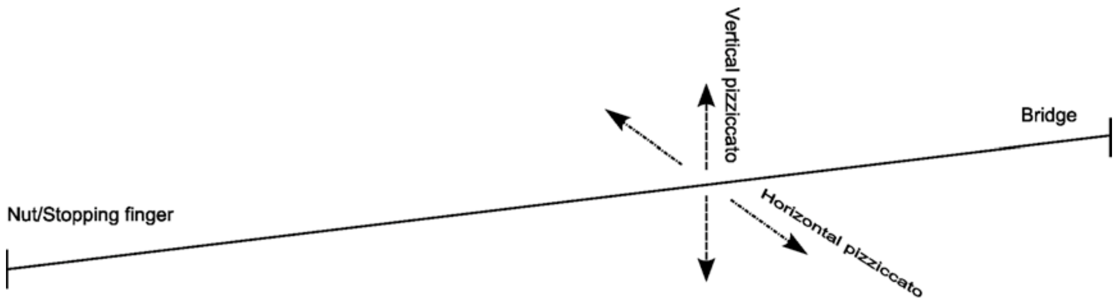

Figure A3 Vertical and horizontal *pizzicato.*

Some applications are:

- Characterising an expressive *pizzicato* passage by changing the plucking angle.
- Plucking vertically to produce a moderately quiet but ringing tone.

[157] See Appendix for a more detailed analysis of these effects.

- Plucking horizontally to produce a *sfz* or in *forte* passages where short tones are required, or in fast tempi, where decay duration is irrelevant.
- Plucking towards the body from underneath the string to increase duration in loud passages without producing unintended *Bartók pizzicati*.

APPLICATIONS SPECIFIC TO STRIKING

Usually, the cellist strikes the string directly over the cello body, i.e. the angle of the attack is perpendicular to the strings. Flexibility in changing the striking angle is limited since a certain amount of 'swinging' distance is required and, at many potential excitation angles, the cello body obstructs this. However, some flexibility is possible, particularly if the bow is exchanged for a shorter hammer. It is possible that, similar to the plucked string, striking the strings from side-to-side has a greater influence on amplitude at the expense of duration and striking the strings directly towards/away from the cello body has the opposite effect.

Horizontal battuto/hitting between the strings/rattling

A tremolo effect can be achieved by positioning the hammer between two strings and hitting each in turn by moving the hammer from side-to-side.[158] The clavichord- and piano-type pitches are heard in turn but, if the motion is moderately fast, associating the pitches with each string is difficult and a fast tremolo between six pitches is heard.[159] If the movement is circular, a noise element contributes to the sound as the hammer scrapes against the string. Since this increases the contact between hammer and string, the amplitude of the piano-type tones is reduced and that of the clavichord-type tones is increased. If the hammer is dense, two contrary motion *glissandi* in the clavichord-type pitches are heard as the hammer-string contact point slides up/down in the circular motion.

[158] This is easiest when using a short hammer, such as a pencil, or the frog of the bow.
[159] There are one piano-type pitch and two clavichord-type pitches for each string, fewer pitches if the strings are dampened.

APPLICATIONS SPECIFIC TO BOWING

Vertical Bowing/rubbing

Vertical bowing is moving the bow directly towards/away from the bridge and nut, i.e. moving in parallel with (rather than perpendicular to) the string. Normal vibration of the string does not take place under these conditions. Various sounds are producible, depending particularly on the bowing object and bow pressure. At very light 'bow' pressures the noise of the bow/object rubbing against the strings is heard. For soft bowing objects, such as the bow hair or fingertips, this is a faint and breathy high-pitched sound. Denser bowing objects such as the fingernails or bow stick produce a coarser and louder sound with a lower pitch. Volume increases with the *speed* of the stroke. As 'bow' pressure increases, the sound becomes slightly louder and less consistent. High, irregular squeaks are occasionally present; this is longitudinal vibration of the string. These longitudinal vibrations can be encouraged by rotating the bowing angle (by ninety degrees) so that the bow is parallel to the string and bowing up/down along the string.

For fairly high bow pressures and very particular bow speeds (steady and slightly slower than 'normal' horizontal bowing), it is possible to generate a very clear pitch by vertical bowing. This is the vibration of the bow hair, brought about by its movement along the string. This is the opposite situation to a 'normal' bow stroke; the string excites vibration in the bow hair.[160] The length and the tension of the bow hair determine the pitch of the tone. Gripping the bow hair between the fingertips (or placing the thumb firmly on the hair) to shorten it raises the pitch. Tightening the bow hair also raises the pitch. There is only a small margin of flexibility in altering the tension of the bow hair in this way; the technique is more difficult to produce with slack or over tight bow hairs. In general, increasing the speed of the stroke increases the volume of the sound. For very slow bow speeds and high pressures, a *nageln*-type effect is possible. For high bow pressure, there is a noisy, 'rough' element to the timbre.

[160] The string is the exciter even though it is the bow that moves. Compare with the possibility under 'normal' bowing conditions of moving the cello left-right under the bow: the strings are moving and the bow is static but the *bow* is exciting the *strings*.

Diagonal/Circular/Square bowing

Motion across the strings at various angles produces a mixed sound, with ‘normal’ sound being produced at/close to the ‘normal’ bowing angle, possible vibration of the bow hair at/close to vertical movement and ‘noisy’/‘rustling’ sounds with occasional, inconsistent string/bowhair vibration at angles in between. The type of sound depends on bow pressure. Under low bow pressures the ‘rustling’ timbre is smooth and contains relatively high pitches, and the bowed sound is low in overtone content, possibly with a weak fundamental. As bow pressure increases the ‘rustling’ timbre becomes grainier and richer in overtone content, ‘normal’ string vibration includes more overtones and ‘vertical’ strokes possibly incite vibration of the bow hair. Under very high pressures both the ‘rustling’ and ‘normal’ sounds are distorted and high-pitched squeaks might be heard.

Specifically:

‘Diagonal bowing’, drawing the bow in a diagonal motion (somewhere between *normal* horizontal motion and vertical motion), produces a ‘poor quality’ bowed string tone with a strong noise-based element.

‘Circular bowing’ is moving the bow in a circular motion across the strings. The sound shifts from *normal* to combined *normal* and noise-based sound to noise-based sound and/or bow hair vibration as the bowing direction changes from horizontal to diagonal to vertical. If the movement at the bow tends to an elliptical rather than a circular motion, the transition from *normal* to noise-based sound (or bow hair vibration, depending on the speed and pressure of the bow) is more distinct. Moving the bow in a square-shaped gesture generates distinct, rhythmic changes between noise/bow hair vibration and string vibration.

Explicatio A3

The set up of the bridge and the strings has been developed to amplify lateral displacement (left↔right across the cello body). However, the string reacts to displacement at any angle between the lateral and the perpendicular plane towards↔away from the cello body. I refer to these two excitation angles as ‘horizontal’ and ‘vertical’ respectively.

The following theory has been adapted from an investigation into plucking angles in guitars by Erik Jansson.[161] Changing displacement angle might change the nature of the coupling between strings, bridge and body in the following way:

The amount of *horizontal* displacement has a greater influence on initial amplitude than *vertical* displacement. This is because horizontal displacement causes lateral vibration of the string and lateral movement at the bridge. This lateral movement directly driving the cello body is the most efficient way that the bridge can act as an amplifier in transferring excitation energy to sound. Excitation energy is spent quickly, tones are loud with short decay.

The excitation energy of vertical excitation is spent more slowly. The bridge rocks towards/away from the tailpiece and transfers energy to the body less quickly. This implies a longer sound with a reduced attack. Angles between the two extremes imply a mixed output. In other words, ‘decay duration’ and ‘initial loudness of attack’ are, for fixed excitation energy, inversely proportional to one another.

A preliminary attempt to test the effects of plucking angle on amplitude and timbre appears in the appendix of this thesis.

A4 Choice of exciter (width and density)

Reducing the width and/or increasing the density of an exciter increase the number of overtones present in a sound and vice versa.

[161] Erik V. Jansson, ‘Acoustics for the Guitar Player’, in Erik V. Jansson (ed.), *Function, Construction and Quality of the Guitar* (Stockholm: Royal Swedish Academy of Music No. 38, 1983) 7-26. The results are opposite in the cello’s case because the guitar bridge vibrates towards-away from the fingerboard rather than laterally. The fact that the guitar bridge is fixed to the body accounts for some deviations in behaviour. I suspect that changing the excitation angle of the struck and possibly the bowed string might follow the same pattern.

APPLICATIONS SPECIFIC TO PLUCKING

Plucking with a plectrum of a particular width is almost equivalent to using two plectra with *outer* edges separated by this width. For example, plucking with two widely spread fingers in the same or opposite directions can reduce overtones significantly. [162]

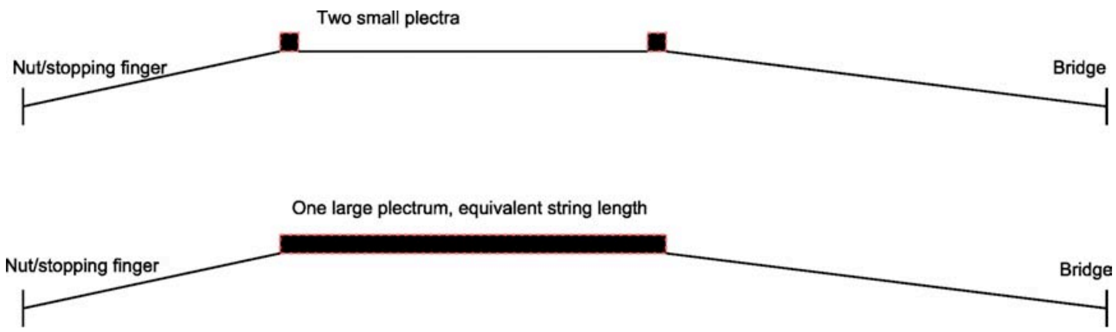

Figure A4a A string displaced by a particular length, firstly by two small plectra, then by one large plectrum with width equal to the spacing between the two small plectra.

Moreover, when two plectra are used, the string vibrates with the combined amplitude associated with the excitation force of each plectrum. For example, if all three plectra in the above figure pull the string with the same excitation force, the string pulled by two plectra will vibrate with twice the amplitude of the string pulled by one plectrum.

APPLICATIONS SPECIFIC TO STRIKING

Changing the width and density of the hammer affects piano- and clavichord-type vibration differently.

[162] Using this technique to produce as overtone-free a sound as possible, a 'flicking' action using the thumb and finger to pull the string in opposite directions is sometimes more comfortable than pulling the string in the same direction with two widely spaced fingers. Different overtones are 'blocked' but the result, reducing harmonics in the overall spectrum, is sonically similar.

As the hammer becomes thinner and/or denser, more partials are included in a piano-type tone. This effect is enhanced since thin, dense hammers, as well as reducing contact area, also reduce contact time between hammer and string, allowing the piano-type vibration to ring for longer with a more overtone-rich spectrum. As the hammer becomes wider and/or less dense, the contact time between hammer and string increases. This stifles piano-type vibration and increases the duration of clavichord-type vibration. For very low densities the latter increase is not substantial since it is almost cancelled by the opposite effect of necessarily increased damping. However for wide, high-density hammers, clavichord-type *battuto* is long and overtone-rich.

Hammer width also influences the pitch of clavichord-type tones. Both clavichord-type pitches are raised by increasing hammer width because the portion of string under the hammer does not vibrate (until after the hammer is released, i.e. in piano-type vibration). Therefore the clavichord-type pitch of a string struck at its mid point ,[163] where the hammer-to-bridge and the hammer-to-nut pitches are equal, is therefore lower for thin dense hammers and becomes higher as hammer width increases and/or hammer density decreases,[164] as shown in the figure A4b.

[163] The middle of the hammer is in line with the middle of the string.
[164] This is because low-density hammers spread out on excitation, increasing contact area between string and hammer.

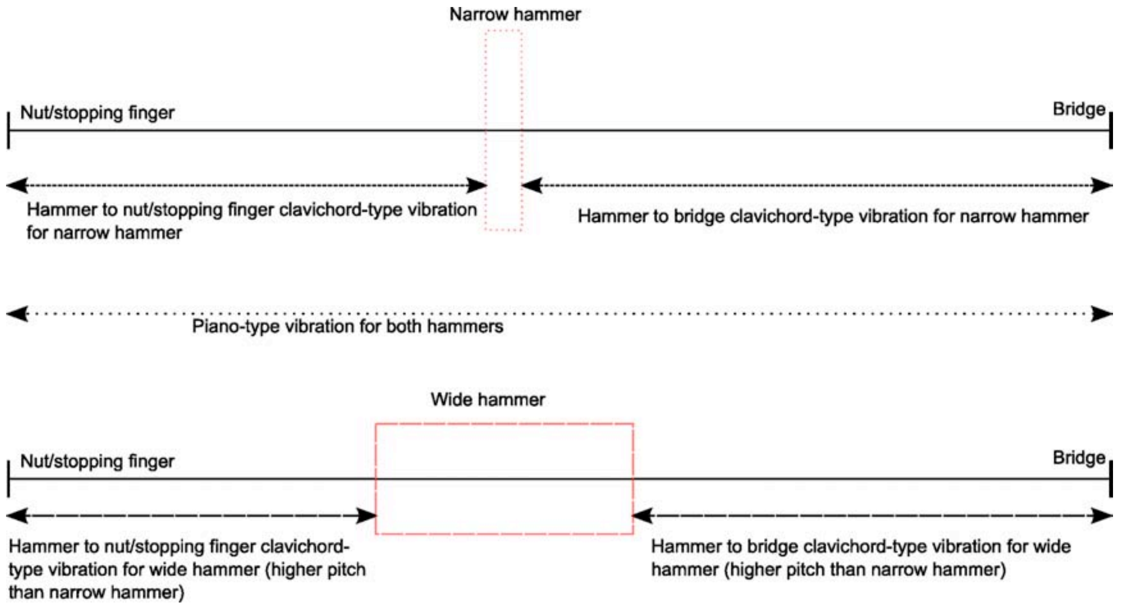

Figure A4b The vibrating string lengths when a string is struck, firstly by a narrow hammer and secondly by a wide hammer.

***Fingerschlag* (*hammer on*)**

The stopping finger can be used as a hammer by placing it onto the fingerboard with a force that causes the string to vibrate. The string responds in clavichord-type vibration. Two pitches are produced as the lengths of string between bridge-edge of stopping finger and bridge, and nut-edge of stopping finger and nut vibrate. The longer part of the string (lower of these pitches) is louder, except around the mid point, where the finger-to-bridge sound is slightly louder. The amplitude of the two pitches is even just above the mid point of the string (towards the bridge). To an extent, decay time, overtone content and amplitude all increase with attacking force. However, at moderately high attacking forces these increases quickly plateau and the ‘noise’ of the contact between finger and fingerboard becomes more noticeable than the pitch content of the sound. Using the fingernail, rather than the finger pad, enriches overtone content and lengthens the decay of the tone. As long as the finger remains in contact with the fingerboard, the sound decays naturally, otherwise it stops as the finger is removed. If the string is dampened or stopped on one side of the finger, a single pitch is isolated. If the stopping finger changes position after impact whilst maintaining finger pressure a *glissando* 'slide' effect is produced.

This technique is often referred to (using guitarists' terminology) as a 'hammer on' (although to guitarists this usually implies that a string is to be plucked before it is hammered). The 'pull off', which often follows the 'hammer on' is a left hand *pizzicato* executed by the hammering finger as it is removed from the string. The pitch of the 'pull off' is the open string, or the pitch of the string stopped by the adjacent finger (in the latter case, the timbre is usually necessarily *sul ponticello*).[165]

APPLICATIONS SPECIFIC TO BOWING

Using a violin or double bass bow is a simple way to influence bow width, although the differences in weight and length also have an impact upon the sound. Tilting the bow is a method of, ostensibly (there are slight differences in the distribution of bow pressure), decreasing the bow width. Cellists often tilt the bow significantly, especially to produce a quiet, clear sound. Tilting the bow, by distributing pressure over a smaller area of string, allows the cellist to reduce bow speed without compromising harmonic content and produce a quiet, overtone-rich sound.

Bowing with the bow stick: *col legno tratto*

Drawing the wood of the bow across the string, *col legno tratto*, produces a 'noisy' but nonetheless pitched sound. The tone is unstable as vibration stops and restarts during the stroke. Vibration is more consistent if the strings or the wood of the bow have a layer of rosin on them. Overtone content and volume are controllable in the same way as 'normal' bowing, (i.e. overtone content becomes richer as contact point moves away from the string's mid point, loudness increases with bow speed) but to a lesser extent. The timbre of the wood-against-strings sound changes with bow speed and pressure. For fast, light bow strokes, there is very little pitch content and the character is a smooth, high-pitched 'sweeping' sound. For relatively light, slower bow strokes, lower

[165] However, this is not the case if the difference between 'hammer-on' pitch and 'pull-off' pitch is relatively wide.

pitches are present and the bow stick rattles slightly against the string. Under high bow pressures and for slow bow strokes the sound is deep and 'grainy' (like a buzzing loudspeaker). As pressure increases, the bow might be able to grip the string in the usual way for a short while and produce a relatively 'normal'-sounding arco tone.[166]

The bow stick can be substituted with other objects. If these *tratto* objects are shiny/slippery, they are less able to grip the string and generate mostly 'sweeping' noise with high pitch-band content. Rougher objects grip the string more successfully and produce lower-pitched sounds, often with a rattle and occasional 'normal'-sounding bowed tones.

Tilting the bow to allow both bow hair and bow stick to come into contact with the string produces a more securely pitch-based sound (often called *half legno tratto*).

Playing with reduced bow tension

As the bow hair tension is reduced, the vibrating string becomes more difficult to control. The sound of the bow stick moving against the string is eventually heard (particularly under high bow pressures) and loudness is significantly reduced.

Explicatio A4

Firstly I will consider the simpler cases of the plucked and struck string. Since the portion of string under the plectrum/hammer is displaced by an equal amount during excitation, this portion of string is fixed as vibrating more or less in the same phase of a wavelength. If a particular partial has a node *and* an antinode within this band the partial will barely sound. The following diagram demonstrates this for the 20th partial:

[166] Necessarily, because of their interdependency (see 'A2 String displacement and excitation force'), point of contact influences the limits of these effects, i.e. bow pressure is less flexible as point of contact moves away from the middle of the string and minimum and maximum bow pressures are increased by bow speed

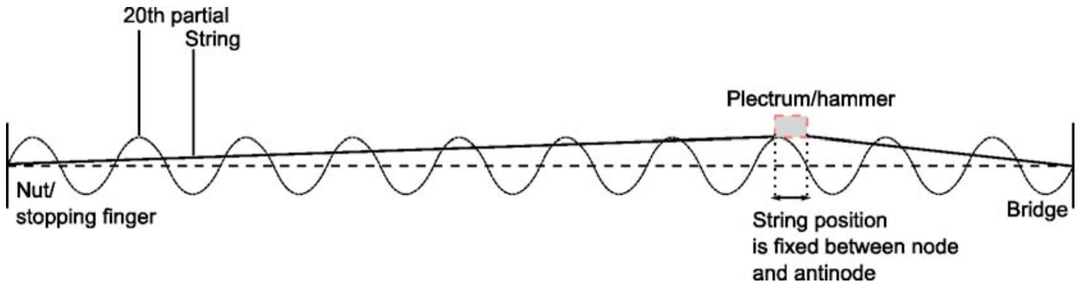

Figure A4c The shape of the waveform of the 20th partial in relation to the shape of a string displaced by plectrum/hammer of width equal to one quarter of the wavelength of the 20th partial.

Such exciters with width ‘antinode-node’ have a variable influence on a partial’s response. In the above case the partial is restricted but if the plectrum/hammer were shifted slightly to the left the partial would respond well. However, if the area of string covered by the exciter spans two points with opposing amplitudes for a particular partial, this partial will be weak.[167] Since two points with opposing amplitude always occur at exactly half a wavelength of a partial,[168] any exciter width equal to or above this excludes the associated partial.[169] For example, in the figure below, the 20th partial will be blocked form the timbre.

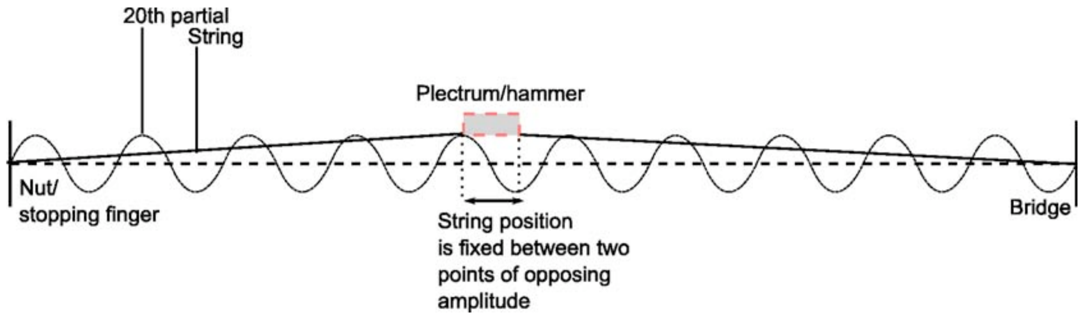

Figure A4d The shape of the waveform of the 20th partial in relation to the shape of a string displaced by plectrum/hammer of width equal to half of the wavelength of the 20th partial.

[167] Theoretically the partial will be completely excluded from the sound, but in practice it is possible that the partial makes a slight contribution to the spectrum.
[168] The only exception to this is a nodal point, which has value (0,0).
[169] Benade, *The Fundamentals of Musical Acoustics,* 108-15.

Therefore the exciter width sets the minimum wavelength of partials to be strongly present in the timbre and this value is twice the width of the exciter.[170] The rate of the 'dropping out' of partials with increasing exciter width is higher for higher overtones, i.e. for a thin plectrum/hammer/bow, small increases in exciter width have a larger impact at first and then a progressively lesser impact for descending partials. This is clear because the difference between wavelengths of adjacent partials increases as the harmonic series descends. For very thin/very thick exciters the overtone content is increased/decreased to the extent that point of contact becomes almost irrelevant to timbre. Theoretically, changes in bow width follow a similar pattern, although the different weights and lengths of wider/narrower bows e.g. violin, double bass, ½ size cello bows also affect sound.

A change in exciter width is, more broadly, a change in contact area between exciter and string. Several other factors equate to a change in contact area: If a soft hammer is used to strike the string, or if excitation force is low, the hammer material spreads out upon impact with the string, increasing the contact area between string and hammer. Dense hammers, or hammers struck with large excitation force, keep their shape on impact and the contact area is true to the width of the hammer, i.e. contact area is minimised. Similarly, the harder/further the plectrum pulls the string, the more tightly the string bends around it, reducing contact area.[171] Therefore: perceived exciter width is inversely proportional to hammer density and the excitation force of the plectrum/hammer, so consequently these factors are proportional to overtone content.

In addition to this, exciter density has an impact on damping: using a dense hammer limits damping at the excitation point. The hammer absorbs less energy upon excitation. This favours higher partials, therefore hammer density

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[170] Neville H. Fletcher, 'Plucked Strings- A Review', *Catgut Acoustical Society*, No. 26 (Nov. 1976), 13-17.

[171] Fletcher, 'Plucked Strings- A Review', 13-17. Fletcher notes the very sharp angle of the harpsichord string pulled by a quill compared to the soft angle of the violin string pulled in its usual way by a finger.

is proportional to overtone content.

By tilting the bow (tipping the stick towards/away from the bridge)[172] the cellist reduces/increases the contact area between bow and string.[173] Contact area is maximised when the bow is flat against the string and minimised when the stick is steeply tilted.

Partials are either enhanced or restricted by two plectra exciting the string in the same or opposite directions. This depends on whether the plectrum is pulling the string *into* the shape of a particular waveform or *against* it. In both examples below, the partial (in this case the 10th partial) is enhanced because the placing of the plectra suits its waveform:

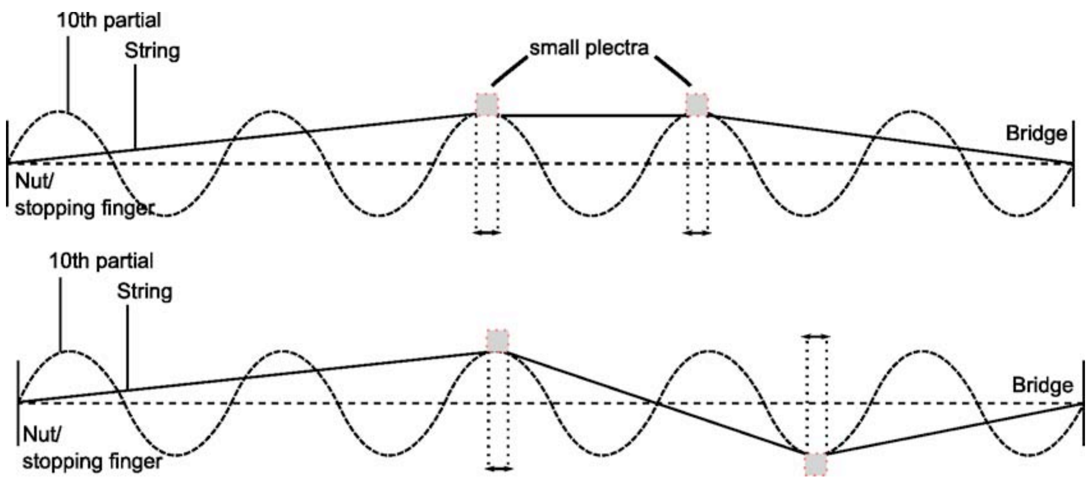


Figure A4e The shape of a string displaced by two plectra in such a way that is compatible with the shape of the waveform of the 10th partial.

In both examples below, the partial (in this case the 10th partial) is restricted because the plectra are pulling the string against the shape of the waveform:

[172] Cellists usually tilt the bow towards the nut rather than towards the bridge (and violinists do the opposite).
[173] Norman C. Pickering, *The Bowed String*, 71.

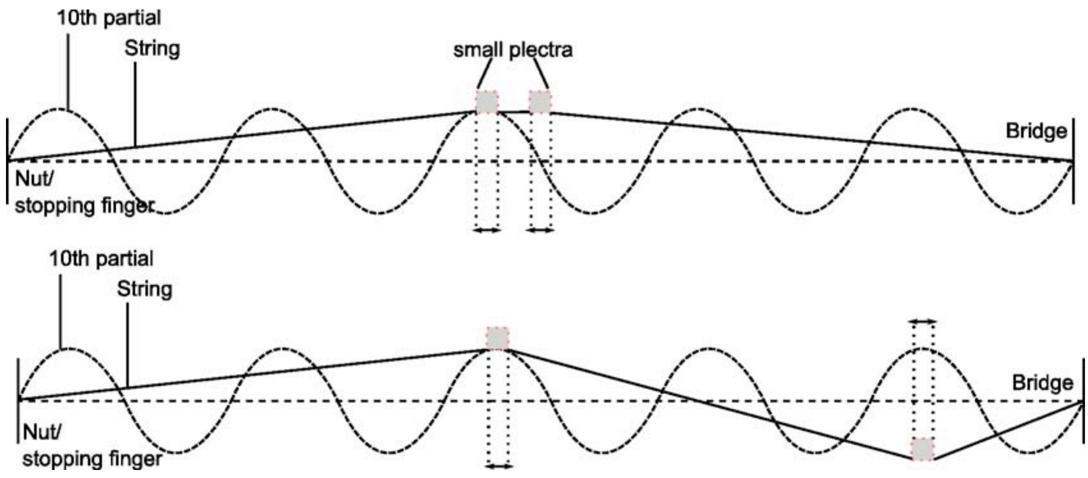


Figure A4f The shape of a string displaced by two plectra in such a way that is not compatible with the shape of the waveform of the 10th partial.

Since this reaction can be difficult to control, using more than one plectrum can have unpredictable results in timbral terms. However, a clear change in timbre and volume is heard between plectra at fixed positions exciting the string in the *same* direction compared with plectra exciting the string in *opposite* directions.[174]

For example, consider a string plucked by two plectra at ¼ of its length and ¾ of its length, firstly with excitation forces in the same direction and secondly with opposing excitation forces. In the former case a strong contribution from the fundamental is heard and in the latter the fundamental is notably weakened and the second partial can be clearly heard in the sound:

[174] Benade, *The Fundamentals of Musical Acoustics*, 108-14.

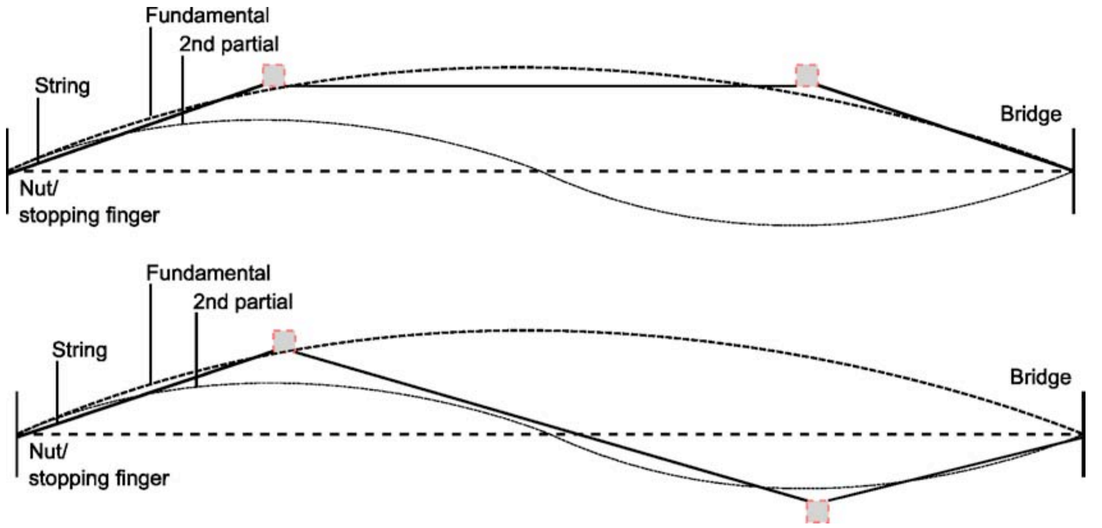


Figure A4g The shape of a string displaced by two plectra firstly in such a way that is compatible with the shape of the waveform of the fundamental and secondly in such a way that is compatible with the shape of the waveform of the 2nd partial.

In the case of the hammered string, thin, dense hammers maximise the overtone content of *piano-type* vibration and wide, dense hammers maximise the overtone-content of *clavichord-type*. This is because as hammer width increases, so does the impact duration between hammer and string. During impact duration, the hammer is in contact with the string and applying a force in one direction. If a particular partial has a period equal to this duration then, by definition it requires the string shape to bend into opposite amplitudes within this time period. This is disallowed because of the single force applied to the string; therefore the partial is excluded from the timbre. Moreover, even if partials have a period equal to half the impact duration they will only be weakly present in the timbre because the movement of the string is not flexible enough to suit their waveform. In fact, a particular partial only contributes strongly to piano-type vibration for impact durations less than half its period. Impact durations of between one and half the period of a particular partial may excite that partial weakly. Since period decreases with ascending partials, overtone content is inversely proportional to contact duration between string and hammer.[175]

[175] Benade, *The Fundamentals of Musical Acoustics*, 116-18.

For clavichord-type vibration, the opposite is true: a partial only contributes if the contact time between hammer and string is greater than or equal to its period, i.e. a stable clavichord-type tone is only heard for impact times equal to one, or preferably more periods of the fundamental. This is clear since, as clavichord-type vibration takes place during the hammer's contact with the string, at least one cycle of vibration must take place between hammer and bridge/nut for the fundamental to sound. Wide, soft hammers maximise duration, whilst soft hammers also have a damping effect; therefore wide, dense hammers produce the clearest clavichord-type tones. Controlling clavichord-type pitches by using hammer width and force to control impact time is not ideal. The damping effects that are associated with soft hammers and low excitation forces reduce the overtone content of the tone considerably, sometimes even restricting the fundamental. Striking with greater force and then holding a dense hammer to the string produces a much richer spectrum.

A5 The left hand

A5.1 Left hand position

Apart from controlling pitch, the position of the left hand has a significant influence on timbre. The cellist often chooses between positions on different strings that produce equivalent pitches. This is effectively choosing the relationship between string length and width (i.e. a low position on a high (thin) string vs. higher positions on lower (thicker) strings). The timbral implications in choosing one position over another are complex. In general an increase in string thickness and/or decrease in length (in practice, higher positions on lower strings) imply a reduction in overtones and vice versa. However, each string has its own particular quality of sound, and each cello body responds in an individual way; a complete picture of timbral variation is complicated and a more detailed summary is difficult.

In addition, the relationship between string length and width has a significant influence on amplitude and decay duration. For short thick strings (i.e. high positions on low strings), initial amplitude is relatively high and decay duration is short. As string length increases and width decreases (i.e. low positions on high strings), duration increases at the expense of initial amplitude.

Explicatio A5.1

The overtone exclusion/inclusion for particular left hand positions can be viewed as 'potential' overtone content under particular conditions. I define potential overtone content as the maximum number of overtones that may take part in the spectrum for a fixed left hand position.

For a particular stopping position, the highest overtone that can be present in the sound is set by finger pressure and density, and overtones are encouraged/excluded by changing point of contact. If the left hand shifts upwards, finger pressure and density remain constant,[176] therefore so does the frequency of the highest overtone. In other words, although the fundamental pitch has risen, the pitch of the highest possible overtone has remained constant. This overtone is a lower order relative to the new fundamental; therefore the potential overtone content has been reduced. The fact that potential overtone content reduces as the left hand shifts upwards implies that the scope for varying overtone content by changing point of contact is reduced, i.e. a less extreme '*sul ponticello'* effect is possible in higher than lower positions. To an extent, a more extreme '*sul tasto'* timbre is possible under these conditions since overtone content is reduced for every contact point. However, the former effect is more extreme, therefore the overall scope for varying timbre is reduced. When choosing between alternative positions for a particular pitch (for example B in first position on the A string vs. fourth position on the D string vs. thumb position on the G string vs. upper third of the C string), the cellist is selecting timbre under these terms.

[176] These factors remain constant unless deliberately changed by the cellist (e.g. by increasing pressure/rolling onto the fingernail).

In addition, string stiffness increases from A to C string. Increased stiffness rounds the shape of the curve of the vibrating string. This has the effect of restricting higher partials.[177] Therefore a less extreme *sul pontecello* effect is possible on the D string than the A, an even lesser effect on the G and still less on the C string.

A5.2 Left hand finger pressure

The greater the pressure with which the left hand stops the string, the more overtones are included in the sound and the longer its decay duration. Rolling onto the fingernail (or using an alternative stopping object that is denser than the finger) increases overtone content and decay duration further.

An application of this increase in decay duration is that high pressures or dense stopping objects, such as a glass or piece of metal, facilitate long *glissandi* in the left hand in the decay part of the sound (after the pluck/strike/stroke).[178]

Since it is more difficult to influence the timbre of a hammered compared with a plucked or bowed string,[179] the effects of increasing/decreasing finger pressure, which are no less effective than for the plucked and bowed string, are nonetheless more significant.

To produce harmonics, the finger touches the string without pressing it to the fingerboard. Within the narrow range of 'harmonic finger pressure' there is scope for some variation and quite a broad range of sounds are possible. At the upper end of harmonic finger pressure (depressing the string but not allowing contact between string and fingerboard) the pitch of the harmonic (probably slightly sharp) and the tone at the stopping point are both present in the sound.[180] Overtone content is reduced. Such an effect is often referred to

[177] Benade, *The Fundamentals of Musical Acoustics,* 118-9.
Pickering, *The Bowed String,* 5-7.
[178] See 'A7 Slide effects'.
[179] Partly because of the awkwardness of changing point of contact and the angle of the strike and partly because changing excitation force and point of contact (the usual means of controlling overtone content) have other associated effects, primarily changing the pitch of clavichord-type vibration, and the contact duration between hammer and string, which can counterbalance the intended effects. See 'A2 String displacement and excitation force'.
[180] There is always one node for which these pitches are equal, that is the touch point nearest to the bridge.

as a 'half harmonic' and is especially noticeable for high harmonics touched in the neck positions. As pressure decreases, the harmonic pitch sounds alone, usually slightly sharp. Its pitch falls to *normal* and overtone content becomes richer as pressure decreases further. Under very low finger pressures, the pitch of the open string is introduced into the sound in addition to a harmonic. When stopped or open string pitches sound in addition to the harmonic, their loudness is inversely proportional to the loudness of the harmonic pitch.

Fixed changes in finger pressure do not affect every harmonic equally. The scope for varying finger pressure is greater for lower harmonics. Because the loudness and overtone content of ascending harmonics become considerably reduced, so does the maximum finger pressure under which 'normal sound' can be maintained. In addition the damping effects of finger pressure and width have a considerably greater effect on ascending harmonics. In order for a high harmonic to sound clearly it might be necessary to reduce pressure or use the fingernail rather than the finger pad (or a thinner/less dense plectrum/hammer/bow). In the case of high harmonics, moderate finger pressures might be large enough that the stopped string pitch is also present in the sound.

APPLICATIONS SPECIFIC TO STRIKING

When the bow is used as a hammer, at least the first seven harmonics can be clearly produced. It is difficult to compensate for the effect of reduced amplitude as the harmonic series ascends because large striking forces increase duration between hammer and string, effectively muting piano-type vibration, in this case the harmonic. Consequently the loudness of the clavichord-pitch quickly overtakes that of the harmonic.[181] At moderate volume, the fourth harmonic might already be quieter than the clavichord pitch. If the point of contact is a short distance from the bridge, the hammer-to-bridge sound is possibly in the region of the harmonic. The cellist can, fairly easily, match and homogenise these sounds to an extent. Exciting the string very close to the bridge/nut inhibits the clavichord-pitch and, as far as possible, isolates the harmonic.

[181] There is only one clavichord pitch because the finger dampens one side of the string.

Multiphonics

For light finger pressures at particular points on the fingerboard, two or more harmonics can sound simultaneously in a multiphonic. Since various definitions exist for the term multiphonic, when I use the term, it will be defined as: the simultaneous sounding of two or more harmonics on a single string. This can include the open string, in the special case described above. The mixing of two or more harmonics is possible by placing the finger with light pressure between two closely located harmonics or by placing the finger loosely near a 'cluster'[182] of harmonics on the string. The general effect of producing more than one pitch simultaneously is easily attained and, with practice, specific pitch outcomes can become quite reliable. The most suitable point of contact is further from the bridge than that associated with 'normal' harmonics (perhaps even behind the stopping finger, see 'B13 Multiphonics' for more information).

APPLICATIONS SPECIFIC TO BOWING

The effects of changing 'harmonic' finger pressure and the production of multiphonics can be relatively easily controlled and clearly heard on the bowed string because of the sustained nature of the excitation and the ability to make adjustments to finger pressure during a bow stroke.

APPLICATIONS SPECIFIC TO STRIKING

Multiphonics are less predictable and less easily controlled for the struck string compared with the plucked or bowed string. The clearly audible clavichord-type tone perhaps has a psychoacoustic effect in 'confusing' the pitch content of multiphonics.

A scale of finger pressure variation might look like this:

[182] I define a harmonic cluster as a position on the string where a few harmonics are clustered around a small area, see 'B13 Multiphonics' for more information.

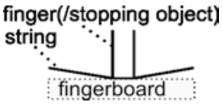
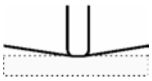
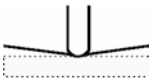
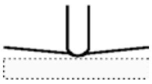
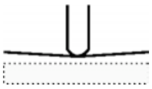
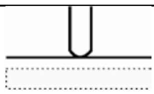
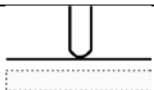
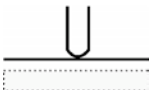
	Finger pressure	Output
	Using the finger nail/other dense object. Very high pressure	Overtone-rich sound, high duration
	↓	Gradual reduction in overtone content and duration
	Normal pressure	‘Normal’ sound
 	↓	Stopped string pitch with low overtone content and harmonic (possibly slightly sharp). The harmonic becomes louder relative to the stopped pitch as pressure decreases.
	High harmonic pressure	Sharp harmonics with reduced overtone content
	‘Ordinary’ harmonic pressure	In-tune harmonics
	Low harmonic pressure	In-tune harmonics with high overtone content
	↓ Very light pressure	Multiphonics: mixture of two or more harmonics and possibly increased ‘noise’ component and/or the open string pitch is heard with the harmonic. The amplitude of the open string increases relative to that of the harmonic as pressure reduces. The stopped string pitch might also be faintly present.

Figure A5 A scale of finger pressure.

Explicatio A5.2

Within ‘normal’ stopped string sound, the pressure and density of the stopping finger/‘object’ influence timbre by the extent to which they dampen the string’s vibration. As pressure and/or density increase, damping decreases, i.e. less energy is lost at the stopping finger and more is reflected back to the bridge. Therefore loudness and overtone content (since damping affects higher overtones more than lower) are proportional to finger pressure/density. Decay duration is also proportional to finger pressure/density[183] since, as energy lost through damping decreases, the string is able to complete more cycles of vibration before ‘spending’ the excitation energy.

Under harmonic finger pressure, as above, increasing the density of the touching finger reduces damping. Contrary to above, however, damping increases with finger pressure. Since string vibration passes the touching finger (rather than the finger reflecting vibration, as above), damping is limited by decreasing pressure, minimizing the energy transferred to the touching finger. Therefore: overtone content, loudness and decay duration of harmonics are proportional to finger density and inversely proportional to finger pressure.

In general, a reduction in overtone content has a more pronounced effect for harmonics than for stopped strings of equivalent pitch. Since fewer overtones are present in ‘normal’ harmonic sound, the exclusion or weakening of upper partials has a larger impact on timbre in relative terms.

A5.3 Contact time between stopping finger and string

If the stopping finger is removed from a vibrating string, the decay of a tone is interrupted. If the finger remains in contact with the string until it stops vibrating, the length of the decay is maximised. This is particularly apparent for plucking, striking and short bow articulations, and less so after long bow strokes. The interruption of the decay is considerable if the finger is removed soon after excitation and marginal if the finger is removed late in the decay process. Reducing finger pressure (but maintaining contact with the string)

[183] This is particularly noticeable for plucked and struck tones, and for short bowed articulations.

after the attack but during decay reduces the spectrum and duration of the decaying sound.

In contrast to the stopped string, the decay duration of harmonics is maximised by removing the finger soon after excitation. Harmonics have an optimum left-hand contact time at which decay duration and overtone content are maximal. This optimal contact time is inversely proportional to the frequency of the harmonic (i.e. longer for lower harmonics). In general, even for low harmonics, this optimal time is very short. As contact between finger and string increases beyond the optimal, overtone content and duration reduce sharply. Eventually, for very long contact times, plucked and struck tones become a short, muffled 'thud' (in the latter case the clavichord-type pitch is very present). For bowed tones, the harmonic barely sounds after the stroke.

Contact times shorter than the optimal time for a particular harmonic encourage the introduction of neighbouring harmonics, particularly higher-order harmonics, and the open string into the sound. Because of this tendency, contact time can be used to manipulate the pitch content of multiphonics. Removing the stopping finger from the string 'too soon' for a particular harmonic encourages closely situated harmonics into the tone. This is especially effective in producing plucked and struck multiphonics.

APPLICATIONS SPECIFIC TO BOWING

In some cases, particularly for loud tones, if the finger is removed *before* the end of the bow stroke the harmonic continues to sound for a short while. If the speed and tension of the stroke remain constant, this effect can continue for a few seconds.

Explicatio A5.3

The decay of a particular sound is maximised if reflection of the kink in the vibrating string is allowed to continue until it runs out of energy, i.e. if the string is allowed to 'spend' all of its excitation energy. If the stopping finger is removed from the string during a tone's decay this process is interrupted, vibration may continue for a short while as the vibration decays in the cello body and the room. Since these effects are weak compared to the vibrating string being radiated to the body/room, removing the stopping finger can be an abrupt damping of sound.

In the case of harmonics, the optimal contact time between touching finger and string, usually very short, is the time taken for the string to vibrate for a few wavelengths at the particular harmonic's frequency. In this time the string begins to vibrate stably at the harmonic pitch and continued contact with the left hand serves only to dampen vibration because, since vibration is reflected at the nut rather than the left hand finger, the kink of vibration *passes* the touching finger with every cycle, loosing energy in the process through damping. Since contact time is dependent on wavelength, optimal contact time reduces for ascending harmonics.

A6 Changing the tension of the string

A6.1 Pulling the string across the fingerboard with the stopping finger

It is possible to increase string tension by pulling the string across the fingerboard with the stopping fingers. This raises the pitch, which lowers again on release. Fluctuations of around a semitone are possible, depending on string length and thickness. If the string is pulled and released during vibration, an upward-downward *glissando* is heard. Alternatively, if the string is prepared before excitation, only the fall in pitch is heard and if the release takes place after the decay, only the rise. The speed of the *glissandi* is easily controlled by the cellist and a target pitch within the relatively limited range can, with practice, be roughly met. Wider pitch variations are possible on lower strings and/or longer vibrating string lengths (i.e. in the neck positions).

A6.2 Pushing/pulling the string between bridge and tailpiece

Pushing down (towards the cello body)[184] upon the string between the bridge and the tailpiece has a similar effect. The pitch is raised and then lowered upon release at a speed easily controlled by the cellist. The action can be done with the right hand immediately after excitation or, for an open string, with the left hand (or, more awkwardly, for a plucked string, with a different finger of the plucking hand), in which case the timing is more flexible (e.g. the increase in tension can take place before the pluck so that only a lowering in pitch is heard). Similarly to above, releasing after the tone's decay prevents a fall in pitch from being heard. Fast repetition of the action produces a *'vibrato'* effect.

INFORMATION APPLICABLE TO BOTH A6.1 AND A6.2

The differences in controlling pitch by changing string tension compared with simply shifting the stopping finger on the fingerboard (i.e. *glissando normal*) are as follows. In the former:

- A slow, narrow and steady *glissando* can be more easily controlled.
- Target pitch is less easily controlled and wide pitch changes are unobtainable.
- The particular, relatively wide '*vibrato'* effect can be controlled (sped up/slowed down) and sustained more easily than a left-hand vibrato in the decay part of a sound since damping effects are reduced.

A6.3 *Scordatura*

The overtone content of a string that has been tuned to a lower pitch is at first slightly increased an then, as the pitch is tuned lower still, reduced compared with the same string tuned normally. The timbral effect of changing contact point is reduced. In the case of the bowed string, initially the string is more easily set into motion by the bow, i.e. the minimal bow force is lower, but as the detuning increases, vibration becomes increasingly difficult to sustain. A noisy, scraping tone begins to sound and the loudness of this and the vibrating string decrease with increasing excitation force. The pitch of the vibrating string often fluctuates. Eventually the pitch of the tone is obscured by the noise element of the sound, which is reduced to a 'fluttering' timbre. For very low tunings,

[184] Pulling upwards, away from the body, is equivalent but less comfortable.

particularly under high excitation force, the string often rattles against the fingerboard. This ratting and the noise-based sounds are more evident for the bowed string since the continued input of excitation energy sustains them. The lower strings are more quickly affected by scordatura; for fixed amounts of detuning, the above effects are heard first on the lower strings.

Scordatura tunings above ‘normal’ are less flexible. If the string is tuned more than a tone higher, it is likely to snap. Slight increases in pitch by *scordatura* increase the loudness of a tone and weaken the upper partial content. It is less easy to excite the string close to the bridge and the string is less easy to set into motion, making fast tones and articulated tones more difficult.[185]

Explicatio A6.3

As a string is tuned down, its tension decreases. Small decreases in tension might at first strengthen the overtone content slightly since the frequency of the highest contributing overtone, set by string width and other factors, stays constant for a decrease in fundamental pitch.[186] However, further decreases in tension weaken the potential overtone content of the string; the less tense string is shaped less sharply at the bridge and nut and more energy is lost to damping as vibration is reflected in these regions. Therefore, for a fixed contact point, the timbre is less overtone-rich and the scope of *sul ponticello* sound is reduced. For small decreases in tension by *scordatura*, the string is easier to set into motion. Therefore a relatively ‘normal’ sounding tones is possible under low excitation forces, *flautando* and overtone-takeover effects are more difficult to produce. As tension becomes very low, the vibration of the string is made up of much torsional movement, causing the string to respond slowly to excitation. This causes some irregular pitch changes and a noise component in the sound. The scope for varying plucking/striking force and bow speed/pressure is reduced, particularly at the upper end of the scale, and loud sounds are unsustainable. For high excitation forces the string often strikes the fingerboard during vibration. Eventually the string becomes too ‘floppy’ to

[185] Norman Pickering, *The Bowed String* (New York: Amereon, 1991), 5.
[186] Further research is needed in this area to find the extent of this effect and the point at which it begins to reverse.

sustain transverse vibration. The lower strings are first to be effected by torsion since their increased width increases the propensity to vibrate in such a way.[187]

As tension increases above ‘normal’ tuning the sound becomes slightly louder since the string exerts an increased force on the bridge; the coupling between bridge and body is strong. Higher partials become weak and out of tune with the fundamental due to string stiffness. Vibration becomes difficult to control, particularly in bowed sound. Rapid bow changes are difficult as the string is very sensitive to changes in plucking/striking force and bow speed/pressure. Longitudinal vibration of the string might be heard in the form of high-pitched squeaks.[188]

If tension of one string increases or decreases significantly, the corresponding change in down bearing force on the bridge affects the amplitude of the other strings. The amplitude of the other strings increases and decreases in inverse proportion to tension.[189]

A7 ‘Slide’ effects

A7.1 Placing an object (‘slide’) on the string during the decay period

Placing an object (quasi guitar slide) on a vibrating string changes the pitch. This is usually a dense object (such as the bow stick), which, like glass guitar slides, need only rest on the string, rather than press it to the fingerboard.

For an open string that is not dampened on either side of the slide/finger, the open string tone is followed by two simultaneous tones. The pitches of these tones are defined by the lengths of string from (nut-edge of) object to nut and (bridge-edge of) object to bridge. Either of the two tones can be easily dampened with the free fingers. A stopped string behaves in the same way (the

[187] Norman Pickering, *The Bowed String,* 5-6.
[188] Norman Pickering, *The Bowed String,* 16.
[189] Carleen Hutchens, *Musical Acoustics Part II: Violin Family Functions,* (New York: Halsted Press, 1975), 498.

stopping finger replaces the nut or the bridge in the above example), but the vibration between stopping finger and object is not heard.

A7.2 Exciting a string after an object ('slide') has been placed onto it (quasi guitarists' bottle neck)

The two lengths of string either side of the slide can be plucked/struck separately. The initial nut-bridge tone is not heard and moreover, the cellist can choose if the slide tones sound simultaneously or consecutively.

INFORMATION APPLICABLE TO A7.1 AND A7.2

Contrary motion *glissandi* effects are possible by moving the slide up and down the string (maintaining pressure). As one pitch is raised the other is lowered.

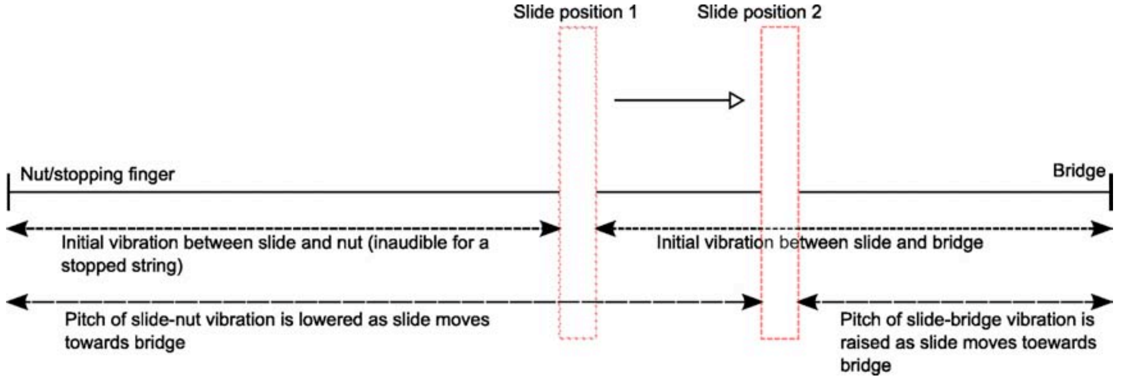


Figure A7 The vibrating string lengths when a slide is moved along a string.
[Bottom right of diagram above – 'toewards' should be 'towards'!]

The amplitude and duration of these pitches are inversely proportional to damping at the slide. Damping is minimised by using a dense slide object and/or by increasing the weight of the slide/the pressure between slide and string. The more damping is reduced, the more possibilities there are for longer, wider *glissandi.*

The amplitude of the longer string is greater than that of the shorter. However at the centre of the string there is a slight bias towards the pitch that is transmitted via the bridge. The pitches have equal amplitude near the centre of the string, a short distance closer to the bridge than the nut.

For light, dense slide objects applied before/after high excitation forces, the string might rattle against the object during vibration, shortening the length of decay and distorting the sound somewhat.

A8 Excitation of string beyond bridge/nut

A8.1 Between bridge and tailpiece

The pitches of the strings between bridge and tailpiece vary from instrument to instrument. Their contact with the bridge means they are well amplified and can be almost as loud as the equivalent length of string between bridge and nut. Variations in pitch, dynamics and tone colour can, on an open string, be quite easily controlled. The absence of a fingerboard means that, when stopping the string, the finger (or preferably the denser fingernail) needs to exert a high pressure on the string to produce a clear sound. Very large stopping finger pressures might stretch the string slightly, sharpening the pitch. Exciting the string between stopping finger and bridge is generally louder and more overtone-rich than exciting between stopping finger and tailpiece.

Harmonics are also possible between the bridge and tailpiece. The clearest sound in this case is produced by exciting the shorter of the two lengths of string that are either side of the touching finger and by releasing the touching finger fairly soon after excitation. Using the fingernail rather than the finger pad of the touching finger increases overtone content. Harmonics can be a more effective way of varying the pitch than stopping the string since the damping effects of stopping the string without a fingerboard can be considerable, especially for higher tones.

APPLICATIONS SPECIFIC TO PLUCKING

The action of plucking between stopping finger and tailpiece (or an open string/harmonic between bridge and tailpiece), in addition to the string vibration, forces the tailpiece to vibrate, producing a low, dull, thudding sound. This is very similar to the sound produced when the edge of the tailpiece is plucked.[190] This sound can be (almost) isolated by damping (e.g. with the palm of the hand) between plectrum and bridge.

APPLICATIONS SPECIFIC TO STRIKING

Clavichord-type vibration takes place between the hammer and the bridge and the hammer and the tailpiece.[191] The former is almost always louder and more overtone-rich than the latter.

APPLICATIONS SPECIFIC TO BOWING

Bowing over the silk-wrapped part of the string close to the tailpiece produces a coarse sound. This sound is similar to the timbre of a string bowed with excess pressure because, in both cases, the bow is unable to grip the string in the 'normal' way. The rolling motion of the string under the bow (torsion) takes the place of the usual side-to-side (transverse) vibration.

A8.2 In the peg box

The pitches of the strings in the peg box also vary between cellos. Because the strings are thick relative to their length and damping effects at the pegs and nut are high, overtone content is weakened and changes in tone colour are restricted. The shortness of the strings (particularly the outer two and especially the 'C' string) excludes much pitch variation by stopping with the left hand. Using a small, dense plectrum (e.g. the fingernail) or a dense, thin hammer (e.g. a thin metal stick like a knitting needle) gives the clearest, most overtone-rich sound. Similarly, if the bow is sharply tilted such that less hair is in contact with the string, clarity and overtone content are maximised. Despite the awkward physical restrictions (there is very little space in which to manoeuvre a plectrum/hammer/bow) it is possible to produce a fairly loud tone.

[190] See 'D2 Plucking, striking or bowing/stroking the tailpiece'
[191] If the string is stopped, only one of these pitches is heard.

The two middle strings, being longer, facilitate slight variation in pitch, dynamic and tone colour. If the middle strings are stopped to vary the pitch, the fingernail rather than the finger pad is more effective; the latter mutes the string almost completely.

Summaries Section A

Summary A1.1

The string vibrates from the bridge edge of the stopping finger to the bridge or, for excitation 'above' the stopping finger, from the nut-edge of the finger to the nut. This has important implications regarding pitch.

Summary A1.2

The overtone content of a sound changes for excitation points across the whole string length. Overtone content is weakest (*sul tasto* timbre) at the string's mid point, or half-way between the stopping finger and the bridge. This is because there is a node at this point for all of the even-ordered overtones, and, being excited directly at a nodal point, a point of zero amplitude, these overtones do not sound. Therefore the potential overtone content is halved. Overtone content gradually increases (with some fluctuations) as the excitation point moves away from the mid point, towards the bridge or the nut/stopping finger, eventually being maximised close to the bridge or the nut/stopping finger (*sul ponticello* timbre). The change in overtone content is symmetrical around the string's mid point. In fact, there is some differentiation from this general pattern in a real cello string and for tones bowed exactly at the mid point.

When excited very close to the bridge or nut/stopping finger, the fundamental and then the lower overtones drop out of the sound. This is because the excitation point is relatively too close to a node of these lower partials to sustain their vibration.

Summary A2

In general, the wider a string is displaced, the louder the resulting sound. This is because wider string displacement causes larger movements at the bridge, and the cello body. The more pressure with which a string is displaced, the tighter the angles into which the string bends during vibration and, as a consequence, the more overtones can take part in the sound, and thus overtone content increases. For the plucked and struck string, string displacement is equal to excitation force. The bowed string is more complicated: bow speed is equivalent to string displacement and bow pressure to excitation force. However, since bow speed and pressure are themselves interdependent, and since increased overtone content has a strong psychoacoustic influence on loudness, this relationship is by no means clear-cut.

The case of the struck string is particularly complicated because of the relationship between striking force and impact duration, and the psychoacoustic effect of damping.

For very low bow pressures, there is insufficient energy to sustain the lower partials. In addition the shape of the vibrating string is not bent in sharp enough curves to allow high partials to sound. The result is a mid-partial dominated timbre, *flautando.*

For very high pressures, the sound becomes distorted. The tension of the string might be increased, which is heard as a sharpening in pitch. For the bowed string, several departures from the normal vibration pattern are possible, depending on the relationship between bow speed and pressure.

Summary A3

It is possible that excitation by plucking from right to left across the cello body maximises loudness at the expense of decay duration, and that plucking directly towards or away from the cello body maximises decay duration at the expense of loudness. The proposed explanation for this is that the cello bridge, in rocking from side to side to incite vibration of the body, is at its most efficient (releases energy fastest) when excited by a sideway movement. If the bridge is impelled to rock backwards and forwards, it uses the excitation energy more slowly. If this proposition is true, a mixed output is heard for excitation angles between these two extremes.

‘Bowing’ or stroking the strings at a vertical angle towards the bridge or nut does not incite string vibration. Instead, the sound of the bowing/stroking action is amplified by the contact between exciter and cello body. Mixing some circular or horizontal movement with the vertical movement results in a mixture of string vibration and bowing/stroking sound.

Summary A4

As exciter width increases, progressively more nodal points for particular partials are covered during excitation. Partials with nodal points covered by the exciter are blocked from the sound. Therefore, overtone content becomes weaker. The denser the exciter is, the more damping is reduced and the sharper the angles in which the string vibrates, increasing overtone content.

Summary A5.1

The position of the stopping finger decides the pitch of the tone and the relationship between string width and length (string width increases relatively as the left hand stops shorter lengths of string). This has important implications in overtone content of the sound because the frequency of the highest possible overtone (set by string width and other factors) remains constant for changes in string length. Therefore overtone content decreases as stopped string length decreases.

Summary A5.2

As the pressure and/or the density of the stopping finger increase, fewer overtones are lost to damping when vibration is reflected at the stopping finger. Therefore, the overtone content of the tone increases with pressure and/or density of the stopping finger.

As finger pressure is reduced from ‘stopped’ to ‘touched’, at first a harmonic is introduced into the stopped string sound (the harmonic is possibly slightly sharp due to increased string tension). For further decreases in pressure the harmonic sounds alone. As pressure is reduced further, the open string, or neighbouring harmonics might be introduced into the sound, in a multiphonic. Finger pressure is relative to harmonic order; higher harmonics are more sensitive to changes in finger pressure.

Summary A5.3

The duration of stopped string vibration increases with contact time between finger and string because the vibration can be reflected again and again at the stopping finger, until the excitation energy has been exhausted. The situation regarding harmonics is the opposite. Since vibration passes the touching finger, and in doing so always loses a certain amount of energy through damping, duration is maximised when contact between finger and string is as short as possible. However, there is a minimum contact time that allows the harmonic to vibrate at a stable pitch. This is usually very short, but is relative to the frequency of the harmonic. If the finger is removed from the string before this, it is likely that other neighbouring harmonics and especially the open string will also be present in the sound.

Summary A6

The tension of the string can be changed by pulling it across the fingerboard with the stopping finger, or by pushing down on the strings between bridge and tailpiece. In both cases a slow and steady *glissando* or a relatively wide *vibrato* can be controlled.

If the tension of the strings is changed by *scordatura*, the outcome depends on the extent of the detuning. Slight decreases in tension increase overtone content since, relative to the new lower fundamental, the frequency of the highest possible overtone increases. However, if the tension is decreased further, overtone content is restricted by the slackness of the string, encouraging damping. Eventually, the string becomes difficult to control and responds slowly to excitation, especially bowed articulation. Increases in tension by *scordatura* are limited because the string is liable to snap under high tension. However, slight increases in tension have the effect of detuning the upper partials and making the string less responsive to excitation, particularly bowed articulation.

Summary A7

Placing an object onto a vibrating string, or exciting a string after an object has been placed on it, causes vibration between the outer edges of that object and the bridge and/or nut/stopping finger. The overtone content and decay duration of the sound is maximised by reducing damping: by using a dense object and increasing pressure between object and string.

Summary A8

The pitches of the strings between bridge and tailpiece and in the peg box vary from instrument to instrument and are rarely a fifth apart. The high degree of damping and the width of the string relative to its length mean that the pitches often have weak overtone content.

Section B Harmonics

An introduction to harmonics, the effects of influencing overtone content, loudness and duration and variations on harmonic sound.

B1 Introduction to harmonics

Harmonics are produced when the plucked/struck/bowed string is touched at particular points with light finger pressure. The string vibrates on both sides of the touching finger.[192] The pitches of the harmonics correspond to each partial of the open string; the first harmonic is the string's fundamental. The points on the open string at which harmonics are generated lie at the nodes of each ascending partial (i.e. where the string is divided by a *whole number* e.g. 1/2; 1/3, 2/3; 1/4, 2/4, 3/4; 1/5, 2/5, 3/5, 4/5…). A harmonic can be produced at several of its nodal points, for example the third harmonic is obtainable by touching the string at 1/3 *and* 2/3 of its length. However a harmonic is not necessarily found at *all* of its associated nodes, for example the fourth harmonic is obtainable at 1/4 and 3/4 of the string length but not at 2/4.[193] I will refer to the nodal points on the string at which a particular harmonic *can* be produced as 'touch points' for that harmonic i.e. the set of 'touch points' for a harmonic is a subset of its nodal points. In other words a touch point is always a nodal point but the reverse is not true. Finding alternative touch points for a particular harmonic and knowing how many equivalent touch points are available can be useful to cellists in minimising shifts in the left hand, especially in fast passages.

Harmonics become quieter, more difficult to control (it is more difficult to find their position, they are more sensitive to changes in bow pressure and speed) and less overtone-rich as they ascend. Harmonics are most overtone-rich on

[192] I refer to the 'touching finger' to differentiate between that and the 'stopping finger'. This is also physically more correct since, in the case of harmonics, the finger does not 'stop' vibration, i.e. vibration passes the finger rather than being reflected at it.
[193] More information about touch points can be found below.

the A string, and are increasingly less overtone rich on the D-, G- and C-strings.[194]

Explicatio B1

The sound quality of harmonics is characterised by their weak overtone content relative to equivalent pitches on the stopped string. The first harmonic, the open string, is the only exception to this, having a very rich overtone content. However, harmonics become overtone-weaker as they ascend. The reduction in higher partials is significant at first and gradually becomes marginal. This reduction can be expressed in the harmonic sequence: 1/1, 1/2, 1/3, 1/4,1/5… 1/n i.e. the fundamental (first harmonic) has the 'maximum'[195] number of overtones, the second harmonic has half as many as the first, the third harmonic has a third of the amount of the first etc. In more detail:

Touching the string (without pressing it to the fingerboard) fixes the area under the finger as a static point during vibration. Partials with *antinodes* at this point are unable to vibrate under these conditions and partials with *nodes* at this point are free to vibrate. The second harmonic is produced by touching the string at its mid point, an antinode for all of the odd partials. The odd partials are 'blocked' from the sound. The overtone content is halved since only the even partials (that is every other partial in the *finite* set of partials available in the open string) are able to vibrate. The new fundamental is the second partial of the open string (since the first partial has been excluded), the new second partial is the open string's fourth partial, the new third partial is the open string's sixth partial etc.

[194] This effect can be clearly felt by cellists. I think it can be attributed to the weakening and increased detuning of upper partials as string stiffness increases. String stiffness is minimal for the upper strings and increases with string width. See: Neville H. Fletcher, 'Analysis of the Design and Performance of Harpsichords', *Acoustica, Vol.37* (1977), 139-47. See also: Benade, *The Fundamentals of Musical Acoustics*, 118-19.

[195] That is the maximum number under fixed conditions e.g. point of contact, plectrum width, bow pressure etc.

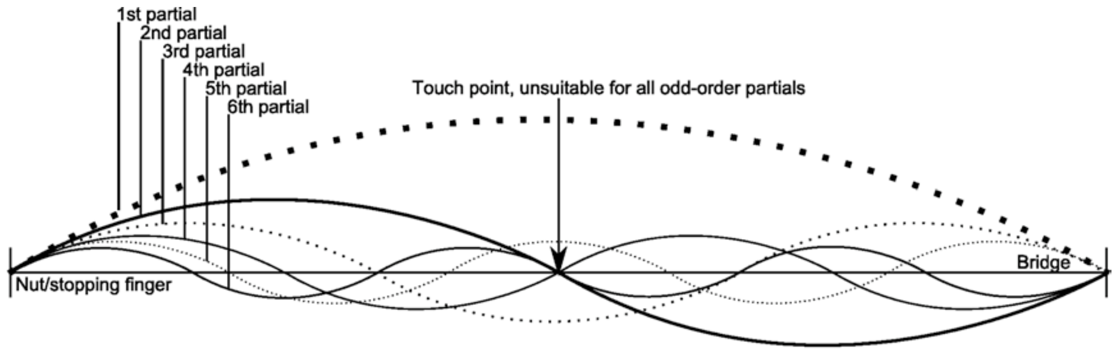


Figure B1a   A string is touched at its mid point. Partials one to six are shown. Those that do not vibrate are drawn with dotted lines.

Similarly, in touching the string at 1/3 or 2/3 of its length, the finger blocks partials with antinodes at, or close to, this point. All partials that have orders of a multiple of three are free to vibrate because they have a node at this point. Consequently, only every third partial sounds, the timbre contains a third of the number of overtones of the open string. The new tone's fundamental is the open string's third partial, the new second partial is the open string's sixth partial, the new third partial is the open string's ninth partial etc.

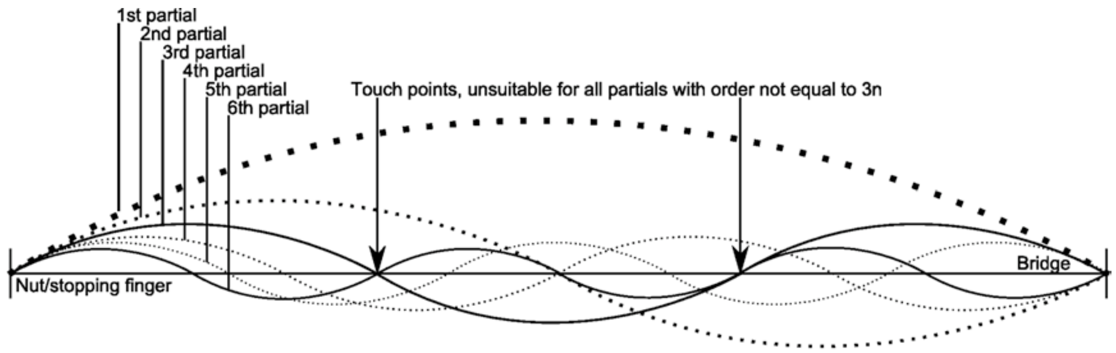


Figure B1b   A string is touched at 1/3 or 2/3 of its length. Partials one to six are shown. Those that do not vibrate are drawn with dotted lines.

In the same way, the fourth harmonic contains a quarter of the number of overtones of the open string, the fifth a fifth of the number etc. This pattern of reduction holds because there are a finite number of available partials on a cello string, bounded by several factors including: string width relative to length, point of contact, exciter properties and cello body responses. These factors are flexible; therefore while the boundary is always finite, its value changes under different conditions. In other words, the *potential* overtone content of a harmonic for various points of contact/excitation forces etc decreases as harmonic order increases.

In reality the pattern of overtone reduction in ascending harmonics is not as consistent as the above description suggests. Partials might only be subdued rather than completely excluded from the sound or extra partials might be included because of responses from the cello body/room or in combinations of various other partials. Moreover, upper partials of the higher harmonics are restricted further than the theoretical model suggests. This is because the effects of damping at the touching finger are relatively larger for higher harmonics, finger width covers a relatively greater proportion of wavelength and string width is large relative to the wavelength of the fundamental. However, despite this, the broad pattern above is generally perceivable.

The reduced overtone content of harmonics in general means that they are particularly susceptible to damping; small increases (for example a slightly less dense plectrum) result in a relatively larger reduction in overtone content than for the stopped string. The exception to this is the first harmonic, the open string, which, being unrestricted by a touching or a stopping finger, is not affected by damping.[196] The combined effect of this and the open string having the largest number of potential overtones means it can ring very ‘brightly’. The timbre can stand out as harsh compared to the stopped string. Cellists often avoid playing open strings because of this effect, preferring to stop a lower string at the same pitch.

[196] Except for the usual damping effects as energy is lost to the air/nut etc.

For a fixed excitation force and contact point, ascending harmonics become quieter. This is clear since at a particular excitation force, the deviation of the string from its rest position is greatest for the first partial and reduces with ascending partials. Amplitude depends on this deviation. The figure below shows a hypothetical situation where a particular excitation force displaces an ideal string. The total amplitude of the first partial is A1, which is greater than that of the second partial A2, which is greater than that of the third partial A3 etc. More precisely, the amplitude of the second partial is half that of the first, the amplitude of the third partial is a third of that of the first etc.

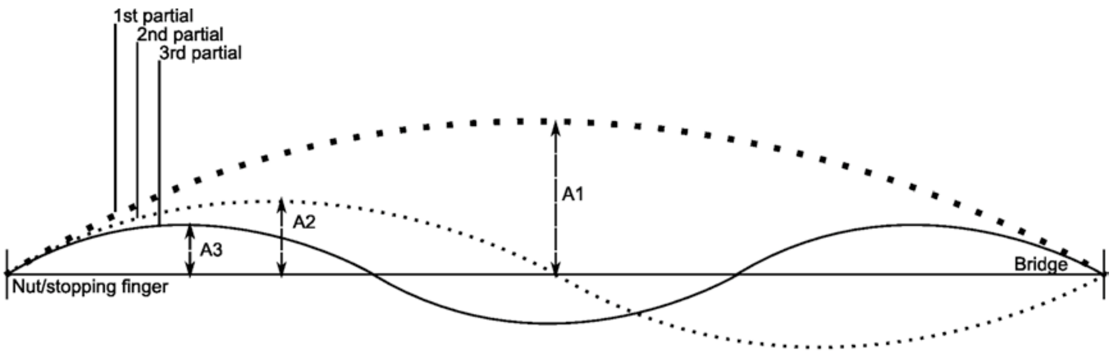


Figure B1c The amplitude of the first three partials in an ideal string.

Under usual excitation conditions, the situation differs from the above figure. The struck string follows the above pattern most closely, with the amplitude of the partials decreasing by 1/n for ascending harmonic order.[197] However, extra effects cause the equivalent equation for the plucked string to be $(1/n)^2$ – in other words, the amplitude of the higher partials decreases more than the example above and more than in the struck string.[198] For the bowed string, the equivalent formula is 1/n multiplied by a numerical constant.[199] Therefore, the

[197] Benade, *The Fundamentals of Musical Acoustics*, 104.
[198] Benade, *The Fundamentals of Musical Acoustics*, 100.
[199] Benade, *The Fundamentals of Musical Acoustics*, 522.

amplitude of the higher partials reduces less than both the struck and plucked string. Applied to real circumstances, amplified by a cello body in a particular room, these results can diverge significantly from the above formulae. However, the pattern of amplitude reduction for partials can be heard loosely to follow the above description.

The reduced overtone content and reduced loudness of ascending harmonics mean that, while they broadly adhere to the principles of the effect of changing contact point, excitation force and means of excitation described in the case of the stopped string,[200] the limits of these inputs are different. Moreover, since there can be multiple nodes on the string for the harmonic's fundamental[201] the 'pattern' of changing contact point is much more complicated in the case of higher harmonics than the stopped/open string.[202] Research in this area is limited. I have made some observations about the loudness of harmonics and the tuning of harmonics, the results of which are recorded in the appendix.

B2 Touch points

The set of touch points for a particular harmonic is a subset of the harmonic's nodes. The difference between the number of nodes and the number of touch points fluctuates for various harmonics. The set of nodes for all harmonics is 'n-1', where n is the harmonic order (i.e. 1 node for the second harmonic, 2 nodes for the third harmonic etc).[203] Therefore, the maximum number of touch points for a harmonic is n-1. All prime number order harmonics have the maximum, n-1 touch points. For example, the second harmonic has one touch point, at ½ of its length and the third harmonic has two, at 1/3 and 2/3 of its length, the fifth has four at 1/5, 2/5, 3/5 and 4/5, etc. The number of touch points of non-prime number harmonics is restricted by another factor: a node is excluded from the set of touch points for a particular harmonic if it coincides with the node of a lower harmonic. For example the fourth harmonic is

[200] See Section A 'Excitation of the string'.
[201] This is a unique situation: the open/stopped string always has two nodal points at the nut/stopping finger/bridge.
[202] See 'A2 String displacement and excitation force' and 'A5 Choice of exciter (width an density) from more information.
[203] Of course, any segment is divided into n sub-segments by n-1 points.

produced when the string is touched at 1/4 of its length *or* at 3/4 of its length, however *not* at 2/4 (=1/2) of its length: in this case the *second* harmonic is produced.[204]

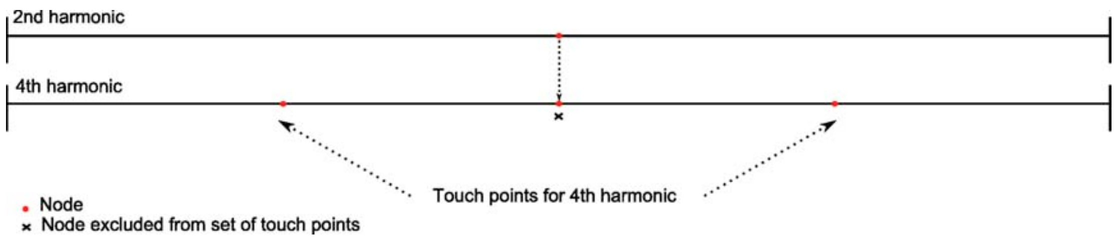


Figure B2a Nodes and touch points for the second and fourth harmonics.

Similarly for the sixth harmonic: the sixth harmonic has *nodes* at 1/6, 2/6, 3/6, 4/6 and 5/6 of the string. However, touch points *only* occur at 1/6 and 5/6 of the length of string since 2/6 (=1/3) and 4/6 (=2/3) are touch points for the *third* harmonic and 3/6 (=1/2) is a touch point for the *second* harmonic.

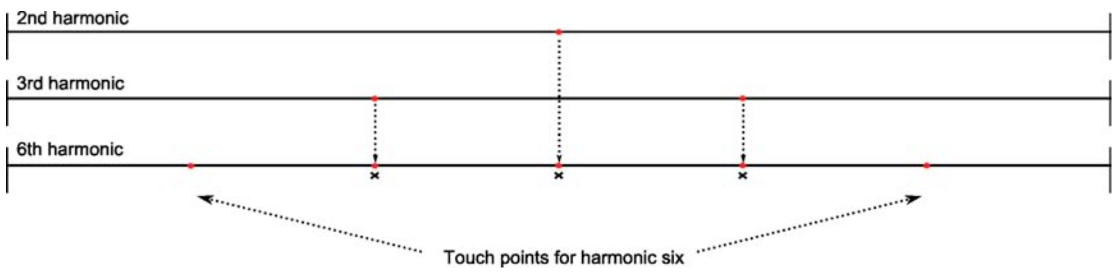


Figure B2b Nodes and touch points for the second, third and sixth harmonics.

Arranging this information in a table for the first sixteen harmonics shows how the number of touch points fluctuates.

Harmonic	Pitch of	Touch points at 1/n of the	No. of	No.	Pitch

[204] In other words the fourth harmonic has three *nodes* (at 1/4, 2/4 and ¾ of the string length) and two to*uch points* (at ¼ and ¾ of the string length).

	harmonic above the open string. Interval above the fundamental +/- cents[205]	length of open string	touch points	of Nod-es	for A string
First	Open string	None	**0**	0	A3
Second	8ve	1/2	**1**	1	A4
Third	8ve +5th +2¢	1/3, 2/3	**2**	2	E5+2¢
Fourth	2 8ves	1/4, 3/4	**2**	3	A5
Fifth	2 8ves +maj 3rd -14¢	1/5, 2/5, 3/5, 4/5	**4**	4	C#6 -14¢
Sixth	2 8ves +5th +2¢	1/6, 5/6	**2**	5	E6+2¢
Seventh	2 8ves +min 7th -31¢	1/7, 2/7, 3/7, 4/7, 5/7, 6/7	**6**	6	G6 -31¢
Eighth	3 8ves	1/8, 3/8, 5/8, 7/8	**4**	7	A6
Ninth	3 8ves +maj 2nd +4¢	1/9, 2/9, 4/9, 5/9, 7/9, 8/9	**6**	8	B6+4¢
Tenth	3 8ves +maj 3rd -14¢	1/10, 3/10, 7/10, 9/10	**4**	9	C#7 -14¢
Eleventh	3 8ves + 4th +51¢	1/11,2/11,3/11,4/11,5/11, 6/11,7/11,8/11,9/11,10/11	**10**	10	D7 +51¢
Twelfth	3 8ves +5th +2¢	1/12, 5/12, 7/12, 11/12	**4**	11	E7+2¢
Thirteenth	3 8ves + min 6th +41¢	1/13, 2/13, 3/13, 4/13, 5/13, 6/13, 7/13, 8/13, 9/13, 10/13, 11/13, 12/13	**12**	12	F7 +41¢
Fourteenth	3 8ves + min 7th -31¢	1/14, 3/14, 5/14, 9/14, 11/14, 13/14	**6**	13	G7 -31¢
Fifteenth	3 8ves + maj 7th -12¢	1/15, 2/15, 4/15, 7/15, 8/15, 11/15, 13/15, 14/15	**8**	14	G#7 -12¢
Sixteenth	4 8ves	1/16, 3/16, 5/16, 7/16, 9/16, 11/16, 13/16, 15/16	**8**	15	A7

Figure B2c Table of pitches, touch points and nodes for the first to the sixteenth harmonics.

The pitches given above are approximate. Irregular tuning deviations occur because of string stiffness, though the extent of these deviations is not clear.

[205] All intervals here are relative to the equally tempered system, '¢' refers to cent/s.

Further research is required. A preliminary analysis of pitch deviation in one cello is found in the appendix of this thesis.

The pattern of available touch points is always symmetrical about the middle of the string. Describing the above table of possible touch points in pictorial terms demonstrates this.

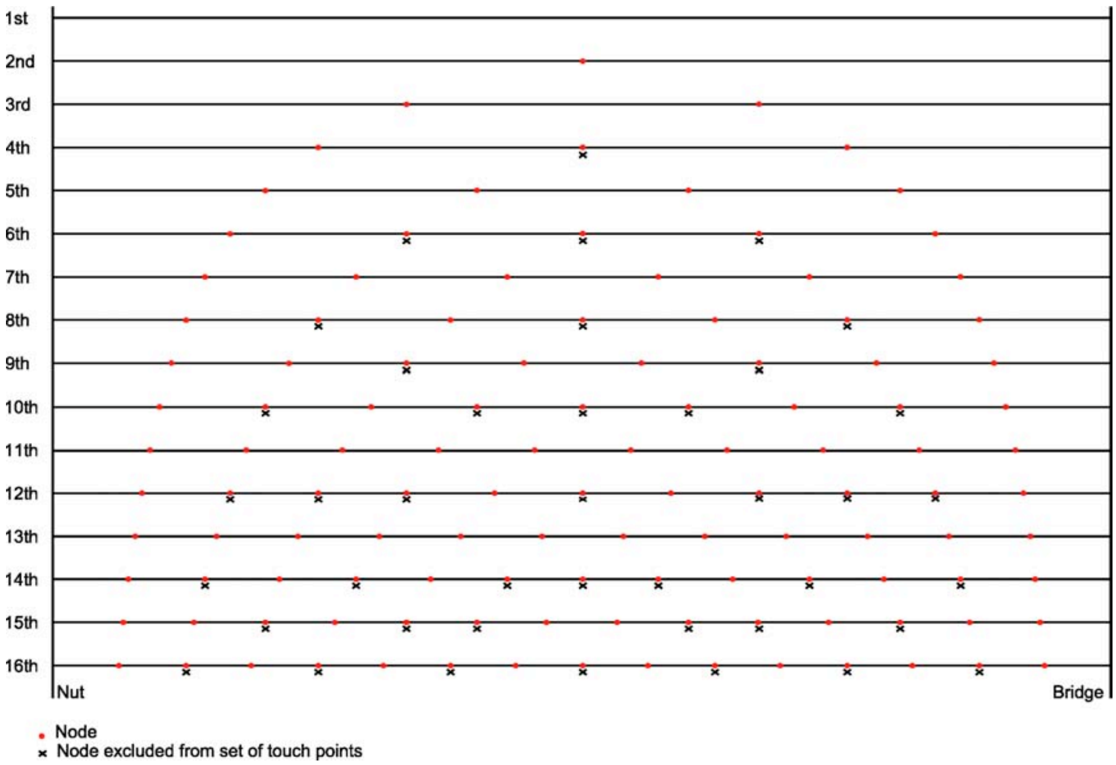


Figure B2d	Nodes and touch points for the first sixteen harmonics

The position of touch points can be described as stopping points on the fingerboard, that is the sounding pitch were the string to be stopped at each touch point. The relative positions for the first sixteen harmonics on the A string are shown below. This is a useful reference point for cellists, but is not an absolutely reliable system. The sensation of touching rather than stopping the string and the fact that the middle of the finger corresponds with the centre of the harmonic node (rather than the bridge-edge of the finger, as is the case with the stopped string) both give the impression of the touch points being closer to the bridge than the relative positions on the fingerboard suggest. In the figure below, the pitch is given alongside the deviation in cents. Touch points for a particular harmonic x are written in the form n.x, where x=1 is the touch point closest to the nut and x=n-1 is the touch point closest to the bridge. Nodes of a harmonic that are included in the touch points of a lower harmonic are written in the form n.(x).

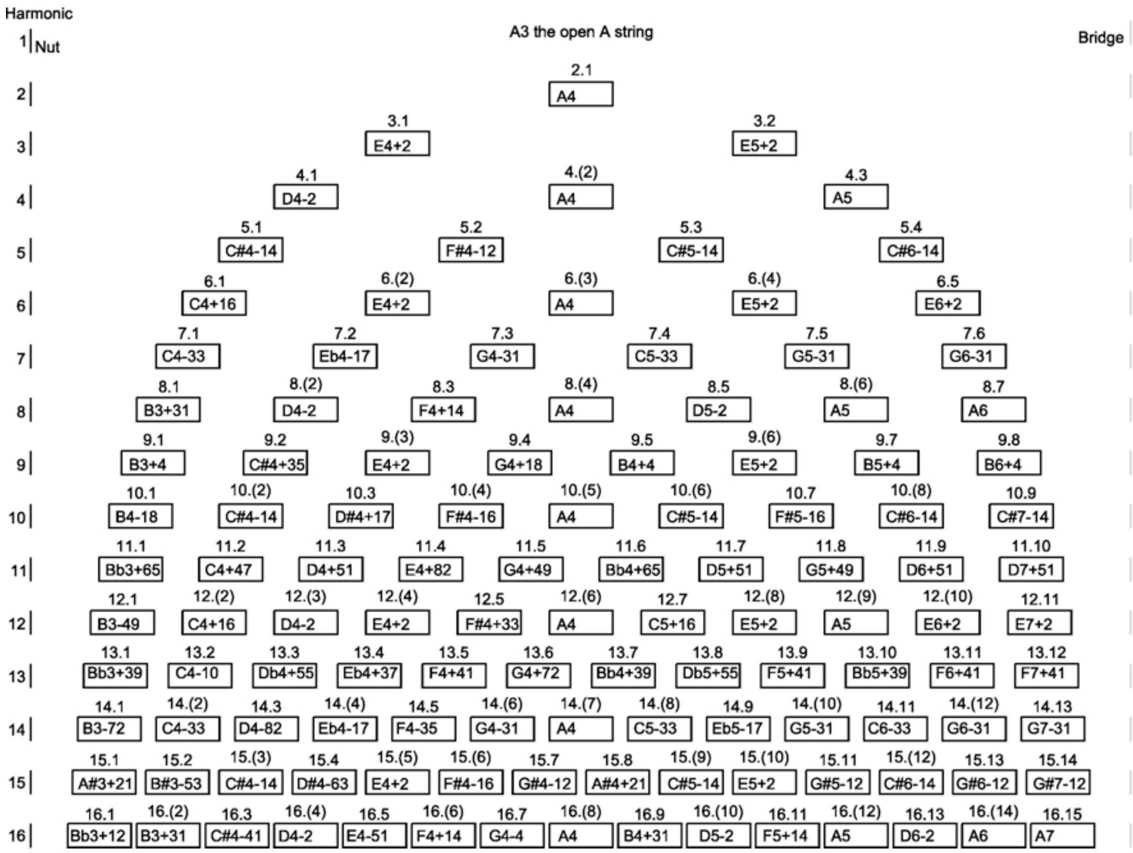


Figure B2e The position of harmonic nodes relative to stopped string pitch.

For example, for the sixth harmonic, the node closest to the nut is 6.5; it is also a touch point, and it is found at the stopped pitch E6+2 cents on the fingerboard. The node for the sixth harmonic immediately below this is 6.(4); it is not a touch point as in coincides with the touch point 3.2 for the third harmonic, it is found at E5+2 cents. The node of the sixth harmonic immediately below this is 6.(3); it is not a touch point as it coincides with touch point 2.1 of the second harmonic and[?] is found at A4. The node of the sixth harmonic immediately below this is 6.(2), not a touch point because it coincides with 3.(1), and is found at E4+2 cents. The final node of the sixth harmonic is the node closest to the nut, 6.1; it is a touch point and is found at C4+16 cents.

Explicatio B2

The easiest way to find the position of touch points for a particular harmonic is by drawing a diagram similar to B2d or by following a simple algorithm:

1. List the nodes as fractions: 1/n, 2/n…a/n…(n-1)/n
2. Remove fractions that can be simplified i.e. 2/(n= 2b), 3/(n=3b)…

The result is the list of touch points in the form a/n. The position of each touch point is the a^{th} node from the nut. For example:

The nodes for the 12^{th} harmonic are:

1/12, 2/12, 3/12, 4/12, 5/12, 6/12, 7/12, 8/12, 9/12, 10/12, 11/12

The following fractions in which can be simplified:

2/12, 3/12, 4/12, 6/12, 8/12, 9/12, 10/12,

Leaving the touch points:

1/12, 5/12, 7/12, 11/12

That is the first, fifth, seventh and eleventh nodes from the nut.[206]

[206] To check the result of the above algorithm, the number of touch points for any harmonic can be quickly calculated using the following formula. This formula can be used to confirm the accuracy of a calculation using the above algorithm. As explained above, nodes are excluded from the set of touch points if they are already touch points for another harmonic – that is, if the harmonic order has integer factors. All prime number order harmonics, therefore, have the maximum number of touch points, n-1 where n is harmonic order. The number of touch points for non-prime harmonics is n-1 minus the touch points for each prime factor of n. This can be summarised for primes and non-primes as:

$\Pi\ [f^a - f^{a-1}]$ a 💿 0

Where f is a prime factor of the harmonic order, n and a is the highest factor of the prime.
This formula was devised by Erik Oña.

For example the sixth harmonic has two prime factors, 2 and 3, its factorisation is 2x3 therefore the number of touch points is:
$(2^1-2^0) \times (3^1-3^0) = 1\times2= 2$

The twelfth harmonic has two prime factors, 2 and 3. Its factorisation is 2x2x3
The number of touch points is:

The simplest way to find the position of the harmonic nodes relative to stopped string pitch (see figure B2e) is to start with the node closest to the bridge. This node, always a touch point, is equal to the pitch of the harmonic. By calculating the harmonic series backwards from this touch point, the position of each node can be calculated. The node immediately below this is an octave higher, the subsequent nodal position is an octave and a 5th minus 2 cents higher, the subsequent nodal position is two octaves higher etc (refer to Figure B2c for the harmonic series). The deviation in cents of the natural harmonic series must be taken into account. For example:

As above, touch points for a particular harmonic x are written in the form n.x, where x=1 is the touch point closest to the nut and x=n-1 is the touch point closest to the bridge. Nodes of a harmonic that are included in the touch points of a lower harmonic are written in the form n.(x).

The pitch of touch point closest to the bridge for the tenth harmonic, 10.9, is C#7-14¢. The pitch of the nodal point immediately below this, 10.(8), is 10.9 – one 8ve = C#6-14¢.

Similarly 10.7 = 10.9 – (8ve +5th +2¢) = C#7-14¢ – (8ve +5th +2¢) = F#5-16¢
10.(6) = 10.9 – (2 8ves) = C#7-14¢ – (2 8ves) = C#5-14¢
10.(5) = C#7-14¢ – (2 8ves +maj 3rd -14¢) = A4
10.(4) = C#7-14¢ – (2 8ves +5th+2¢) = F#4-16¢
10.3 = C#7-14¢ – (2 8ves +min 7th -31¢) = D#4+17¢
10.(2) = C#7-14¢ – (3 8ves) = C#4-14¢
10.1 = C#7-14¢ – (3 8ves +maj 2nd +4¢) = B4-18¢

B3 Point of contact

$(2^2-2^1) \times (3^1-3^0) = 2\times2 = 4$

The seventh harmonic has no factors apart from itself since seven is a prime number. The number of touch points is:
$(7^1-7^0) = 7-1 = 6$

When the string vibrates at a harmonic, the whole string length vibrates from nut to bridge. Therefore, exciting the string on either side of the touching finger produces the same pitch.

At first glance, point of contact seems more flexible for harmonics than for the stopped string; the whole string length is available when choosing contact points and, since the string is not pressed to the fingerboard, it is less awkward (particularly while bowing) to play in the region of the fingerboard. However, changing point of contact for harmonics has *less* influence upon timbre than is the case for the stopped string[207] for several reasons.[208] As described above, fewer overtones become available to the cellist as harmonics ascend and this reduction in overtone content is more extreme than the reduction associated with equivalent pitch increases by shifting up the stopped string.[209]

The pattern of including and excluding overtones from vibration is not as easily summarised for harmonics as for the stopped string,[210] i.e. is not, broadly, minimising overtones at the mid point of the vibrating string and maximising overtones at the bridge and nut/stopping finger. In fact, because there are several nodes for each harmonic's fundamental, the pattern of '*sul ponticello-sul tasto-sul ponticello'* observed in the case of the stopped string might repeat itself several times along the string length for each harmonic; three times for the third harmonic, four for the fourth etc.[211] This makes the contact point a fairly unreliable quantity, particularly in higher harmonics (for example finding excitation points *exactly* at the antinodes of the fundamental of harmonic six is already fairly difficult). The changing effect of contact point, particularly for high harmonics, becomes too erratic to judge meaningfully. A broad summary of the

[207] The exception to this is the first harmonic, the open string.
[208] This is discussed more deeply in 'Explicatio B3' below.
[209] The extent of this could be more fully researched, for example comparing the difference in overtone content between a harmonic on the A string with a high stopped position for the equivalent pitch on the C string with a high harmonic on the C string and the equivalent stopped pitch on the A string. The difference in overtone content in the latter case is larger than the former but the spread of the distribution in examples between these two extremes is not clear.
[210] See 'A1 Point of contact'.
[211] I came to this conclusion when trying to find an explanation for harmonics' erratic response to changes in contact point. The theory requires more detailed research but, for initial experiments with my cello, seems to hold.

effect of changing point of contact within the boundaries of a cellist's judgement is as follows:

- Overtone content is maximal when point of contact is fairly close to the node, that is the bridge and/or the nut and/or either side of the touching finger.[212]
- Overtone content is minimal when point of contact is at a particular distance away from any node. This is precisely half the distance from one node to another, or half the wavelength of the associated harmonic (i.e. 1/12 of the string for the 6th harmonic, ¼ of the string for the 8th harmonic).[213]
- Overtone content reduces as the point of contact moves from the positions associated with the maximal to minimal result.

The 'overtone-takeover point' for harmonics is, compared with equivalent pitches on the stopped string, relatively far from the bridge. In addition, since there are relatively few partials available to take over the timbre, the noise element of plucking/striking/bowing close to the bridge becomes very present in the sound for contact points in this area. Particularly when bowing, the coarse bow-bridge noise strongly characterises the sound. For high harmonics, this noise element dominates the sound very quickly after the 'overtone-takeover' point. The 'optimum' bowing point then, at which maximally overtone-rich sounds and limited noise are produced, is slightly further from the bridge than a stopped string of equivalent pitch.

B4 Excitation force

APPLICATIONS SPECIFIC TO PLUCKING AND STRIKING

The relationship between excitation force and loudness in the case of harmonics is broadly the same as that of the 'normal' stopped string.[214]

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[212] The other nodal points for the harmonic in question also maximise overtone content, however, as explained above, these are difficult to find, especially for high harmonics.
[213] Similarly to the stopped string, this is not strictly true in the case of bowing (see 'A1 Point of contact'). Bowing restricts partials with nodes *and* antinodes at a particular point (however, bowing close to an antinode allows the partial to vibrate well). This accounts for the certain 'black spots' found on a string for each harmonic. At these points, antinodes for the associated harmonic, a light stuttering sound with little or no pitch is heard. For high harmonics, several of these 'black spots' occur; the number of antinodes for a partial is the same as the partial's order; accounting for a rising number of such regular contact points that do not seem to suit the harmonic as harmonic order increases.
[214] See 'A2 String displacement and excitation force'.

Plucked and struck harmonics become louder and more overtone-rich as plucking/striking force increases. However, the limits of excitation force are different for harmonics compared with the stopped string, and so are the particular conditions for producing a specific sound. The band within which 'normal' sound is produced in harmonics is narrower than that of the stopped string. At the upper limit of this band (high plucking/striking forces), harmonics become less overtone rich, the pitch is sharpened and the duration of their decay is reduced. The pitch of the open string or the pitch of the string, were it to be stopped at the touching finger position, may be heard in addition to this. At the lower limit (low plucking/striking forces), the fundamental is weak and higher partials of the harmonic become more prominent in the sound in the 'overtone-takeover' process. Since there are relatively few partials present in harmonics, the overtone-takeover process is fast and noise elements quickly become present in the sound. Since harmonics become less overtone-rich as they ascend, high harmonics are more quickly affected by changes in excitation force.

APPLICATIONS SPECIFIC TO BOWING

Similarly to the stopped string, bowed harmonics become more overtone-rich as bowing pressure increases and louder as bow speed increases.[215] However, the 'optimal' bow speed and the limits of bow speed and pressure in relation to one another are different for harmonics than the stopped string. In general, harmonics are less well sustained under slow bow strokes than the stopped string, especially at high pressures.[216] Under these conditions multiphonics may be produced as harmonics from the surrounding part of the string vibrate in addition to the fundamental; the open string can also be included in the sound. Bow strokes that produce a 'normal' harmonic sound are faster and bow pressures lighter than for the stopped string. A faster and lighter bow stroke is possible within 'normal' sound. At the upper limit of bow speed and lower limit of bow pressure, the sound of the bow moving along the string is a prominent part of the tone, particularly for high harmonics.

[215] The increases in bow pressure and bow speed are relative to one another, see 'Explicatio A2' for more information.
[216] Exceptions are the open string and low harmonics compared with short lengths of stopped string.

Compared with the stopped string, harmonics are sensitive to relative changes in bow speed, pressure and point of contact. For high harmonics, where the touching finger might be very close to several touch points, slight alterations in bow speed/pressure or point of contact can cause shifts between these neighbouring harmonics, even if the left-hand position remains steady.[217]

B5 Choice of exciter (width/density)

Altering the width and/or density of the exciter of the plucked, struck or bowed string can be a more effective way to manipulate the number of partials present in a sound than changing point of contact. As harmonics are overtone-weak, the 'blocking' of higher partials with a wide/soft plectrum/hammer/bow can produce very thin sounds with only a few overtones. This is a more reliable way of producing a relative quasi *sul tasto* timbre than moving point of contact towards the mid point of the string, which, as discussed above, can have unpredictable effects. Overtone content increases with decreasing exciter width and increasing exciter density. However, harmonics are also unstable under these conditions, especially high harmonics. Reducing plectrum/hammer width and density and tilting the bow can encourage multiphonics, or a shifting between two harmonics and can make the sound unstable as well as more overtone-rich. In general, a relative quasi *sul ponticello* sound is difficult to achieve, especially above the first few harmonics.

An alternative way of producing a *sul ponticello* timbre in plucked harmonics is rubbing rosin on the finger and stroking/brushing the string upwards with very low pressure.[218]

B6 Position of the touching finger

[217] This is a clear pitch change rather than a multiphonic 'extra pitch'. The exact reasons for this are unknown. As far as I am aware, no research has followed up Bertram Truetsky's remarks regarding this effect: Bertram Turetzky, *The Contemporary Contrabass* (2nd edn., Berkley: University of California Press, 1989), 124.
[218] This trick was devised by Thomas Demenga.

The finger that touches the string to produce harmonics is in the middle of a node, not at its upper edge, as is the case for the stopped string. Therefore, when learning harmonic finger positions in relation to stopped-string finger positions,[219] the harmonic pitch is slightly closer to the bridge than the stopped string pitch (more/less so depending on the width of the fingers relative to wavelength). The sensation of touching rather than suppressing the string, and the angle of the touching finger, can exaggerate this feeling that harmonic nodes are located slightly closer to the bridge than expected. The cellist often needs to compensate by shifting the left hand towards the bridge.

There are various alternative positions for a particular harmonic on one string (see figure B2c above). These touch points are not absolutely equivalent. The difference in choosing one touch point over another is complicated (intonation, timbre and sustainability of harmonics are all influenced); it depends on the manner of excitation and differs between cellos. It is an area where considerable research could yet be done. However, one notable and easily explainable difference is the shifting of a component pitch. This is the pitch of the string if it were to be stopped at the touch point. This is always faintly present in the timbre of a harmonic and is more noticeable for high harmonics as a ‘shadowy’ ‘second fundamental’. It is clearly perceivable by comparing harmonics played at various alternative touch points in succession. This component pitch certainly plays a role in the overall timbre of a sound. Of course, for each harmonic there is always a touch point for which the finger-bridge pitch is the same as the harmonic pitch. In this case the ‘shadowy’ component is not present in the sound.

B7 Pressure of the touching finger

The pressure of the finger that touches the string during harmonics can be varied within *normale* timbre for harmonics and increased/decreased to various effect, see ‘A5.2 Left hand finger pressure’ for more information.

[219] Harmonics are often notated in this way.

In addition to this, the limits of finger pressure, and the ‘optimum’ finger pressure for producing a ‘normal’ harmonic tone, are relative to excitation force. High excitation forces require greater finger pressure than low excitation forces. Low excitation forces are able to produce harmonics under lower finger pressures.

B8 Contact time between touching finger and string

If the touching finger leaves the string very soon after the plectrum/hammer/bow, the harmonic rings for a maximum amount of time. Increasing the contact time between finger and string mutes the decay of the harmonic. This affects plucked and struck harmonics more than bowed, especially those under long bow-strokes. As contact time between finger and string increases, the duration and overtone content of plucked and struck harmonics are reduced until only a muted ‘thudding’ sound with faint pitch content is heard. If the finger leaves the string very early the open string or neighbouring harmonics might sound with the intended harmonic. For bowed harmonics, if the finger leaves the string before the bow stroke has finished, the harmonic will continue to ring for a short while. This period of time is increased by fast bow speed and light bow pressure. This can be a useful aid in shifting *legato* between two distant harmonic positions. Eventually, if the bow stroke continues, the sound of the open string takes over.

B9 Qualities of the touching finger/object

An object other than the finger pad can be used to touch the string. A narrow and/or dense object (such as the fingernail, glass/metal rod) allows more upper partials to be included in the sound and lengthens the decay of the harmonic. For increasing width and decreasing density of the touching object, overtones are gradually restricted and the harmonic rings for a shorter period of time after excitation. Very wide and/or soft stopping objects eventually stop the fundamental from sounding and, for the plucked and struck string, produce the ‘thudding’ sound described above. For the bowed string, the sound of the bow hairs moving along the string is very present in the sound and the pitch content is limited. For very thin and/or dense touching objects, multiphonics are produced and/or the open string is present in the tone.

B.10 Artificial harmonics

Artificial harmonics are harmonics with a fundamental base in a stopped string pitch rather than the open string. One finger (usually the left hand thumb or index finger) stops the string and a free finger (usually of the left hand) touches the string at a node of a partial relative to the stopped string pitch. Thus the second harmonic is produced when the touching finger is half way between the bridge-edge of the stopping finger and the bridge, the third harmonic is produced when the touching finger is at 1/3 or 2/3 of the length of the string from stopping finger to bridge etc. Common artificial harmonics are those produced by touching a fourth, a third and perhaps a fifth or second above the stopped note. These intervals are respectively: a quarter, a fifth, a third and an ninth of the vibrating string length, corresponding to the fourth, fifth, third and ninth harmonics. The string vibrates on either side of the touching finger, from the stopping finger to the bridge.

If, as is usually the case, both the stopping finger and the touching finger are fingers of the left hand, the distance that the cellist can stretch these fingers limits the region of possible touching points. Otherwise, while the left hand stops the string, the right hand can touch the string and simultaneously pluck it or strike it (e.g. touch the string with the third finger of the right hand and pluck with the thumb/strike the string with an object held between thumb and index finger)[220] or the left hand can pluck/strike the string close to the stopping finger while the right hand touches the string.

The overtone content of artificial harmonics is reduced compared with natural harmonics due to the dampening effect of the stopping finger and the reduced string length relative to width. Overtones become increasingly restricted for

[220] For very short bow strokes this is also possible, but more awkward.

stopping finger positions close to the bridge (i.e. as the vibrating length of string is shortened).

The intonation of artificial harmonics is more flexible than that of natural harmonics. The cellist can compensate for the mistuning of harmonics or adjust to a required pitch by shifting the stopping finger. Also, effects such as *vibrato*-like gestures and *glissandi*[221] are easily produced.

B11 Multiple node natural harmonics

The pitch of each harmonic is unchanged if, rather than one touch point, any number of its touch points are touched simultaneously. For example touching the string at 1/3 *and* at 2/3 of its length produces the same pitch as touching it at 1/3 *or* 2/3 of its length. Similarly, combining a node that has been excluded from the set of touch points (because it is a node for a lower harmonic) with a touch point results in the higher associated harmonic (e.g. if a string is touched at 1/6 and 1/3 of its length, the sixth harmonic sounds). In addition, and with most interesting applications: the combination of two nodes of a partial which have *both* been excluded from the touch points of a particular harmonic, produces that harmonic, provided the touch points are not common nodes for a different, lower partial (e.g. touching the string at 1/3 and 1/2 of its length produces the sixth harmonic).

Applications of this latter effect become interesting when it is more convenient to produce a harmonic by combining two nodes that have been excluded from the touch points of that harmonic, for example in fast passages that take place in a particular region of the fingerboard. An example is the generation of harmonic six by touching the string at 2/6 *and* 3/6 of its length. Touched individually, 2/6 (=1/3) is a touch point for harmonic three and 3/6 (=1/2) is a touch point for harmonic two. However, touched together they can only produce harmonic six because they fix points at one sixth of the string length.

[221] To produce constant *glissandi,* the distance between the stopping and touching fingers becomes narrower as the fundamental pitch ascends, maintaining the relative interval (i.e. a fourth) of the original.

This is particularly useful when the cellist requires harmonic six and is in the region of 4th position, for example when fast changes between stopped notes in 4th position or the second harmonic and the sixth harmonic are required, or in double-touching harmonics (if, for example, the sixth harmonic on the A string and the third harmonic on the D string are required simultaneously). Also, the tenth harmonic is producible by combining points at 4/10 and 5/10 (which are equal to 2/5 and 1/2) of the string length.

Combining touch points, even if it has no influence on the pitch of a tone, can be interesting in timbral terms. As the number of touch points in use increases, the overtone content of a harmonic is reduced and the pitch is lowered slightly.

B12 Left hand methods that particularly differ from the stopped string case

B12.1 Double-touched harmonics [222]

Harmonics can be played simultaneously. For plucked and struck tones this is relatively easily achieved. However, ‘double-touching’ bowed harmonics is restricted compared with the stopped string. The particular, narrow requirements of bow speed and bow pressure for each harmonic mean that the ‘ideal’ bow speed, pressure and contact point of one might not suit another. Since this margin is so narrow, a consistent sound for double-touched harmonics can be difficult to maintain. The substantial reduction in volume, especially between the first few harmonics can also make the balance of double touches difficult to control. Well-matched pairs of harmonics are not always easy to predict. In general, the further the node order of the harmonics from one another, the more difficult they are to control in double-touching. For example, double-touching the third harmonics on the A and C string (by bowing under the bridge) is easier than double-touching the third and eighth harmonic on adjacent A and D strings (although the latter two are closer in pitch).

[222] ‘Double-touching’ is equivalent to ‘double-stopping’ in the stopped string. I use the term for physical accuracy, consistent with my use of the term ‘touching’ finger.

B12.2 Vibrato and Pitch bends

A narrow vibrato is producible in harmonics by oscillating the finger in the usual way. Vibrato-like fluctuations in pitch are also producible by increasing and decreasing the pressure of the touching finger or shifting the touching finger towards/away from the bridge. The resulting small pitch variations are more readily produced on the lower harmonics; for higher harmonics, slight deviations in the touching finger position/pressure cause a shift to a neighbouring harmonic.

B12.3 Trills

Bowed trills between two harmonics on the same string are difficult to perform. The string has a tendency to 'stick' at a particular harmonic pitch after the finger is removed from the touching point and so often only the first pitch is heard. If it is possible to combine the two touch points to produce a different harmonic then an aggregate higher harmonic is often present in the sound instead of or as well as the intended trill.[223] This is particularly the case for fast trills. Low speed trills between natural harmonics are much more readily produced, especially if the trilling fingers pluck the string lightly as they release it.

B12.4 *Bisbigliando*

Performing a trill between two equivalent touch points of a particular harmonic has a *bisbigliando*-like effect. Slight variations in timbre between the two alternative positions are audible and the jumping in pitch of the 'shadowy' touching-finger-to-bridge pitch may be perceived.[224] The fingers can jump on and off the string in this action or one finger can stay in contact with the string. The timbral outcome is different in each case. In the bowed string, the rhythmic articulation of the fingers is stronger in the former and smoother in the latter.

B12.5 *Glissandi*

Performing a slow *glissando* with harmonic finger pressure causes many harmonics to sound successively as the finger touches the various touch points of the string. The harmonics are ordered according to their position on the

[223] See 'B11 Multiple node natural harmonics'.
[224] See 'B6 Position of the touching finger'.

string, so sometimes wide ascending and descending fluctuations in pitch are heard. Eventually, moving towards the nut or the bridge, the ascending harmonic series occurs consecutively. High harmonics are only present if the touching finger moves relatively slowly. As the speed of the touching finger increases, this *glissando* contains fewer tones; higher harmonics are excluded.[225]

A smooth, continuous *glissando* is possible for artificial harmonics if the hand shifts such that the distance between the stopping and touching fingers remains constant in relative terms. For example, for harmonics touched a fourth above the stopping finger, the *glissando* is constant if the distance of a fourth is maintained along the string. In practice, this equates to reducing distance between finger and thumb for ascending *glissandi*.

Performing artificial-harmonic *glissandi* with a fixed distance between the stopping and touching fingers (i.e. not maintaining the relative distance of, for example, a fourth) produces a series of repeating *glissandi.* The *glissandi* start at the same pitch and have the same range (usually not more than a minor third). If the *glissando* is fast, the effect has a birdsong-like quality (it is often referred to as the 'seagull effect').

B13 Multiphonics

A multiphonic is the simultaneous sounding of two or more harmonics on one string. The component tones of multiphonics can be difficult to predict, but with practice their reliability can be improved.

There has been little research exploring multiphonics in stringed instruments; an acoustical explanation of the effect is still lacking. However, while it is difficult to be precise about multiphonics, it is possible to summarise some certain playing conditions that facilitate them.

[225] See figure B13 below, which shows a distribution of the harmonics along the string length.

In general, the conditions that produce multiphonics are just outside the boundaries of 'normal' harmonic sound: high bow pressure, reduced bow speed and very light left-hand finger pressure. Reproducing tones with particular pitch content relies on the accurate reproduction of these quantities, essentially muscle memory.[226] Multiphonics sound more readily if the point of contact is a short distance away from the bridge and if the excitation force is slightly higher than the optimal for producing 'normal' harmonics. Multiphonics work well when the contributing harmonics have similar 'ideal' points of contact and finger pressures, i.e. when the span of the orders of contributing harmonics is not very wide. If two or more harmonics are very far apart in pitch, the point of contact is unlikely to be close enough to the ideal conditions of both harmonics to induce them to sound simultaneously. However, a multiphonic that contains harmonics of incremental order is difficult and, in the higher registers almost impossible (for example, under high bow pressure harmonics 6 and 7 might sound together, however harmonics 10, 11, 12, 13… rarely sound together, even though they are closely situated and have similar ideal contact points).

Certain areas on the string contain several harmonics within a short string length; I refer to these areas as harmonic 'clusters'. Multiphonics are more reliable at clusters that contain several of the mid-range harmonics. The figure below shows all the nodal points on the string up to the thirteenth harmonic. Clusters are visible, for example around the sixth harmonic at point A and around the eighth harmonic at point B at which reliable multiphonics are produced. It is also clear from the figure that there are no clusters which include the second harmonic; the only possibility to use this harmonic in a multiphonic is to combine it with the open string by gradually releasing pressure at the touching finger. It is also clear from the figure that the distribution of harmonic clusters is symmetrical about the string's mid point. Therefore, for every reliable multiphonic found, a 'twin' multiphonic exists at the same distance on the opposite side of the string's mid point.

[226] This is essentially the same process under which, for example, correct intonation or good bow control is learnt.

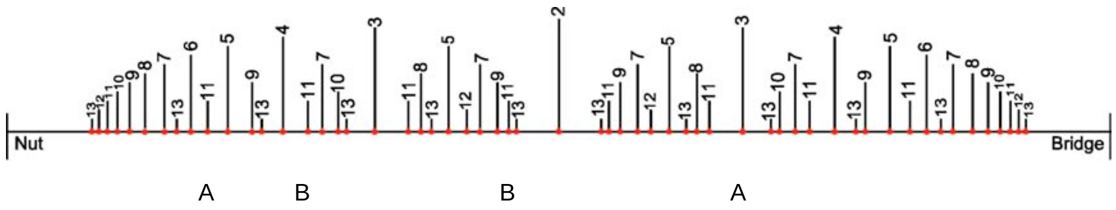

Figure B13 Every nodal point on a string for harmonics 1 to 13. The number next to each (red) touch point is the harmonic order. Clusters can be seen at certain points.

The type of multiphonic that is simplest to produce is a harmonic plus the open string. A reliable way of introducing the open string pitch to a bowed harmonic is to bow 'behind' the touching finger. This is easier for touch points close to the bridge, especially the lower strings and the mid-range harmonics (i.e. in the region of harmonics seven to twelve).

B14 Tuning of harmonics

The deviation between equal temperament and the harmonic series is clear and well documented.[227] However, harmonics in a real cello also deviate from this 'ideal' harmonic intonation because of string stiffness. These deviations are irregular and vary from string to string. To an extent the cellist can compensate for this by fine-tuning harmonics with finger pressure and finger position. Measurement done for this thesis can be found in the appendix showing the deviation in several cellos for bowed strings.

Summaries Section B

Summary B1

When anti-nodal points are touched with the fingers, certain overtones are blocked from the sound, producing harmonics. Harmonics have very reduced overtone content compared to stopped string tones. The relative reduction in

[227] See Figure B2c.

overtone content from one harmonic to the next is large at first and reduces gradually for ascending harmonics.

Summary B2

The number of touch points for a particular harmonic is not always equal to the number of nodes. The former fluctuates according to the ability to factorise the latter. Therefore harmonics with prime number order have the most touch points. The position and number of touch points can be easily calculated.

Summary B3

Overtone content is more complicated to determine in the case of harmonics than the stopped string. Timbre is most overtone-rich for contact points close to a node of the associated harmonic, and is weakest exactly half way between two nodes. However, since there are several nodes on the string for the harmonic's fundamental, there are multiple points of maximum and minimum overtone content.

Summary B4

String displacement and excitation force have similar effects on harmonics to their effects on the stopped string. However, the extent of changing these factors is slightly different in the case of harmonics, usually having narrower limits and being less flexible.

Summary B5

Exciter width influences the overtone content of harmonics in the same way as the open string. However, increased exciter width can have a particularly notable effect in blocking overtones.

Summary B6

Finger position is notably different for harmonics than stopped pitches because the finger lies in the middle of the node.

Alternative finger positions are possible for each harmonic, which have implications in terms of timbre.

Summary B7

Finger pressure, which is relative to harmonic order, can be varied to influence sound in various ways.

Summary B8

Contact time between finger and string is relative to harmonic order. Therefore the contact time within which 'normal' harmonic sound is produced increases for lower harmonics. Above the 'normal' contact time, the harmonic has a low overtone content because of damping effects. Below the 'normal' contact time, the open string or neighbouring harmonics might be included in the sound.

Summary B9

The quality of the touching object influences damping. As the density of the object increases, or as its width decreases, damping is reduced. As a consequence, the overtone content and decay duration increase.

Summary B10

Artificial harmonics have their fundamental base in a stopped note rather than in the open string. When nodal points in relation to the stopped note are touched, harmonics that are relative to the stopped tone sound. The overtone content of artificial harmonics is reduced compared to natural harmonics.

Summary B11

It is possible to touch two nodes of a harmonic simultaneously. This might change the pitch of the harmonic normally produced when each point is touched separately. It will always reduce the overtone content compared to harmonics touched on a single node.

Summary B12

In order to play two harmonics on different strings simultaneously, they must have similar ideal points of contact and bow speeds.

Vibrato is possible by oscillating the finger, moving backwards and forwards slightly or by changing the pressure of the touching finger. More variation is possible on the lower harmonics.

Fast trills between two harmonics on the same string are difficult to produce. The string tends to 'stick' at one harmonic pitch or combine the two nodal points to produce an aggregate harmonic.

A *bisbigliando* effect can be produced by trilling between alternative touch points for a harmonic on one string.

A *glissando* can be performed between successive harmonics as they lie on the string. A smooth *glissando* can be produced by starting from an artificial harmonic and maintaining the relative distance between stopping and touching fingers. If the artificial harmonic *glissando* is performed with a constant distance between stopping and touching fingers, several short *glissandi* follow one another.

Summary B13

Several harmonics can sound simultaneously on one string in a multiphonic. These are produced at points on the string where a group of harmonics (that do not have incrementally ascending or descending harmonic order) are clustered together. The excitation force is slightly greater than for 'normal' harmonic production and finger pressure is slightly lighter. The distribution of harmonic clusters is symmetrical about the string's mid point.

Summary B14

The tuning of harmonics deviates from the natural harmonic series.

Section C The prepared cello: using external objects such as mutes and ‘rattles’

The effects of resting soft and dense mutes against the string and the possibilities of preparing a string with various mutes, and of muting at the bridge are explained.

C1 Soft objects/mutes

The effect of dampening string vibration with a soft object, in effect a mute, depends on the mute’s size and placement:

C1.1 Damping with a large, soft object/mute (e.g. the flat hand)

Damping the string with a large, soft mute after excitation stops the vibration.

APPLICATIONS SPECIFIC TO PLUCKING

Damping the string with a large soft mute before plucking results in a dull thudding sound.

APPLICATIONS SPECIFIC TO STRIKING

Damping the string with a large soft mute before striking prevents piano-type vibration and the clavichord-type pitch that corresponds to the muted length of string. The other clavichord-type pitch vibrates normally.

APPLICATIONS SPECIFIC TO BOWING

Damping the string with a large soft mute before or during a bow stroke prevents significant vibration of the string. The sound of the hairs moving against the string is heard, possibly in addition to faint harmonics and/or pitches were the string to be stopped at the bridge-edge of the muted region.

If the mute is removed from the string in the early stages of decay, vibration might resume.

C1.2 Damping at the bridge/nut with a small soft object/mute (e.g. the fingertips)

Pressing lightly with a small, soft mute close to the bridge reduces volume and upper partial content (if the pressure increases, eventually sound is stopped completely or, for an open string, the mute stops the string and it vibrates with frequency ‘mute-to-nut’). The equivalent effect occurs when pressing at the nut.

APPLICATIONS SPECIFIC TO PLUCKING

The side of the right hand can be used in a similar way (similar to the guitarist’s ‘palm mute’). The little-finger edge of the palm rests on the string. This frees the right hand fingers and enables more intricate *pizzicati*.

APPLICATIONS SPECIFIC TO STRIKING

Muting is likely significantly to reduce, perhaps totally dampen, piano-type vibration and the clavichord-type tone that corresponds to the muted length of string. The other clavichord-type tone is free to vibrate.

Explicatio C1

In the case of large, soft mutes, damping effects are so high that vibration is completely absorbed. If the mute maintains contact with the string until the excitation energy is expended, no sound is heard. Otherwise the string resumes vibration as the mute is removed. Because of the mute’s damping effect, the resumed tone is reduced in overtone content, amplitude and duration compared with the ‘normal’ tone at each respective point of decay.

In the latter case, if the mute is smaller and placed very lightly on the string, close to the bridge/nut/stopping finger (where the displacement of the string is minimal) the vibrating string’s energy is only partially absorbed. The damping effect of the mute filters the higher overtones from the sound, reduces overall amplitude and reduces decay duration. This effect becomes more extreme as pressure between mute and string increases and/or for decreasing mute density/increasing mute size. Eventually the damping effects are such that the tone is dampened completely, as above.[228]

C2 Dense objects/mutes as 'rattles'

A dense object can be placed close to the string so that either:

- The object 'stops' the string and two possible pitches: mute-to-bridge and mute-to-nut are audible. In this case the object is acting as a slide.[229]

or

- The two 'rattle' against one another as the string vibrates. A 'normal' plucked/struck/bowed tone, the open or stopped-string tone (reduced in overtone content and loudness) is heard alongside the rattling sound. In this case the object is effectively a mute since it dampens the string's vibration. The pitches from object to bridge/nut might also be present. The cellist can influence the character of the sound by controlling the loudness, overtone content and the duration of the rattling in several ways. In general, loud rattling implies short rattling and quiet, short open/stopped-string tones. As the loudness of the rattling decreases, it is possible to sustain the rattling and open/stopped string tones for longer, or to remove the rattle and allow the open/stopped string sound to ring for a relatively long time and loudly. In more detail this is controlled by:

Excitation force (the force of the pluck/strike or bow speed)

- Loudness:

  Increasing the force of the pluck/strike or increasing bow speed (i.e. the loudness of the tone) increases the loudness of the rattle.
- Duration:

  If the position of the object is fixed, increasing force of the pluck/strike reduces the duration of the rattling part of the sound. For high bow

[228] The explanations for the reactions of a string muted in various ways seen throughout this section are devised from information about damping and the decay of sound. For background information see: Benade, *The Fundamentals of Musical Acoustics,* 32-49.
[229] See 'A7 Slide effects'.

speeds, the rattling is sustained for the length of the bow stroke but once the bow is released the decay is short.

Density of object

- Loudness/overtone content:

  The loudness of the rattling and the inclusion of higher partials in the sound are increased by fairly heavy dense objects, such as the fingernail, nut of the bow, pencil etc. Light, dense objects, such as paper, produce a quieter sound with fewer overtones. Soft objects, such as foam or polystyrene, prevent a rattling sound (a light tapping might be heard) and substantially reduce the loudness and overtone content of the string's vibration.
- Duration:

  The denser the object, the greater the duration of the rattle in the tone's decay.

Contact force

- Loudness/duration:

  The duration of the rattling in the sound's decay *increases* and the loudness of the rattling *decreases* if contact force is *reduced*, that is by:

  - Limiting excitation force (plucking/striking force/bow speed), see above
  - Applying the mute after the first few, most vigorous, vibrations (applicable to plucking and striking or in the decay of a bowed tone)
  - Placing the object as far from the string as possible, whilst still allowing contact
  - Placing the object at the nut or bridge rather than in the more mobile middle section of the string

  Under these conditions the object absorbs a minimal amount of energy from the vibrating string.

Conversely, reversing the above conditions (increasing contact force between object and string) reduces the duration of the rattling in the decay and increases the loudness of the rattling tone. If the pluck/strike/short bow stroke is very loud or the object is placed very close to the string, the two come into contact only a few times; the string is left ringing or vibration stops completely. Or, for sustained bow strokes, the rattle is loud relative to the *arco normale* tone and vibration might be irregular/unstable. It is likely that the object-to-bridge pitch will be present in the sound and there will be a very strong noise element in the timbre.

Placing of object

- Duration:

  To maximise the duration of the rattling in the sound's decay, the object should be moved towards the string as it begins to lose energy (that is after the pluck/strike/bow stroke) since string displacement moves inwards as vibration decays. Otherwise, the string rings on after the rattling sound stops.
- Usually the object is placed to the side of the string, but if its position corresponds to the direction that the string is plucked/struck/bowed (that is, respectively, above/below or to the left/right of the string if the string is excited towards/away from or right/left across the cello body) the rattling duration will be maximised.

APPLICATIONS SPECIFIC TO PLUCKING

BARTÓK PIZZICATO/SNAP PIZZICATO

Pulling the string directly away from the cello body with such force that it rebounds against the fingerboard upon release produces a *Bartók pizzicato/ snap pizzicato*. The fingerboard acts as in the same way as the mute above, but rather than a rattling, usually only one, sharp hit is heard. If the stopping finger maintains contact with the string, the initial 'snap' attack-sound is followed by the decay; a 'normal'-sounding *pizzicato* tone.

The character of *snap pizzicato*, that is the loudness of the snap and the loudness and duration of the *pizzicato normale* decay, can be controlled in various ways:

Plucking force (or equivalently 'amount of displacement')

- For low plucking force no snap is present.
- A moderate plucking force limits the initial loudness of the snap and lengthens the decay.
- As plucking force increases, the 'snap' gets louder and the decay becomes relatively shorter.

Plucking direction

- Plucking directly *away from* the cello body gives the most consistent, loudest snap with a reduced decay.
- *Horizontal pizzicato* (plucking left-right across the cello body) or plucking 'towards' the cello body (by placing the hand underneath the strings between fingerboard and bridge and pulling the string downwards, or by pushing the string to the fingerboard and then releasing) produces no snap or a quiet snap and the decay is relatively long.
- Plucking in a diagonal plane produces a mixed result between these two extremes.

Point of contact

- Plucking close to the nut/stopping finger reduces the loudness/presence of the snap.[230] It is possible to use relatively high plucking forces in this position without producing a snap at all.[231]
- Moving the plucking point towards the bridge produces a progressively louder snap and reduces the decay duration. Eventually, fairly close to the bridge, this relationship reverses.
- Plucking very close to the bridge reduces the snap.

[230] Sometimes this is physically awkward. To reduce this, the cellist can prepare the string by placing the plucking finger under it before applying pressure with the stopping finger, or use a small plectrum.
[231] This is not obvious to cellists, who often move instinctively towards the bridge to reduce the snap against the fingerboard.

Bartók pizzicato is more difficult to produce on short string lengths, where the string is less easily manoeuvred. The differing weights of the four strings cause slight changes in sound quality from A to C string.

Explicatio C2

In the extreme case, the pressure between mute and string is so high that the kink of the displaced vibrating string is prevented from passing the mute and so is reflected back to the bridge/nut/stopping finger, the new pitch being defined by the string length from bridge-mute or mute-nut, the 'slide' effect.[232]

As pressure between mute and string is reduced, the kink of vibration is able to pass the mute, forcing the mute to bounce back from the string as it does so. Some vibration might still be reflected at the mute, causing vibration between mute and nut/bridge. The process of the mute being thrown from the string and falling back onto it repeats for every cycle of vibration until the excitation energy is expended. As vibration decays, the string moves towards its original rest position. Because of this decrease in displacement width, the string can usually no longer reach the mute towards the later stages of decay and is able to continue vibrating in the normal way.

The loudness and overtone content of the rattling and the open/stopped string pitch both increase with string displacement and as the density of the mute increases, since less energy and fewer high overtones are lost to damping. The decay duration of the open/stopped string sound is proportional to excitation force. However, an important effect can counteract this: the decay duration of the rattling sound and the vibrating string sound depend on the percentage of the excitation energy transferred to the mute and the speed of this energy transfer i.e. damping. The outcome lies between these extremes:

- If much energy is quickly transferred to the mute, the rattling tone is loud and short, accompanied and followed by a quieter, short open/stopped

[232] See 'A7 Slide effects'.

string pitch. In this case most of the excitation energy is spent very fast in damping effects at the mute.

- If a small amount of energy is transferred to the mute relatively slowly, the rattling tone is quiet and long, accompanied by a relatively loud open/stopped string pitch and perhaps followed by a short open/stopped string pitch. In this case the excitation energy is transferred slowly to the mute and little or no energy is left for the decay of the vibrating string.

In the second case, if the mute is removed from the string after a short time (i.e. a small amount of energy is transferred to the mute for a short time), the rattling tone is quiet and short, accompanied and followed by a relatively loud open/stopped string pitch. In this case a small amount of the excitation energy is transferred to the mute and the rest allows the vibrating string to ring well during and after the rattling.

Reorganising the information in ‘C2 Dense objects/mutes as ‘rattles’’ under these more general terms explains the effect of controlling this energy transfer. Energy transfer to the mute is controlled by:

THE DENSITY OF THE MUTE

The mute’s density is inversely proportional to damping. Therefore dense mutes minimise energy transfer from string to mute.

THE MUTE’S PROXIMITY TO THE STRING

The closer the mute is to the string’s rest position, the greater the force with which they impact upon excitation since the string travels at its fastest in the initial moments of excitation as it leaves its rest position. Distance between mute and string is therefore inversely proportional to energy loss.

THE AMOUNT OF STRING DISPLACEMENT

String displacement is proportional to the force with which the string hits the mute, i.e. it is proportional to speed of energy loss.

THE IMPACT POINT BETWEEN MUTE AND STRING

String displacement is maximal at the string's centre. Therefore the amount of energy lost is maximised for impact points in this area and minimised at points of narrow displacement close to the bridge/nut/stopping finger. Consequently, distance between the impact point and the middle of the string is inversely proportional to energy loss.

C3 Preparing the string with a fixed object/mute

An object can be attached to a string so that it moves with the string's vibration. The object strikes the fingerboard (and possibly the other strings) as the string vibrates and essentially acts as a mute as it dampens the string's vibration. The loudness of the fast, repeated tapping of the object against the fingerboard increases with the mute's weight and overtone content increases with the object's density. For example a peg, relatively heavy and moderately dense, produces a louder tapping sound with fewer overtones than a light and dense paperclip, which produces a louder and more overtone rich sound than a (light, soft) piece of polystyrene.

Tapping sounds are loudest if the object is attached to the middle of the string and become quieter as the object is attached nearer to the nut/stopping finger. If the object is beyond the fingerboard, i.e. close to the bridge, no tapping is heard but the object dampens the string's 'normal' vibration.

For heavy objects the sound might be distorted. This is especially the case if the mute is attached to the mid point of the string. Vibration becomes more stable as the point at which the mute is attached moves away from the middle of the string.

Explicatio C3

The loudness of the tapping sound is proportional to the weight and density of the object since larger, heavier objects hit the fingerboard with greater force. Increased density reduces damping and minimises the impact area between object and fingerboard, increasing overtone content. The opposite is true for reduced density.

Since the string is more mobile at its centre, objects attached at this point will move more during vibration. This increases the force with which the object strikes the fingerboard and consequently the loudness of the tapping. However this can make the sound unstable, since the extra mass of the mute changes the shape of the vibration of the string. As the point at which the mute is attached moves away from the middle of the string, vibration becomes more stable and the tapping becomes quieter.

C4 Preparing the strings such that their vibration is interdependent

Two or more strings can be connected in various ways (for example by threading a knitting needle, coin or paperclip through the strings, by taping the strings together or by cutting grooves in a semicircular slice of cork which is placed between two strings so that it rests there without touching the fingerboard). Plucking, striking or bowing one string causes the connected strings to vibrate. If the mute is relatively flexible and moves with the strings' vibration (cork, knitting needle), the sound of a plucked or struck string has a gong-like quality. Changes in pitch are heard if the mute is moved up and down the string.[233] A bowed string rings less well and a 'stuttering' effect is often heard; long strokes are particularly difficult to maintain. For less flexible, denser mutes that do not move with the string (e.g. a coin, paperclip), a rattling sound is heard as the string strikes the mute on vibration. The pitches from mute to bridge and the harmonics at the mute's position might be clearly audible.

[233] The pitch content of such tones is often hard to decipher, but this fact indicates that the pitches 'mute-bridge/nut' can usually be heard in the timbre.

Explicatio C4

For such preparation, as one string is plucked/struck/bowed, the connected string/s are excited at the same frequency. Since the pitches are not usually at the same frequency, and since the weight of the mute limits vibration, the resulting pitches are often unclear, there is a large amount of noise content and overtones are weak. The pitch of the resulting tones often contains many components; the pitches from bridge-edge of mute to bridge and nut-edge of mute to nut are usually present, perhaps in addition to the open/stopped string pitch and harmonics at the muting point can also be included in the sound. For the plucked or struck string, where the string vibrates from a single impulse, or for short bow strokes, the pitches of the resulting tones are clearer and vibrate more freely than under the continued excitation of bowed sound.

C5 Muting at the bridge/(body)

Applying a mute at the bridge weakens upper partial content and reduces amplitude. This effect increases with mute weight. Various mutes are available: rubber, plastic, leather, wood etc. Each has a particular sound quality. Similarly if the hand/another muting object is placed on the cello body vibration is dampened. The degree of this dampening increases with the mute's size and weight and with the pressure between mute and cello body.

Explicatio C5

Applying a mute to the bridge of the cello adds weight to the bridge and the cello body. This lowers their resonant frequencies, which changes the body's response, and inhibits energy transfer from string to body, reducing overall amplitude.[234] The lowering of the cello's body resonance frequency can be observed in the lowering of the pitch of the wolf note. Higher partials are particularly weak because of the damping effects of the mute. As heavier

[234] Bernard Richardson, 'Cello Acoustics' in Robin Stowell (ed.), *The Cambridge Companion to the Cello,* (Cambridge: Cambridge University Press, 1999), 37-51.

mutes are used, for example hotel mutes and practice mutes, these effects become more extreme.

Summaries Section C

Summary C1

Damping the string with a soft mute either dampens vibration completely or, for small mutes, especially if they are placed close to the bridge or nut/stopping finger, absorbs some of the string's vibration. In this case the overtone content, loudness and decay duration of the tone will be reduced.

Summary C2

A dense object applied to a vibrating string either acts as a slide, causing vibration between object and bridge or nut/stopping finger, or acts as a rattle. In the latter case the string vibration passes the object (although some vibration might also be reflected at the object). The object is thrown from the string on every cycle of vibration, resulting in a rattling sound. The loudness, overtone content and decay duration of both the rattling and the 'normal' vibration depend on several factors.

Summary C3

If an object is fixed to the string, it rattles against the fingerboard as the string vibrates. The loudness and overtone content depend on the density and weight of the object. For very heavy objects the sound can be unstable.

Summary C4

If the strings are prepared so that their vibration is interdependent, the excitation of one string initiates vibration in the other. This can sound distorted, particularly for the bowed string, but plucked and struck strings prepared in such a way can produce a gong-like effect.

Summary C5

Mutes applied at the bridge add weight to the cello body, inhibiting vibration and increasing damping. The sound is therefore quieter and less overtone-rich.

Section D Excitation of the body, bridge, tailpiece and bow hair

The effect of exciting the body and its components and of using these components to amplify other vibration is explained, as is the means of varying the overtone content, loudness and duration of this vibration.

D1 Striking or bowing/stroking the body and bridge

The cello body can respond to striking or stroking/bowing[235] with many different pitch-bands and timbres, significant variation is heard from cello to cello. In general, striking or stroking/bowing in the centre of the cello body produces lower tones. Higher tones are produced at the edges of the body surface and on the ribs, and higher still on the fingerboard and pegs. For a fixed excitation force/speed, the loudness of the tones is greatest at the centre of the cello body and reduces as excitation point moves towards the edges. Loudness is further reduced for excitation points on the fingerboard and pegs.

The bridge can be struck or stroked/bowed on its surface, top or sides. As above, some generalisations can be made about the pitch region of the resulting tones. The pitches produced at the base of the bridge's feet are low and become higher as the excitation point moves towards the top of the bridge. Bowing on the top of the bridge may generate some sound from the strings between the bridge and nut or bridge and tailpiece.

Regular bow speed and relatively high bow pressure can incite vibration of the whole bridge. This generates a 'wailing' sound, usually fairly loud. This is most reliably achieved by bowing on the bridge's shoulder (with the frog of the bow

[235] I use the word 'stroking' to broaden the idea of the group of bowing actions. The 'bow stroke' is a special case in this group, the slip-stick motion of which, in coupling with the body, enables a significantly louder sound than stroking with the fingers, the wood of the bow or another object. However, they are all bowing/stroking actions.

pointing towards the tailpiece and the tip pointing towards the nut, or vice versa). On my cello this pitch is a slightly flat G5.

The overtone content of body and bridge excitation increases as:

- The width of the hammer or bowing/stroking object reduces
- The density of the hammer or bowing/stroking object increases.

The overtone content of a struck tone changes according to the point on the hammer at which the body is struck. Higher overtones become stronger and lower overtones less prominent as this striking point moves from the hammer's base (where it is held) to its tip.[236]

Loudness increases as:

- The striking force or the bowing/stroking speed increases
- The density of the hammer or bowing/stroking object increases.

Stroking/bowing the cello body under high pressure might induce high-pitched squeaking sounds. The sustainability of these sounds improves with increased friction at the excitation point, for example by using a rubber ball or damp fingers. Similar squeaks occur if, as the bridge is bowed on its surface, a few bow hairs become stuck under the curve of the bridge's shoulder.

D2 Plucking, striking and stroking/bowing the tailpiece

PLUCKING

Plucking the tailpiece (pulling upwards/pushing downwards and releasing) results in a deep, 'thudding' tone. The sound is loudest and lowest if the tailpiece is plucked at one of its 'corners' close to the A- or C-string adjuster. It becomes quieter and higher as the plucking point moves towards the cello's end-pin. If the strings between bridge and tailpiece aren't dampened, they are

[236] This is true for stick-like hammers, e.g. the bow. The results are more complicated for different shaped hammers. In general the lowest pitches are heard for striking points close to the point at which the fingers grip the hammer. This is because of the damping effects of the hand.

set into motion by the pluck and clearly audible in the sound. The strings between bridge and nut might also be heard.

STRIKING

Several pitches can be produced by striking the tailpiece. These pitches are lower and louder in the thicker part of the tailpiece and become higher and quieter moving towards the thinner tailpiece base. Relative to this, higher pitches are produced at the right/left-hand edges of the tailpiece and lower pitches at the middle. Loudness increases and decreases with striking force. Increases in hammer density increase loudness and overtone content. If un-dampened, the strings between bridge and tailpiece, and possibly those between bridge and nut will also be heard.

BOWING/STROKING

When bowed, the tailpiece can produce two clear pitches: one at its wide upper region and the other at its thinner base. The pitch of these tones varies for different tailpieces, however the former is always lower than the latter. On my cello's tailpiece these pitches are a slightly sharp C2 and a flat A3. These pitches require particular playing conditions: a fairly low bow speed and high bow pressure (less speed and more pressure for the lower pitch). Their timbre is quite weak in overtone content, and both timbre and volume are relatively fixed because of the specificity of the playing conditions and the restricted bow movement (the bowing angle cannot deviate much from a position parallel to the cello body without the bow coming into contact with the body, which, since the tailpiece curves downwards from the middle, renders is outer edges unreachable by the bow). At low bow pressures, quiet harmonics are produced. The pitch of these harmonics shifts with changing bow pressure and point of contact.

Stroking the tailpiece with the fingers generates a much quieter, 'rubbing' sound, the loudness of which increases and decreases with the speed of the stroking action. As pressure increases, slight increases in overtone content are heard. For high pressures, high-pitched squeaking sounds are generated.

Explicatio D1 and D2

There are three factors that affect the loudness and overtone content of bridge/body/tailpiece responses. Firstly: the component of the body where excitation takes place (e.g. back, fingerboard, tailpiece…). The loudness and overtone content of the response is maximised when the component is well coupled with the body. Therefore, excitation of the main part of the body, the bridge and tailpiece are potentially louder with a richer overtone content than excitation of the fingerboard, pegs, scroll etc. Secondly: the exact point of contact on the particular component (e.g. the edge of the back, the centre of the fingerboard, the upper left hand corner of the tailpiece…). The modal responses of the components of the cello body are more complicated than those of, for example a square or round membrane and the slight variation from instrument to instrument can have a significant impact on sound. However, in general it is possible to say that excitation at the middle of a component of the cello body produces low-pitched responses since, in general, lower partials have antinodes at the centre. Higher partials, which generally have nodes at the centre, are restricted. The edges of a component of the cello body are generally close to points of antinodes of higher partials and nodes of low modes, therefore when the component is struck/bowed in this area higher pitches are heard.[237] For striking points between the middle and the edge of a component, it is possible that both low and high modes are fairly strong. For a fixed excitation point, the loudness of the body component's responses increases as the contact point moves towards the centre, where the antinodes of lower partials predominate because, for a fixed excitation force, the amplitude of each partial is inversely proportional to partial order.[238] Thirdly: loudness of the component response is directly proportional to excitation force, the amount of energy put into the system; that is the force of the pluck/strike and the speed of the bowing/stroking motion.

The resonant frequencies of the cello body and its components, or the modes of the resonant frequencies can often be discerned in the sound. These values

[237] Benade, *The Fundamentals of Musical Acoustics,* 124-35.

[238] Colin Gough, 'Musical Acoustics', in Thomas D. Rossing (ed.), *Springer Handbook of Acoustics* (New York: Springer, 2007), 585-6.

vary slightly from instrument to instrument. The modes of the resonant frequencies are usually not in harmonic proportion to their fundamental. The lowest resonant mode of the cello bridge is around 985Hz.[239] This pitch, very slightly flatter than B5, is clearly audible if the bridge surface is bowed or struck, especially on the upper part of the bridge surface. Similarly, the main wood resonance of the cello body, 175Hz,[240] ~F3 can be clearly heard when the cello is struck, especially near the centre and can be faintly perceived when a bow strokes across the cello body.[241]

APPLICATIONS SPECIFIC TO STRIKING

Overtone content is inversely proportional to contact time between hammer and body component. The reason for this is that partials with period less than contact time are excluded from the timbre. This is clear because partials with a particular period require opposing values for amplitude within this time band. If contact between hammer and component exceeds this, i.e. the hammer is applying a force in one direction for longer than the period of a particular partial, that partial is necessarily unable to vibrate. The highest mode that can be included in the vibration of the body component has a period higher than the contact time between exciter and component. Therefore, as contact time increases, the number of overtones present in the sound reduces. Contact time is minimised by withdrawing the hammer as soon as possible, by striking in the middle of a long straight hammer (or at the 'balancing point' of the bow) and by small dense hammers, which are thrown quickly from the excitation area after impact. Similarly, holding the hammer down upon impact, striking with a long straight hammer close to where is held or using large soft hammers maximises contact time between hammer and body component.[242]

Similarly, contact area between hammer and component is inversely proportional to overtone content. This is because, upon the hammer's impact, the whole contact area between hammer and component is forced to vibrate at

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239 Colin Gough, 'Musical Acoustics', 570.
240 Benade, *Fundamentals of Musical Acoustics,* 536-7.
241 The wood resonance of the cello body causes the wolf note; therefore the pitch of the wolf note is always equal to this value.
242 This is comparable with the influence of impact duration of a struck string, see 'Explicatio A4'

a fixed amplitude. If two antinodes for a particular partial occur within this region, the related partial will not sound, since it requires that these points vibrate at opposing values. The shortest distance between two antinodes, i.e. the wavelength, decreases as partial order increases; therefore as contact area decreases, more pitches are able to contribute to the sound. Contact area is dependent on hammer size and hammer density. It is proportional to the former and inversely proportional to the latter since dense hammers keep their shape upon impact and soft hammers spread out. Therefore, small dense hammers maximise overtone content and as hammers become bigger/softer, successively more overtones are blocked from the sound. Moreover, contributing further to the above effect is contact time's proportionality to hammer size and inverse proportionality to hammer density (since small, dense hammers bounce quickly from the body and vice versa).[243]

APPLICATIONS SPECIFIC TO BOWING/STROKING

Bowing/stroking the body/bridge/tailpiece of the cello either:

- Amplifies the sound of the bow hair/other object moving across the surface of the instrument, possibly exciting a response from various harmonics of the body component
- Incites vibration of a component of the cello body (i.e. bridge/tailpiece)
- Incites vibration of the bowing/stroking implement as it rubs against a surface

In the first case, the bowing/stroking motion is transmitted to the cello body by coupling with the bridge or tailpiece, or directly, if the point of contact is on the main part of the cello body. Vibration in the cello body amplifies the sound of the bowing/stroking object's contact with a surface and/or the sound of the bow hairs' contact with each other. Some of the cello body modes respond to this excitation. However, since the original sound is quiet and since the sustained action of bowing/stroking at once excites and dampens the body/bridge/tailpiece, the resulting sound is quiet and contains few pitches. Amplitude is proportional to the speed of the stroke because an increase in speed increases the movement of the stroked component. Overtone content is

[243] This is comparable with the influence of contact area of a struck string, see 'Explicatio A4'

proportional to the density of the object. This is due to damping effects, which increase as the object becomes softer.

Inciting vibration in a component of the cello body requires very particular conditions for bow speed and pressure (in general, relatively low bow speeds and high pressure). The bridge and the tailpiece are relatively easily excited in such a way. The components vibrate at their main body resonances or at an overtone of this frequency,[244] in which case much less pressure is required. In both cases a very steady bow speed is required for a consistent sound. Since the conditions for producing these tones are so inflexible (bow speed, pressure and point of contact are within a narrow band), variation in loudness and overtone content is very limited.

In the third case, where bowing/stroking incites vibration of the bowing/stroking implement as it rubs against a surface, excitation conditions are also very particular. Such sounds are produced under very high bowing/stroking pressures. The objects vibrate at their own frequencies. Several pitches are producible, all high frequency, with pitch being proportional to bow speed. The tones are very sensitive to changes in bow speed; very steady bow speeds are required to maintain sound. The sound is more easily produced if the frictional forces are increased, i.e. if the bowing/stroking object is slightly 'sticky', for example a rubber ball or a damp finger.

D3 Using body/bridge as amplifier

The body and the bridge can be used to amplify sounds other than string vibration. If the bow hairs are pressed to the body of the cello and the bow is rotated slightly on the surface of the body, the bow hairs rub against one another. This is particularly effective on the cello back because the large surface allows good contact and freedom of movement. The hairs make a snapping sound which, amplified by the cello body, can be quite loud. The loudness increases with pressure against the cello body. If the motion is sped

[244] The pitches of the overtones of the fundamental of such components may be inharmonic, unlike the case of the string.

up, a ‘crackling’ or ‘splintering’ effect is heard. Timbre and loudness change according to point of contact on the cello body, the sound being louder and more overtone-rich in the centre of the body and quieter and more overtone-weak at its edges.

If the bow is pressed to a component of the cello body and the bow hairs/stick are stroked/rubbed, the stroking/rubbing sound is amplified by the component. The loudness and the timbre of the resulting sound are relative to the loudness of the action, for example, stroking the bow stick is quieter and less overtone rich than stroking the bow hairs. Loudness and overtone content increase with the density of the stroking object (e.g. the fingernail produces a louder, more overtone-rich sound than the finger tips) with increased pressure at the component and with the speed of the stroke.

Explicatio D3

In the above case, the cello body, rather than being excited directly, is being used as a cavity through which sound is amplified. The amount of energy that is absorbed and transmitted by the body depends on the object’s contact with and point of placement on the body. The greater the force of contact between object and body, the louder and more overtone rich the amplified sound will be since less energy is lost to the surroundings through damping. For the same reasons as those stipulated in ‘Explicatio D1’ and ‘Explicatio D2’, if the object is placed at the centre of the cello body, loudness is maximised and low frequency responses predominate. Contact points close to the edges of the cello body produce quieter responses with high frequency components. Loudness and overtone content are maximised at contact points of strong coupling with the body (especially the bridge) or the body itself, where unwanted damping losses to the surroundings are minimised. Conversely, loudness and overtone content are minimised at contact points that are not well coupled with the body, e.g. the fingerboard/pegs.

Summaries Section D

Summary D1 and D2

The loudness of tones produced by striking or bowing/stroking the cello body is relative to the excitation force, width and density of the exciter, and the amount of coupling between the struck/stroked component and the body; tones are loudest on the body itself, then the bridge, the fingerboard, the pegs etc. Low tones are produced in the middle of such components and high tones around the edges. Sometimes the resonant frequencies of the components can be clearly heard, especially if the bridge is bowed.

When plucked, struck or stroked, the tailpiece also vibrates at its resonant frequency or its harmonics. Lower tones are found at the thicker end of the tailpiece and higher tones at the thinner end. Overtones are particularly strong when exciting the edge of the tailpiece.

Contact time between exciter and component is an important factor in struck tones.

The nature of bowed/stroked tones varies according to whether the body component is amplifying the stroking motion or if the stroke is forcing the component to vibrate at its resonant frequency.

Summary D3

It is possible to use the body or bridge to amplify other sounds. The loudness and overtone content depend on the action before amplification and the contact between the vibrating object and the body.

Epilogue

The resource in this thesis forms the basis for a new kind of handbook. It provides a structure upon which further research can be based. The resource can be expanded primarily in two ways.

The first of these is through deeper acoustical research. The acoustical research in this thesis is on several levels. Often the information in the resource was well supported by the existing acoustics literature or the literature could be easily adapted to offer an explanation. However, vast areas in respect to modern instrumental technique remain under-researched. Where available information was insufficient to back up proposals, I conducted empirical research, found in the Appendix. This empirical research comprises initial experiments that point towards certain conclusions. These experiments could be expanded with different cellos and players, and with a physical model of the instrument. In addition, empirical research could be undertaken in many other areas. A specific area of research that would benefit from immediate attention, and an area which I think will become important to string technique, is multiphonics. A full acoustical explanation of the technique would be a solid framework for experimentation. A strategic exploration of the relationship between sound outcome and finger position, finger pressure, point of contact and excitation force would give acousticians the information and interest required to develop such an explanation. Acoustical research could also help musicians to be more exact in describing certain aspects of technique, for example, if we were able to be fairly precise about the average deviation of cello string harmonics from the harmonic series, we could consider the deviation when harmonics are detuned further under scordatura tunings. It is possible that, for particular scordatura tunings, certain harmonics might deviate much more, or might even ‘correct’ themselves relative to certain intonation systems. This would have interesting implications for performers and composers.

The second area for exploration is the development of new sounds and finding a place for these new sounds within a continuum of cello technique. The challenge for developing technique is finding something idiomatic, even specific to the cello, even though the sound itself might be far removed from cello sound as we know it. Xenakis said of his famously virtuosic piece, *Nomos Alpha:* ‘it lasts thirteen minutes and can only be played on the cello. But not one second of those thirteen minutes is supposed to sound like a cello.’[245] This idea is central in the development of new techniques that are logical and consistent with cello sound and not just arbitrary effects (a charge that has been made against newly devised techniques, perhaps not always unfairly). This is the method of thinking that I hope my research will promote: an essentially scientific basis that guides logical and idiomatic experimentation. This thinking is not a threat to the instinctive process of a performer responding to a score, nor to traditional performance methods. Instead it informs and gives freedom in these processes.

[245] Siegfried Palm in Michael Schmidt, ‘Capriccio für Siegfried Palm’
From the (publisher approved) English translation of extracts from this book, available at: <http://www.gema.de/engl/press/news/n171/palm.shtml> (accessed 1st October, 2009).

Appendix

Experiment 1: the influence of plucking direction

AIM

To investigate the influence that plucking direction has upon loudness and duration of a tone

METHOD

Three cellists plucked the string ‘normally’, ‘vertically’ (away from the cello body) and ‘horizontally’ (side-to-side across the cello body). The *pizzicati* were performed at three dynamics: *forte, mezzo forte* and *piano.*

Each cellist plucked each string in first position, one tone above the open string (the open string was deliberately avoided due to its very long decay duration). In addition, one cellist also plucked the string one octave above the open string.

The cellists decided individually:

- The angle of the normal *pizzicato*
- The dynamic measures *forte, mezzo forte* and *piano*
- The plucking position (distance between plucking point and bridge)

I asked that each quantity remained as constant as possible. The cellists maintained contact between stopping finger and string until the sound had decayed.

If a vertical *pizzicato* at a particular (high) dynamic tended to become a *Bartók pizzicato,* the cellist plucked at an alternative point over the fingerboard, with the length of string between stopping finger and plucking point being equal to that previously between stopping finger and bridge. The cellists always dampened the strings that they were not plucking to avoid resonance from the other strings influencing the results. Each cellist plucked a different string first. This was to spread the effect of a ‘warm up’ period, in anticipation that the *pizzicati* would become more consistent as the recording session went on. Each *pizzicato* was performed 5 times and an average value taken.

The experiment was performed in a dry acoustic at the Elektronisches Studio Basel. Care was taken to keep the recording conditions constant (type and placement of microphone, position in room).

HYPOTHESIS

- Horizontal *pizzicato* has a louder attack and a faster decay than normal *pizzicato*
- Normal *pizzicato* has a louder attack and a faster decay than vertical *pizzicato*

RESULTS

The majority of the vertical *pizzicati* began at a lower amplitude than the normal and horizontal *pizzicati.* The pattern of decay depended on loudness:

Forte* and *mezzo forte pizzicati

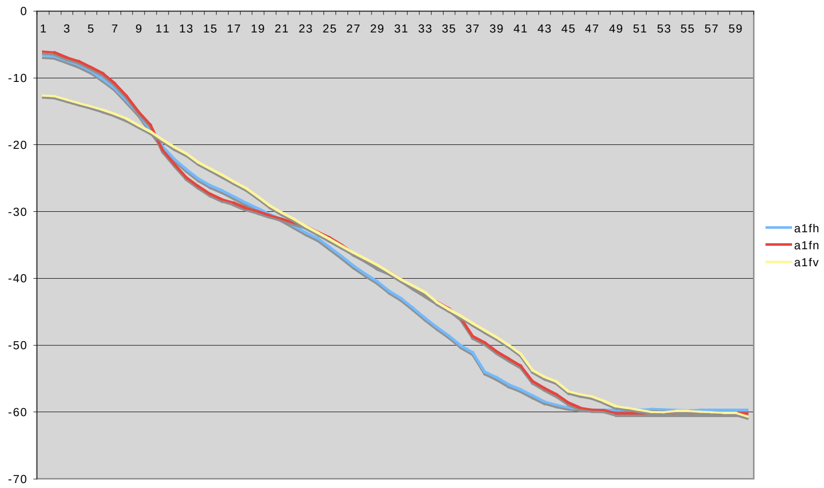
The amplitude of the normal and horizontal *pizzicati* decayed faster than that of vertical *pizzicato,* which usually overtook them in the first few seconds of decay. If the amplitude of vertical *pizzicato* did not overtake that of horizontal and/or normal *pizzicato,* the difference in amplitude between the three *pizzicati* types almost always narrowed. Horizontal and normal *pizzicati* began at about the same amplitude and seemed to decay at similar rates.

Piano pizzicati

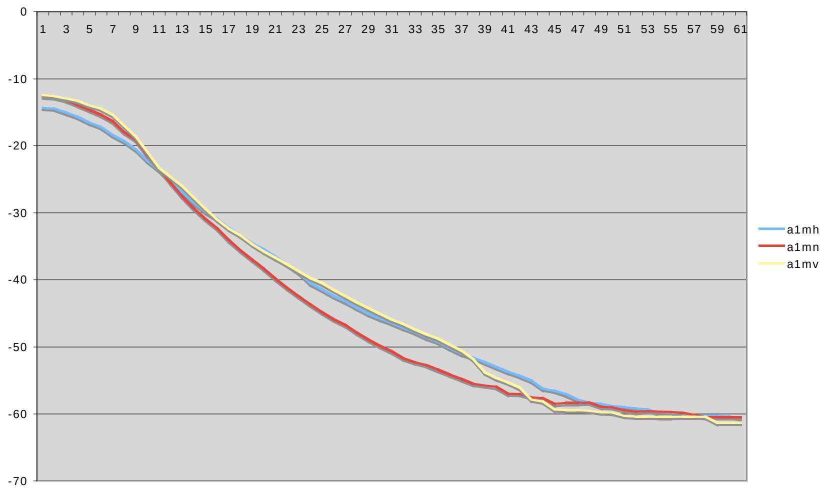
The decay of all types of *pizzicati* was similar without vertical, normal or horizontal *pizzicati* being particularly prominent at any stage of the decay process.

Below are some graphical representations of the results taken from each of the three cellists.

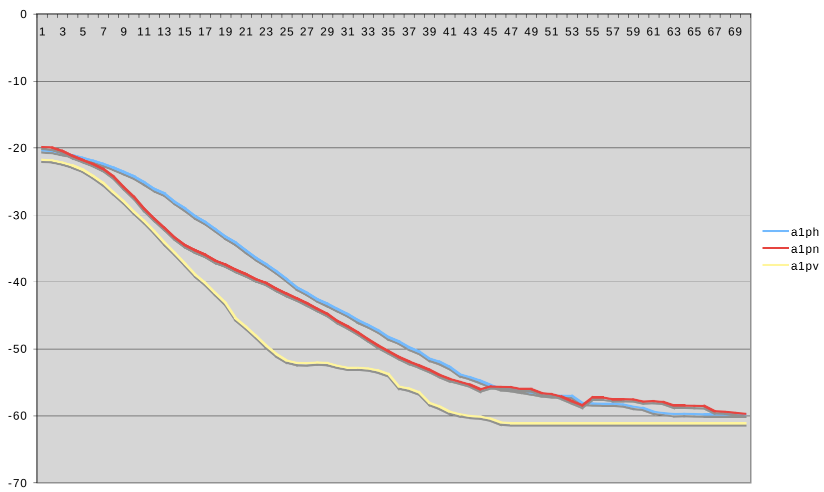
The x-axis shows amplitude in decibels and the y-axis shows time in 10 millisecond units. The blue line shows horizontal *pizzicato,* the red normal and the yellow vertical.



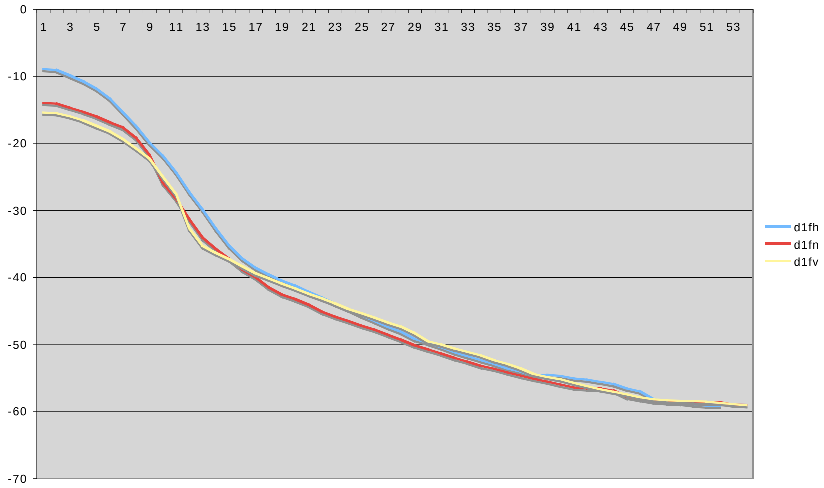
Cellist 3, B3, stopped first position on the A string, *forte*



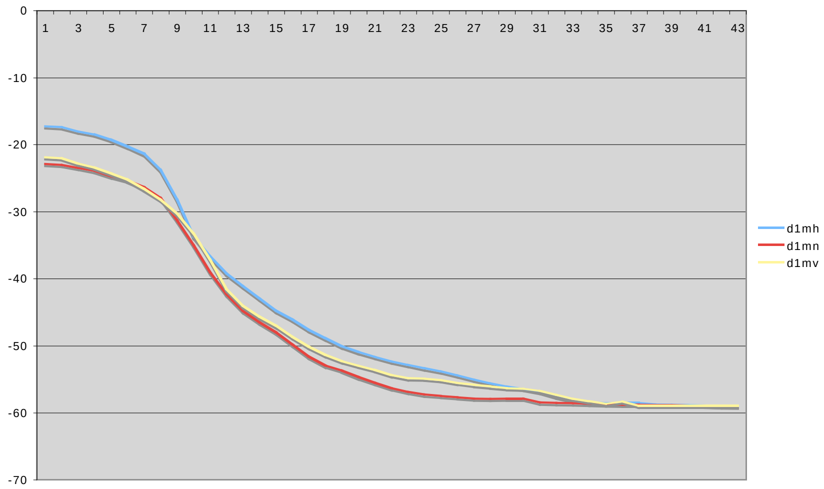
Cellist 3, B3, stopped first position on the A string, *mezzoforte*



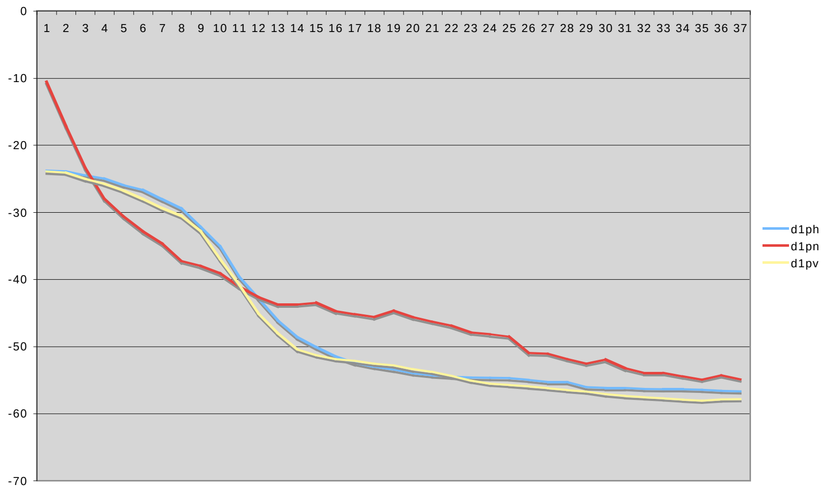
Cellist 3, B3, stopped first position on the A string, *piano*



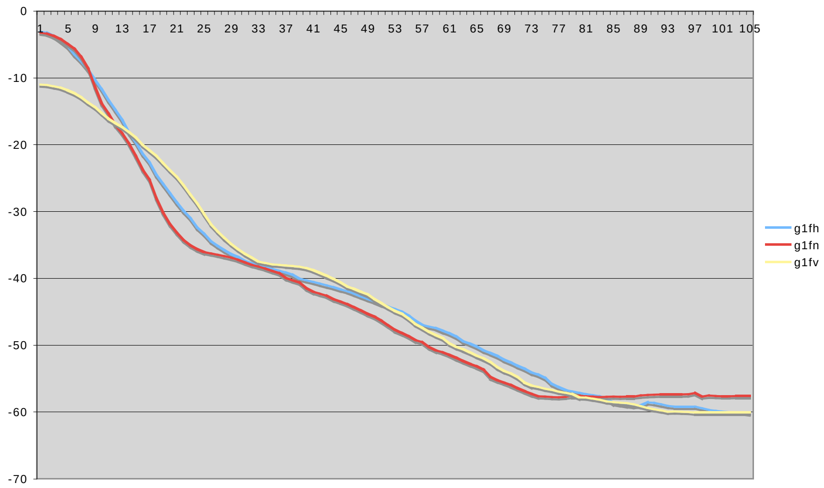
Cellist 2, E3, stopped first position on the D string, *forte*



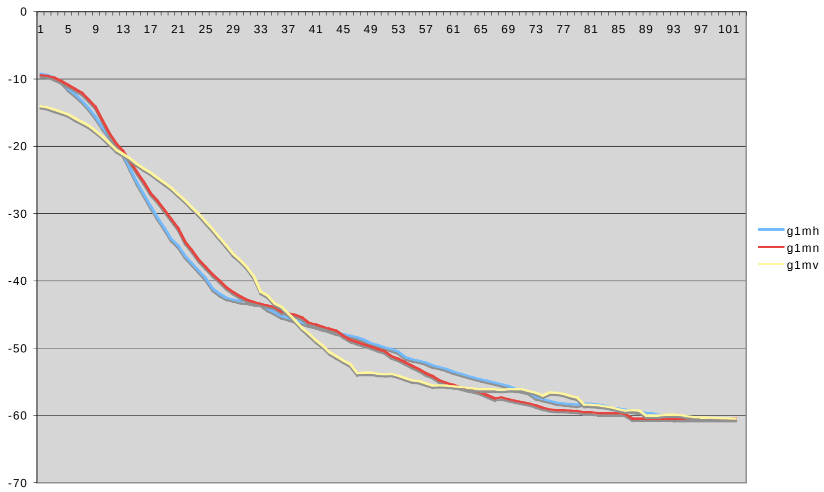
Cellist 2, E3, stopped first position on the D string, *mezzo forte*



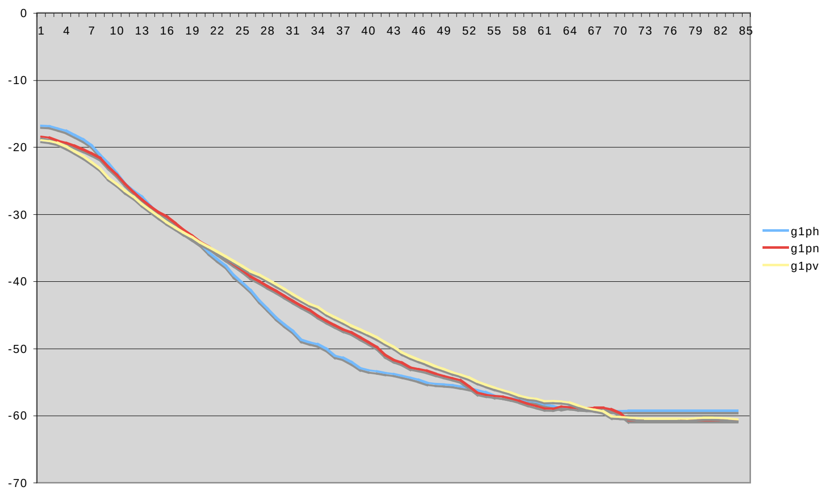
Cellist 2, E3, stopped first position on the D string, *piano*



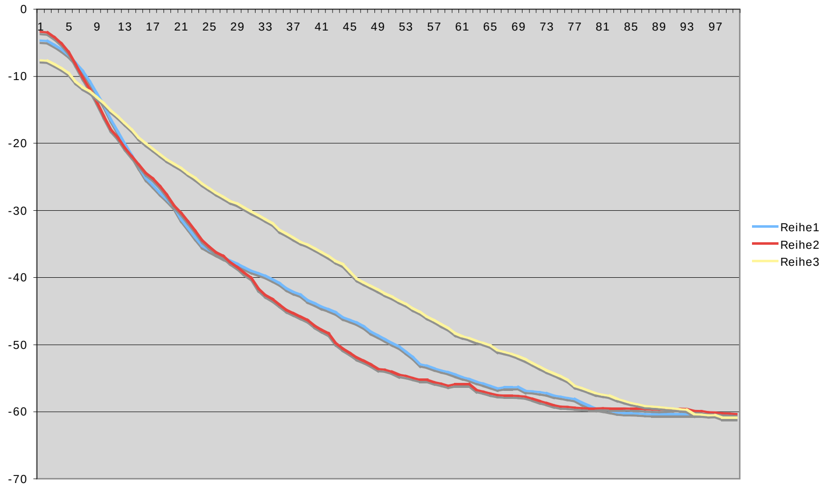
Cellist 1, A2, stopped first position on the G string, *forte*



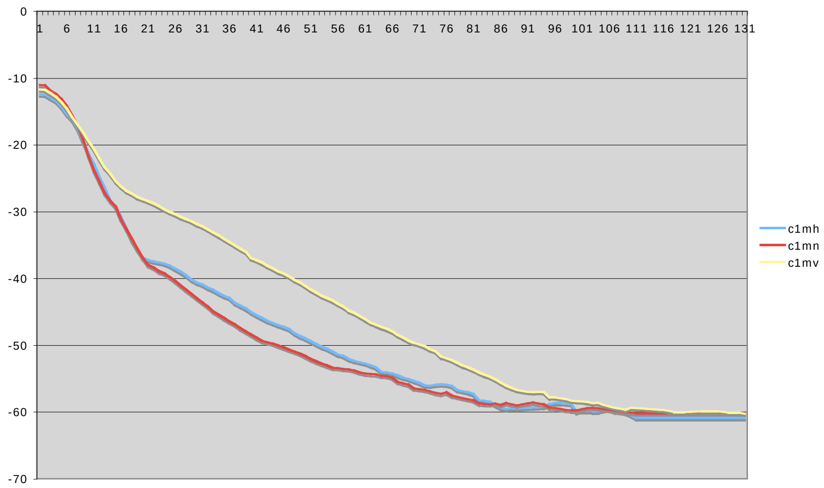
Cellist 1, A2, stopped first position on the G string, *mezzo forte*



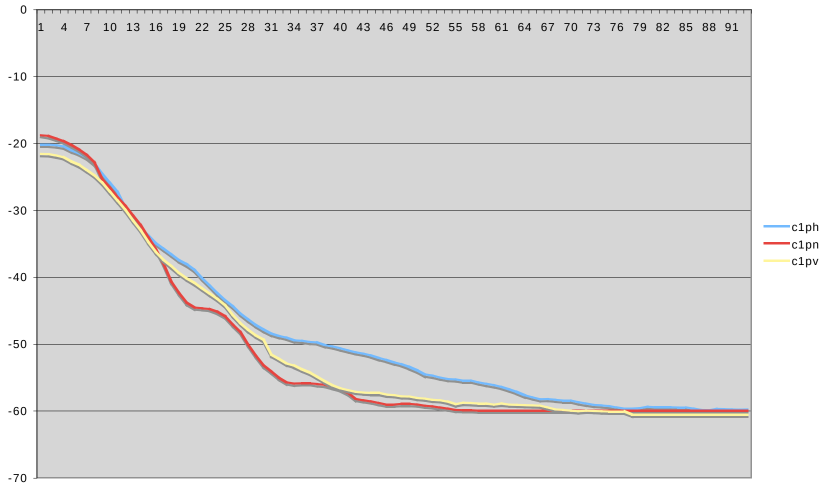
Cellist 1, A2, stopped first position on the G string, *piano*



Cellist 1, D2, stopped first position on the C string, *forte*



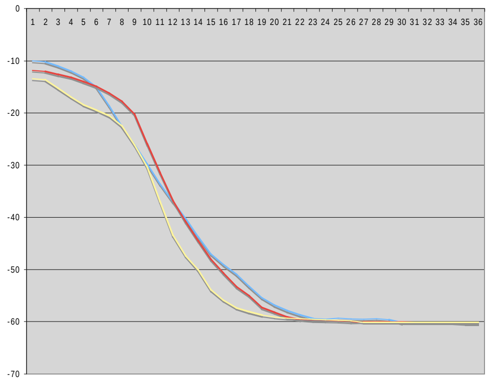
Cellist 1, D2, stopped first position on the C string, *mezzo forte*



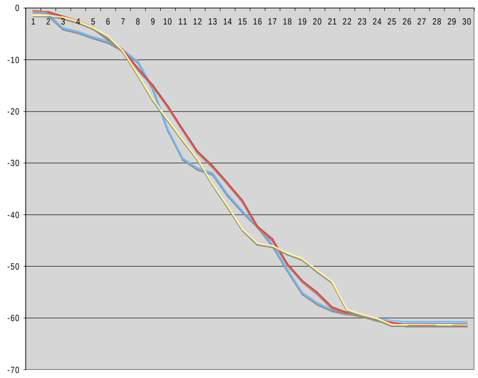
Cellist 1, D2, stopped first position on the C string, *piano*

Higher Positions

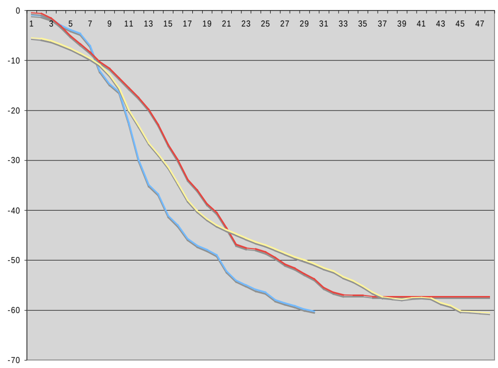
For a string stopped at half of its length, the plucking direction was less significant, even in the case of higher dynamics. Of course, decay time was, in general, reduced. This can be seen in the following graphs, which represent the *forte pizzicati* for tones stopped one octave above the open string. As before, the blue line represents horizontal *pizzicato,* red normal and yellow vertical. The lower dynamics showed even less significant results.



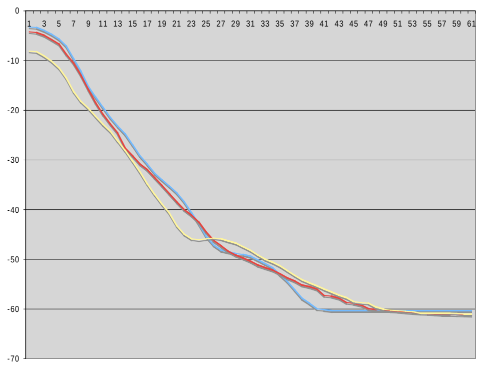
A4 stopped on the A string, *forte*



D3 stopped on the D string, *forte*



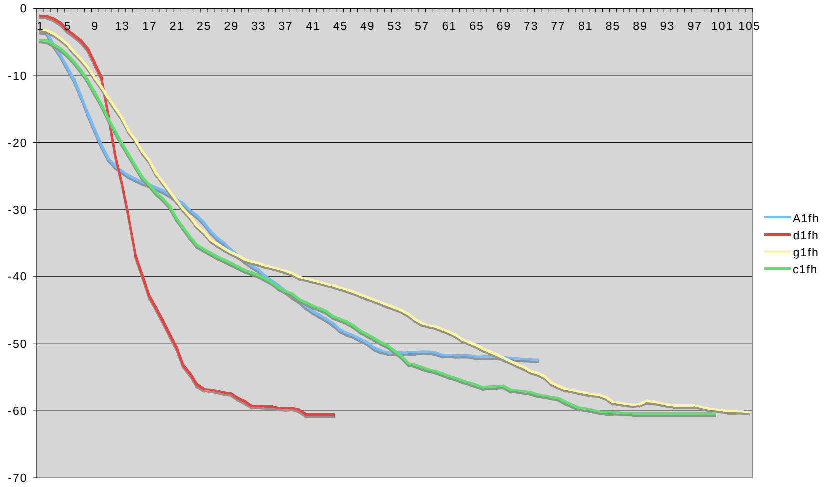
G3 stopped on the G string, *forte*



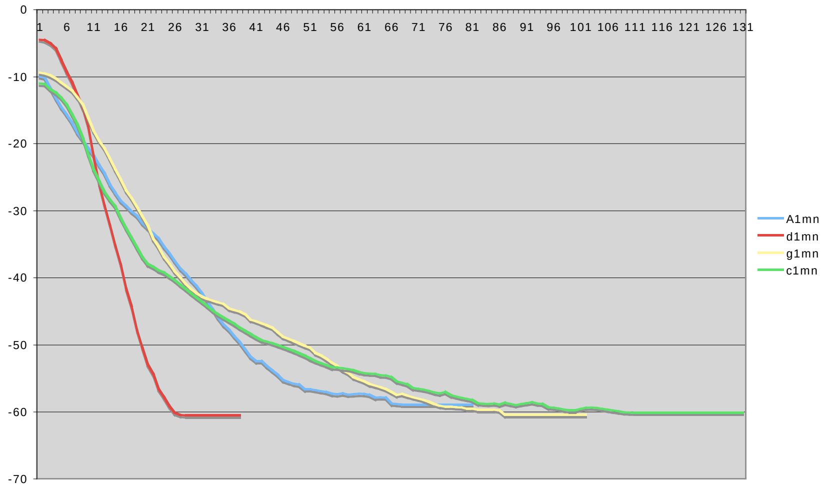
C2 stopped on the C string, *forte*

General comments

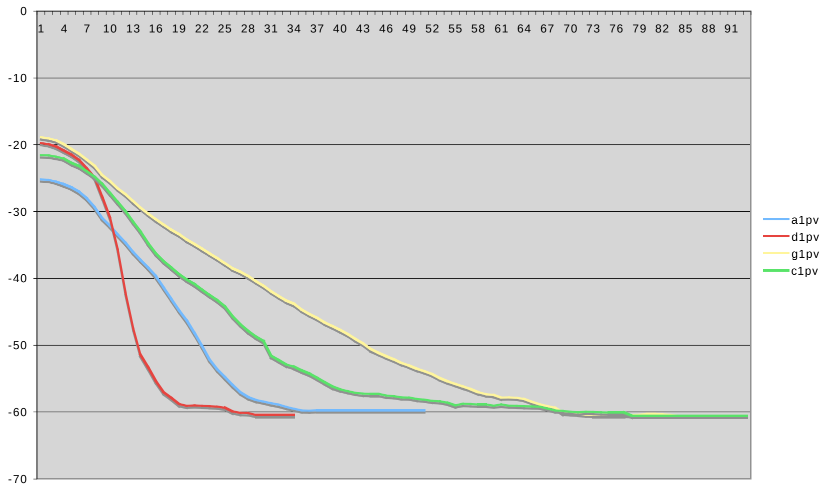
The G and C strings of both cellos decayed significantly more slowly than A and D. The D string decayed especially fast. This is shown in the graphs below. This is probably the case only for this particular position on the D string. It is possible that the frequency matched a characteristic mode of the room or the instrument body. One possible explanation is the presence of the main body resonance, which is usually around a 175Hz (around F3). In this case the string was plucked at E3, but it is possible that the frequency is close enough to absorb a considerable amount of the vibration.



Horizontal *pizzicati* at a *forte* dynamic. B3 stopped on the A string (blue), E3 stopped on the D string (red), A2 stopped on the G string (yellow), D2 stopped on the C string (green).



Normal *pizzicati* at a *mezzo forte* dynamic. B3 stopped on the A string (blue), E3 stopped on the D string (red), A2 stopped on the G string (yellow), D2 stopped on the C string (green).



Vertical *pizzicati* at a *piano* dynamic. B3 stopped on the A string (blue), E3 stopped on the D string (red), A2 stopped on the G string (yellow), D2 stopped on the C string (green).

CONCLUSION

The results point towards the theory that horizontal and normal *pizzicati* are generally initially louder and decay more quickly than vertical *pizzicato.* This is only significant in a medium to high dynamic range. There is not a significant difference between the decay times of horizontal and normal *pizzicati*. Many more live recordings of cellists and a similar experiment on a model of a cello string would give more reliable, conclusive results.

Experiment 2: frequency variation of harmonics

AIM

To investigate the difference in the frequency of harmonics relative to harmonic intonation of an ideal string. To observe differences in frequency between alternative touch points for particular harmonics.

METHOD

A cellist played harmonics 1 to 11 on the A string and 1 to 8 on the D, G and C strings. The harmonics were played at every nodal point, starting from that closest to the nut. If a node was a touch point for a lower harmonic, that node was touched in combination with the adjacent node in the nut direction, i.e. 'double touched'. For example, the 2nd node of the 6th harmonic produces the 3rd harmonic when touched alone, therefore it was touched in combination with the 1st node of the 6th harmonic. Similarly, the 3rd node of the 6th harmonic produces the 2nd harmonic when touched alone, therefore it was touched in combination with the 2nd node of the 6th harmonic. Four bow strokes were performed for each touch point. The cellist tried to keep bow speed, bow pressure, relative point of contact and finger pressure as constant as possible.

Each recorded result was analysed by a computer programme, which recorded the pitch of the open string and then measured the intonation of every subsequent harmonic relative to the open string pitch. The programme gave the difference in cents between the recorded harmonic and harmonic intonation relative to the open string.

The experiment was performed in a dry acoustic at the Elektronisches Studio Basel. Care was taken to keep the recording conditions constant (type and placement of microphone, position in room).

HYPOTHESIS

- As they ascend, harmonics become increasingly sharp relative to harmonic intonation
- Double touched harmonics are sharper than harmonics touched at a single touch point
- Some variation is perceivable between alternative touch points and across the four strings

RESULTS

The deviation from harmonic intonation seemed to increase for ascending harmonics. This deviation tended to be sharp. This is especially apparent from the results recorded on the A string (see below), where 24 of the 27 touch points from harmonic 9 to 11 were sharper than harmonic intonation.

In general, double touched harmonics deviated more from harmonic intonation than harmonics touched at a single touch point. This deviation was usually sharp. This can be well perceived in the charts below for the 10th harmonic of the A string, 4th of the G string and 6th of the C string. However, some deviations were considerably flatter than harmonic intonation, as is the case for the 6th and 8th harmonics of the A string below.

The following charts show the deviation in cents from harmonic intonation. One value is shown for each touch point, for example, one open string value (always zero), one value for the 2nd harmonic, two values for the 3rd harmonic etc. The values for each touch point are presented in an ascending order from the nut to the bridge. For example, if touch points are expressed in the form h.x where the number x is the touch point for a harmonic h, x=1 is the touch point closest to the nut and x=h-1 is the touch point closest to the bridge, the touch points are presented in the following order (double touch points are shown with the x value in brackets):

1st harmonic 1

2nd harmonic 2.1

3rd harmonic 3.1, 3.2

4th harmonic 4.1, 4.(2), 4.3

5th harmonic 5.1, 5.2, 5.3, 5.4

6th harmonic 6.1, 6.(2), 6.(3), 6.(4), 6.5

7th harmonic 7.1, 7.2, 7.3, 7.4, 7.5, 7.6

8th harmonic 8.1, 8.(2), 8.3, 8.(4), 8.5, 8.(6), 8.7

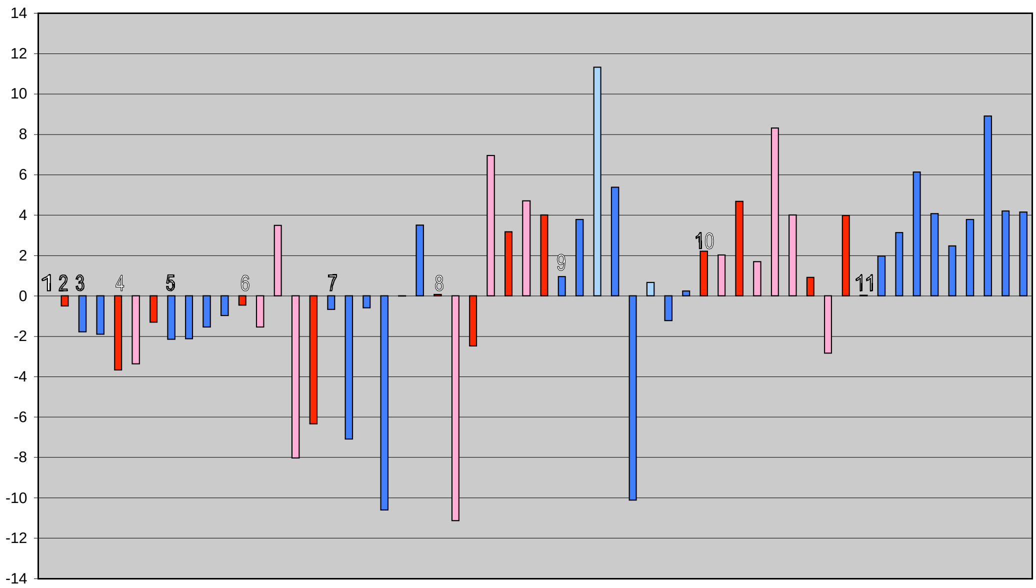
9th harmonic 9.1, 9.2, 9.(3), 9.4, 9.5, 9.(6), 9.7, 9.8

10th harmonic 10.1, 10.(2), 10.3, 10.(4), 10.(5), 10.(6), 10.7, 10.(8), 10.9

11th harmonic 11.1, 11.2, 11.3, 11.4, 11.5, 11.6, 11.7, 11.8, 11.9, 11.10

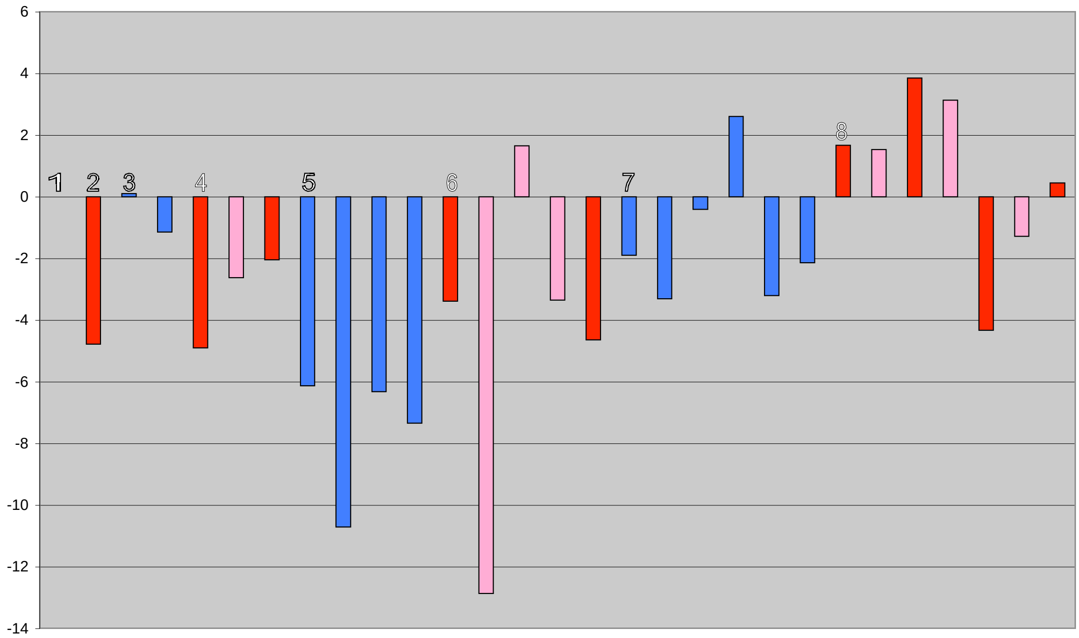
For clarity, the values for the odd harmonics are shown in blue and the even harmonics red. Light blue and pink signify double touch points. The y-axis shows deviation in cents. The threshold by which humans are able to differentiate between two tones is 2 cents. Pitch differences up to 5 cents are very difficult to discern. Therefore, deviations within the bracket 'harmonic intonation +/- 2 cents' are not perceivable.

The results show a difference in intonation between the four strings but no discernable tendency. There is no obvious pattern for intonation deviation at particular touch points. However, the intonation of the touch points in the middle of the string often deviates more than that of touch points close to the bridge or nut. Furthermore, the intonation at touch point h.1 (closest to the nut) is quite often the closest to harmonic intonation.



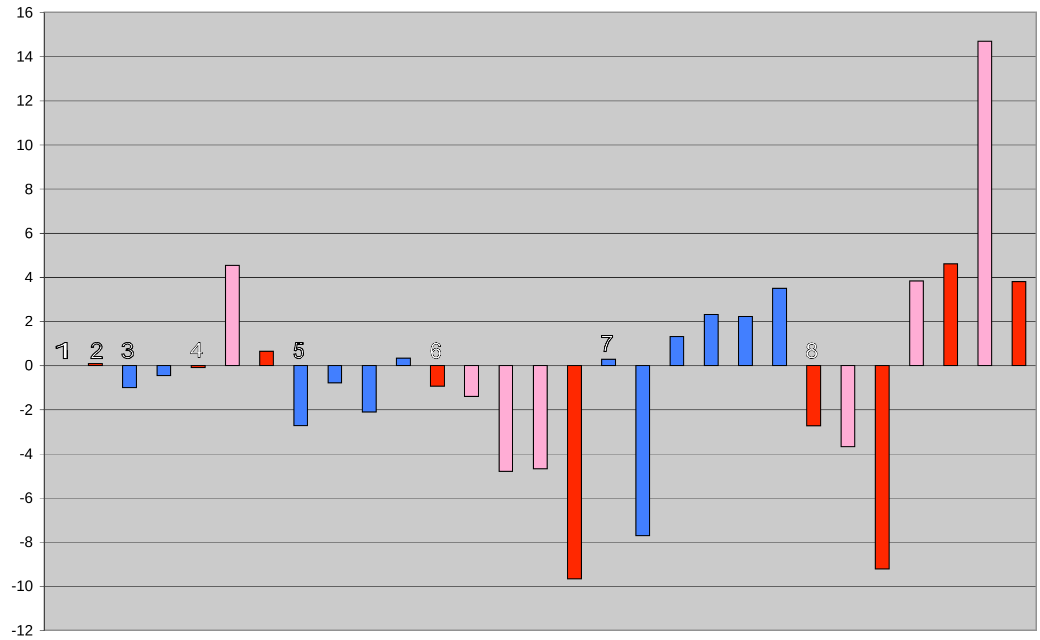
A string

A tendency of increasing sharpness for ascending harmonics can be seen. Double touch points usually deviated more than singe, and were usually sharp. Harmonics began to be notably slightly ‘out of tune’ from the 6th harmonic upwards.



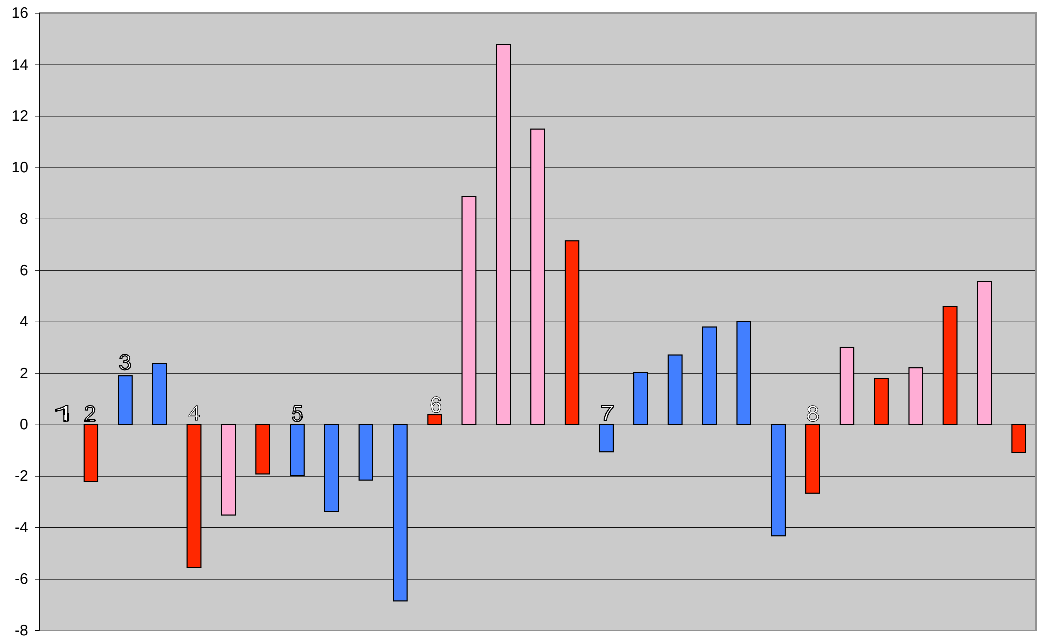
D string

The 7th and 8th harmonics were closer to harmonic intonation than in the case of the A string above. The 2nd and 5th harmonics were particularly flat. This might be an anomaly. Except for 6.(2), the intonation at double touch points was not notably different from single.



G string

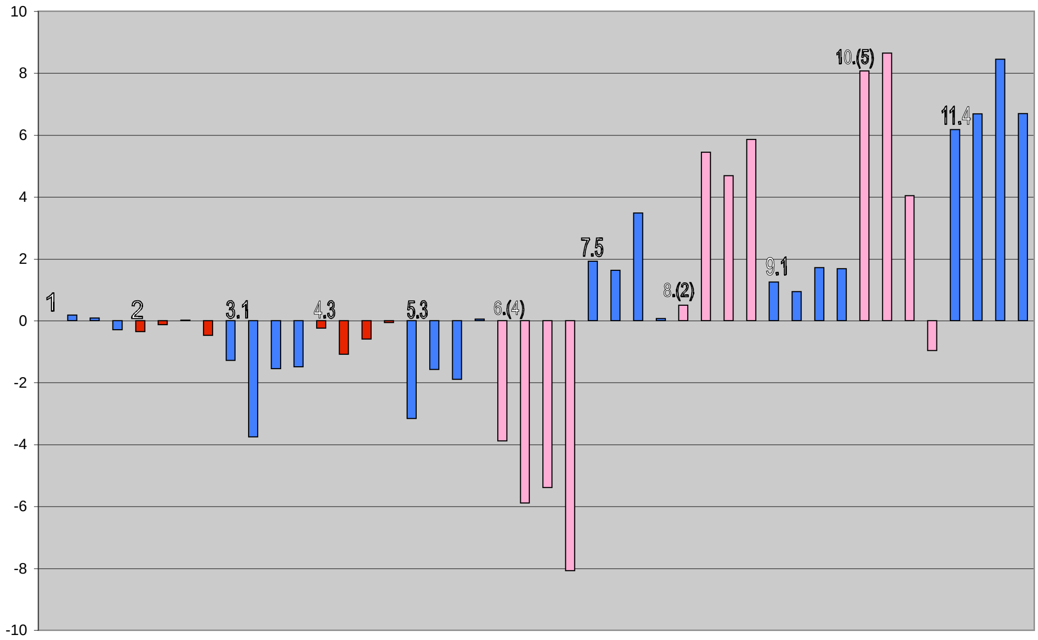
Most harmonics were fairly ‘in tune’ but deviations became wider for ascending harmonics. A sharpening effect for double touch points is strongly apparent for the 4th and 8th harmonics.



C string

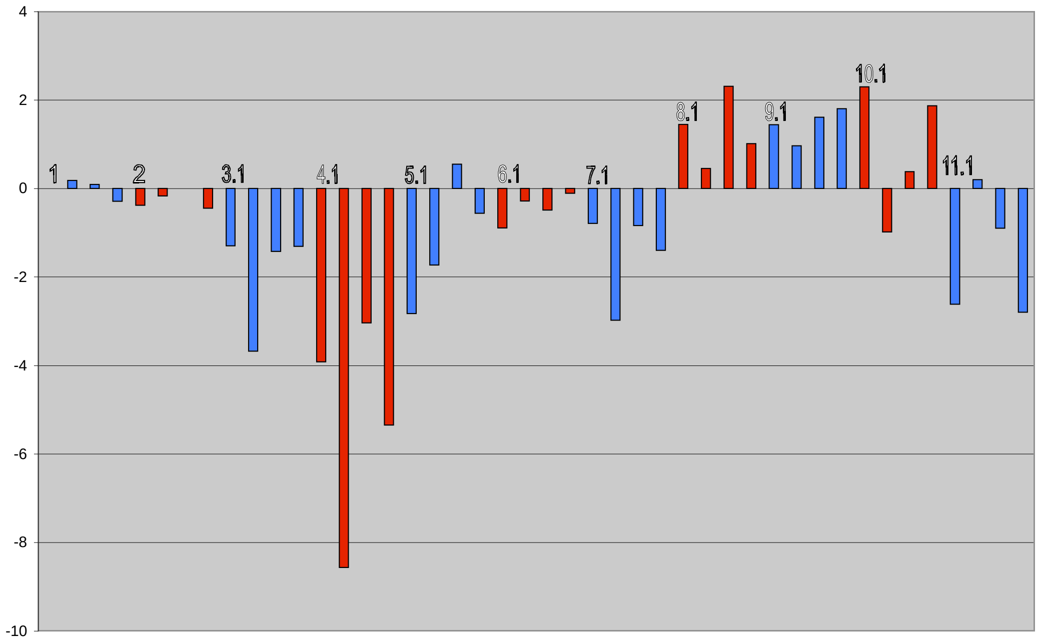
Differences in intonation did not particularly increase for ascending harmonics. The double touch points 6.(2), 6.(3) and 6.(4) were especially sharp.

The results showed some variation between the four bow strokes for each touch point for some of the higher harmonics, especially those that were double touched. The first three harmonics are particularly stable; pitch variation with bow stroke in their case was unperceivable. The following charts show four bow strokes for the same touch point of each harmonic one to eleven on the A string. The first chart shows varying, randomly selected, touch points for each harmonic and the second chart shows the touch point h.1 for each harmonic (this was chosen because in the above charts it seemed to be more 'in tune').



A string, four bow strokes for each randomly selected touch point.

There was virtually no variation in intonation for the four bow strokes on the open string and 2nd harmonics. A slight increase in variation occurred for ascending harmonics. The intonation of the 3rd to 5th harmonics varied very little. The variation of harmonics 7, 9 and 11 was slightly more but probably unperceivable. The double touched harmonics were notably less stable in intonation and varied considerably with bow stroke.



A string, four bow strokes for each touch point h.1.

Almost no variation in intonation occurred with bow stroke for the open string and 2nd harmonic. The 3rd and particularly the 4th harmonics were more variable. This could be an anomaly. Variation in the intonation of the 5th to 11th harmonics was barely perceivable.

CONCLUSION

Many more recordings need to be made to be able to discern regular patterns in frequency deviation of harmonics. Recordings with several celli and several string types would be necessary. However, within the limited scope of the experiment undertaken, a gradual sharpening effect seems to be discernable for ascending harmonics. This is probably due to string stiffness.

Harmonics appear to have slightly less consistent intonation for touch points near the middle of the string. This could be because touching the string at the middle, the most mobile part, restricts the movement of the string and changes vibration in some way.

Factors other than varying touch point can have a considerable influence on the intonation of harmonics. The results show that when consciously trying to maintain constant bow speed and pressure, variation in intonation between bow strokes is usually very slight, therefore I expect that these factors are changes in left hand finger position and pressure.

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