A Multidisciplinary Study of the Phenomenon of Violin Vibrato

---

Wilken Craill Calitz

Thesis presented for the degree of
Masters of Music in Music Technology
in the Faculty of Arts, University of Stellenbosch.

March 2009

Supervisor: Mr Theo Herbst
Co-supervisor: Prof Johan Vermeulen

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: 3 March 2009

Abstract

Violin vibrato is the action by which a violinist periodically changes the frequency of a sustained note by moving the finger on the string, rapidly backwards and forwards. If it is artistically applied, it adds life, character and warmth to an otherwise dull sounding note. Although it has been used since the sixteenth century, very little research has been done on the reason why humankind would experience such periodic fluctuations as an object of beauty in violin performance.

In answering the question, this study explores a variety of angles of approach in order to understand the phenomenon in its full context. The history, development and geographical origin of the technique are firstly discussed in a diachronic fashion and provide the background for the subsequent synchronic research on the physical nature of violin sound and violin vibrato. The vibrato rates and widths of four virtuosi are measured and compared to highlight the differences and individuality which are argued to be a contributing factor to the perception of beauty of the technique. It is established in the final chapter that the brain is stimulated more by sounds with periodic changes than those that are presented in the steady-state which cast some light on why vibrato may be experienced as an appreciated addition to sound.

The thesis aims to present a unique view on the possibilities of interdisciplinary research of the phenomenon of violin vibrato. It further aims to present the research findings in a concise, logical, and systematic manner that could be of interest to both musician and scientist.

Opsomming

Vioolvibrato is die aksie waardeur die violis die frekwensie van ‘n gespeelde noot periodiek verander deur die vinger op die snaar vinnig agtertoe en vorentoe te beweeg. Indien dit artistiek aangewend word, gee dit lewe, karakter en wamte aan ‘n andersins oninteressante noot. Alhoewel die tegniek al sedert die sestiende eeu in gebruik is, is daar nog baie min navorsing gedoen oor die rede waarom die mens dié periodieke veranderings as ‘n element van skoonheid in viooluitvoering ervaar.

Om die bogenoemde vraag te antwoord, word daar in hierdie studie ’n verskeidenheid invalshoeke ondersoek ten einde die verskynsel in sy volle konteks te verstaan. Die geskiedenis, ontwikkeling en geografiese herkoms van die tegniek word eerstens op ‘n diakroniese wyse bespreek en dien as agtergrond vir die daaropvolgende sinkroniese navorsing oor die fisiese aard van vioolklank en vioolvibrato. Die vibrato tempi en -wydtes van vier virtuose word gemeet en vergelyk om die verskille en individualiteit te belig, wat na bewering ’n bydraende faktor is tot die belewenis van die skoonheid van die tegniek. In die laaste hoofstuk word vasgestel dat die brein meer gestimuleer word deur klanke wat periodiek verander as deur eentonige klanke, wat deels verklaar waarom vibrato ervaar mag word as ‘n gewaardeerde toevoeging tot klank.

Die studie het ten doel om ’n unieke blik te verskaf op die moontlikhede van interdissiplinêre navorsing oor die verskynsel van vioolvibrato. ’n Verdere doel is om die navorsingsbevindings op ‘n kompakte, logiese, en sistematiese wyse aan te bied wat vir beide die musikant en wetenskaplike van belang kan wees.

Acknowledgements

I would like to thank the following:

- Mr Theo Herbst for his academic support, guidance and excitement for the project over the past years.
- Prof Johan Vermeulen for his help with Matlab and advice on technical matters.
- Renate Riedemann for performing the violin samples needed for the study.
- Wietsche Calitz for introducing me to the scientific side of music, proofreading the document and many years of blissful music making.
- Dolf Bredenkamp for his friendship, support during the endeavour, and many hours of help with Matlab.
- My dear parents, Estian and Karin for their love and support in everything I do. Thank you for your academic inspiration and help with finalizing the document.
- My brother Christian and sister Karlien for their interest and understanding in difficult times.
- Yusuf Ras and Esmarelda Tarentaal at the Konservatorium library for their help in finding much of the academic material required for the study.
- To Java coffee shop in Stellenbosch for providing me with much needed social interaction and liquid sustenance over the past years in and outside times of working in isolation for months.
- Annemarie Swanepoel, my violin teacher for twelve years, for cultivating an undying love for violin playing in me.
- Him, for the love of music.

Contents

Chapter 1: Introduction

Chapter 2: History and development of violin vibrato

Chapter 3: The sound of the violin

Chapter 4: Fundamentals of violin vibrato

Chapter 5: Vibrato measurement and comparison

Chapter 6: Vibrato perception

Chapter 7: Conclusion

Appendices

List of figures

List of tables

Chapter 1

Introduction

1.1 Basic description of violin vibrato

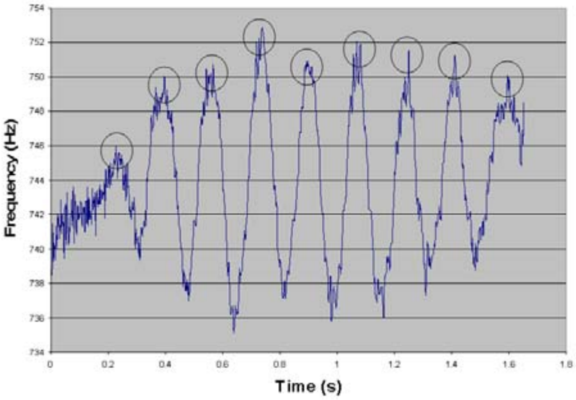
The action of violin vibrato[1] involves a series of very small backward and forward movements on the string by any of the four fingers that are used in violin playing to stop the string. This action causes periodic shortening and lengthening of the string which induces periodic fluctuations in pitch.[2] In this thesis constant reference will be made to this movement and it is therefore important to see exactly what it entails. Below are two photos demonstrating the basic procedure.

The first picture demonstrates the position of the vibrato finger in its highest position during a vibrato cycle. At this particular moment the pitch is at its maximum height from the position where the finger would normally produce a steady note. This position denotes a ‘forward’ or ‘up’ position from the norm. The accompanying graph is a presentation of the changes in pitch (frequency) over the duration of a note played with vibrato. The circles indicate positions where the finger (in this case the middle finger, also referred to as the second finger in string instrument playing) will be in a ‘forward’ position. It will be noticed on the graph that there are approximately six minima and six maxima per second, denoting a *vibrato rate* of 6 Hz. The distance between the highest frequency excursion and the lowest is approximately 17 Hz. This is known as the *deviation* and is expressed in cents. 17 Hz in this case denotes a deviation depth of 41 cents. This relationship between Hertz and cents is discussed in chapter 5.

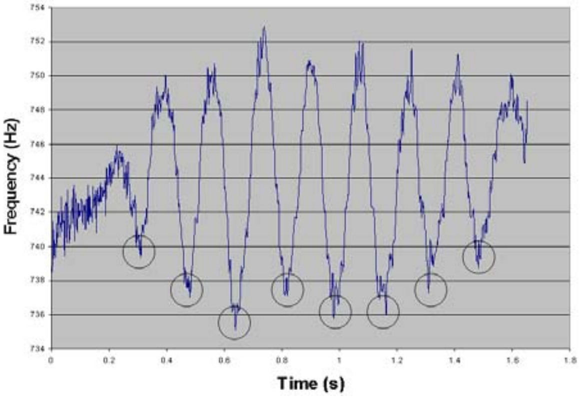
---

[1] Typically, a pedagogical distinction between finger, wrist and arm vibrato is commonly accepted. This research does not focus on the qualities and characteristics of these actions, but on the general, resulting, auditory impression.

[2] Amplitude and timbre also fluctuate with pitch but this will be discussed in more detail in chapter 4.



The picture below shows the position of the second finger in the ‘backward’ or ‘down’ position playing the same note as above. At this moment in the vibrato cycle the pitch is at its minimum. This position causes a lengthening of the vibrating section of the string and thus a lower sounding pitch. The circles in the accompanying graph indicate the moments in time where the finger will be in the ‘backward’ or ‘down’ position.



All the research documented in this current thesis is based on this periodic left-hand movement.

1.2 Motivation

Violin vibrato is indeed a strange musical phenomenon. For more than 450 years violinists have been aware of the musically expressive potential of these small periodic backward and forward movements of the stopping finger on the string during sustained notes. For the same number of years, violinists have also been painfully aware of the difficulty of playing in tune and that even the slightest slip of the finger away from the intended pitch during performance would render shudders in even the most tone-deaf of concert goers. Yet, doing so periodically at an approximate rate of 6 Hz, strangely enough has never bothered anyone. In fact, no violinist dare step on stage without the intention of gracing the majority of his or her notes with vibrato. It thus seems strange that periodic 'out of tune' playing by a master (of course within in a very small margin as described in chapter 4) can evoke feelings of longing, love, sorrow, content, amazement and bewilderment.

The reason why vibrato has become arguably the unprecedented expressive technique of violin playing has baffled many a scholar, musician and listener for centuries. Its effect on the emotions has never been doubted but why such a simplistic left-hand movement has been given the honour of securing the violin amongst the most lyrically communicative of instruments has not been entirely solved.

In an attempt to unveil this "holy grail" of violin performance, the first large scale scientific investigation on vibrato was published in 1932 by the psychology department at the University of Iowa in the USA.[3] The research consisted of many papers addressing various aspects of vibrato in both singing and violin playing. Despite relatively primitive scientific investigation techniques, the head of the investigation Carl E. Seashore and his associates were able to scientifically measure and quantify various parameters of violin vibrato. By achieving this, they could authoritatively state what vibrato is, how it works, how different violinists apply it, and what distinguishes a 'good' vibrato from a 'bad' one.

This acquired knowledge and proof that vibrato is in fact a researchable entity initiated major interest in vibrato research in diverse academic disciplines. The historian became concerned with the origins of the phenomenon, both geographically and musically. The natural scientist was curious about the individual application of the technique, its effect on the sound quality of a played note, and how it is produced on the violin to add such a colourful dimension to artistic violin playing. The musician also

---

[3] Seashore, C. 1932. *The vibrato*, Iowa: University of Iowa.

became concerned with the ‘how’, but from a musically interpretative and investigative point of view. Lately, the fields of physiology and neurology have contributed valuably in terms of how the human auditory system, from the ear canal to the higher interpretive centres in the brain, recognizes and interprets vibrato tones.

From studying the literature it became evident that researchers all fundamentally ask the same questions: *Why is vibrato such an important aspect of violin performance and why do we like it?* No research has however been found that specifically address the issue and there is also very little interdisciplinary communication between the various disciplines. It became apparent that there is a need for research that is first of all dedicated to the above questions and secondly to order the vast amount of core and fringing literature into a concise and systematically presented work. This thesis is an attempt at telling the ‘vibrato story’ from its origins in the mid-16th century, through the modern scientific endeavours and ending with the most recent research concerning the reason for our fascination with it for the last four and a half centuries.

A personal motivation for this study flowed from the researcher’s profession as a performing violinist and with a keen interest in how science can be a tool to discover new perspectives on music.

1.3 Objectives

The main objective of the thesis is to search for possible answers to the main research questions presented above. In the process of doing so the following secondary objectives will also be pursued:

- To introduce the reader to the various aspects of vibrato that has been researched and documented.
- To distil relevant and readable material from the related scientific literature in order to ensure accessibility for a wider audience.
- To bridge the gap between music and science and explore how the one can be a tool to better understand the other in a particular context; in so doing, to explore how scientific tools can be of assistance in music analysis.
- To serve as an educational tool to students, teachers, and researchers by broadening their understanding of the origins and scientific intricacies of the phenomenon.

- To provide a platform on which further research can be built and expanded upon.

1.4 Sources and research approach

Literature on violin vibrato can generally be divided into three main categories: historical, educational-tutorial, and scientific. The historical angle of approach is less defined than the latter two since the technique is but one of the multitude of subjects to cover on the origins of violin playing, let alone the origins of the instrument itself, socio-musical position etc. Although applicable, reference to vibrato is often of minor significance in less specialist publications. As a result, some sources used for the historical part of the thesis (chapter 2) are often not directly related to the topic but still provide a firm background from which well-argued conclusions can be drawn. Educational-tutorial literature overlaps with both the historical development of the technique and science as a vehicle for music education. The tutorials of violin pedagogues since the 17th century proved to be a very valuable source in formulating, where other literature often lacked, a clearer view of the history and development of the technique. Educational sources that use scientific tools mostly provide quantified data of recordings of professional violinists' vibrato which then serve as a basis from which students can improve their own playing.

The scientific category incorporates many sub-disciplines namely: physics, digital signal processing, anatomy, physiology, neurology, to name but a few. Sources needed for adequate description of the sound of the violin, the properties of vibrato, in-performance measurement thereof, and aural perception, were drawn from the various scientific sub-disciplines. Online journal archives such as the Google-Scholar supported *J-stor* proved a very valuable source of information in this regard as it is continuously updated with the most recent research.

It can hardly be stressed enough that this study is mainly explorative in nature. Basic research guidelines, such as chapter headings and research methodologies, were laid down before hand but the outcome is a time-line of researched findings. The objective was not to perform a single experiment that would directly answer the research question. An attempt was rather made to plough a way through the vast fields of vibrato documentation and continuously documenting what may be of use in ultimately understanding why this technique in violin performance is so much appreciated. The study is therefore not only a destination but also a journey in itself.

The basic operation of three computer programs had to be studied for the purpose of thesis: Csound, for the synthesis of sounds to be analyzed; Matlab 7.1, for Fourier-analyses and graphs, and Praat 5.0.05 for vibrato data.

1.5 Methodology and structure

This study covers a wide range of associated vibrato topics, all canopied by the fundamental research question stated above. The methods applied are not unlike those of a botanist scouting the land for specimens to be studied in his laboratory with the hope of discovering something exciting or merely confirming the known. The many sound samples, articles, music scores, data sheets, graphs, computer programs, audio CDs, brain scans, and many more were all gathered from the vast fields of music history, the physical sciences, digital signal processing, and the medical sciences, to be studied with excitement and anticipation of what the end may have in store.

Each of the chapter headings have been selected to denote a particular sub-genre of violin vibrato. It proved difficult to present a systematic with-in chapter chain of thought that would logically follow on the previous chapter and comfortably lead to the next. The reason is that certain key concepts which required intermediate linking, were viewed in a way that have not yet been presented in this manner in the reviewed literature.

Below is a short summary of the research chapters in the thesis illustrating the reasoning methodology applied:

Chapter 2: History and development of violin vibrato. This chapter provides a diachronic view of the origins and development of the violin and violin vibrato from the 1550s to the 1930s. Various manuscripts, tutorials, scores etc. were consulted in order to sketch the time-line of its uses and applications. During the 1930's vibrato was no longer only used as an occasional ornament but came to be applied as a continuous feature, as it is still practiced today. Perhaps not coincidentally, the same decade also saw the first major scientific investigation of the technique at the University of Iowa and sparked an international interest into the mystique of the phenomenon. This provides the link to the remainder of the study which synchronically discusses vibrato in a scientific milieu.

Chapter 3: The sound of the violin. This chapter initiates the scientific research in the thesis by describing the sound of the violin from a physics point of view. It traces the vibration process right from the moment when the bow sets the string in motion up to where the sound waves leave the instrument. It touches on topics such as standing waves on a vibrating string, vibration properties of wood and the timbre of the violin sound.

Chapter 4: Fundamentals of violin vibrato. This chapter continues and describes the nature of violin vibrato and how the sound of the violin changes during these periodic alterations. It defines the three vibrato quantities, pitch, amplitude and timbre and describes how they fluctuate periodically and simultaneously when vibrato is added to a played note.

Chapter 5: Vibrato measurement and comparison. In this section, the vibrato rates and widths of 4 professional violinists playing J.S. Bach’s Sonata No.1 in G minor for solo violin, BWV 1001, are measured. It highlights the differences and unique trademarks that exist between the players in terms of their vibrato application.

Chapter 6: Vibrato perception. This chapter concludes by describing the physiological and psychological processes involved in vibrato perception and explores the possibility that specialized neuronal activity may be involved at the centre of the process.

Chapter 7: Conclusion. This chapter summarizes the content of chapters 2-6. A list of the unique contributions made in this thesis to the study of violin vibrato is presented in addition to ideas for future research.

Chapter 2

History and development of violin vibrato

2.1 Introduction

This chapter provides an overview of the history and development of violin vibrato. The discussion starts off at the birth of the violin itself in the mid-16th century and views its acceptance into the musical milieu of Northern Italy at that time. Violin playing during the 1500s mainly revolved around performing for dance events and accompanying singers. It is believed that vibrato was 'borrowed' from the voice in these early years of collaborative music making. The first formal reference in a musical score to a type of vibrato dates from 1617 and it is argued that this serves as the origin of vibrato as an accepted element of expression. From this point onwards, vibrato has been favoured by some violinists and composers and disdained by others. However, by the 1930s, vibrato was no longer an embellishment as it was in prior years but rather an organic part of tone production. The last section of this chapter briefly addresses the first scientific literature on this topic which appeared in the same time that the so-called 'new' vibrato was starting to be accepted universally.

This chapter serves as a background for the rest of the study which focuses on the main advances of scientific approaches to this topic from the 1930s to the present.

Figure 2.1 is a map of Northern Italy and other places important in the early history of the violin and violin playing. The remainder of the chapter refers to some of the locations indicated on the map.

Figure 2.1. Map of places important in the history of the violin, violin playing and the development of vibrato (Source: Boyden (1965)).

2.2 History of the violin and violin playing

2.2.1 Origins of the violin

The violin as we know it today has its origins in three earlier instruments, namely: the rebec, the renaissance fiddle and the *lira da braccio*. Each contributed to either the construction or the development of its playing technique. The rebec, a three stringed instrument, was held at the neck and the soprano member of this string family was tuned to G3[4], D4, and A4, the same as the three lower strings of the violin today. It had no frets, a rarity in stringed instruments of the early 16th century. The renaissance fiddle had frets, and the principles by which it was constructed were subsequently borrowed in the manufacturing of its modern nephew. By the early 1500s it was already constructed from a top and back plate with connecting ribs. As a rule, it had five strings, of which the lowest one was a drone and not touched by the finger. Its shape was not standardised, however, and ranged from oval shaped to indented forms, similar to the guitar. The *lira da braccio* seems to have been the main contributor to the violin's unique body shape and features. It had an arched back and top, overlapping edges, ribs and a sound post. The typical *lira da braccio* in the 1500s had seven strings, the lowest two being drone strings.

David Boyden (1965:10) remarks in his treatise on the origins of the violin[5] that "some unknown genius pursued the virtue of combining the greater sonorities and the more efficient playing potential of the fiddle with the musical advantage of the rebec's stringing and tuning"; added to this of course the shape and structural qualities of the *lira da braccio*. In short it seems that the early violin resulted out of combining the best sonorities of each in a single instrument. Dilworth (1992:8) warns against the assumption that these were only forerunners for the violin. Throughout the 16th century all of the above instruments went through some structural design changes and one instrument did not subdue the other. Rather, their construction and playing technique developed in parallel. Dilworth notes that the *lira* and the viol[6] still persisted in Northern Europe and especially England as the premier bowed instruments for the greater part of the 17th century.

---

[4] Two common systems for naming pitches and the octaves in which they fall are in use today. Helmholtz (1885) suggested a rather cumbersome method using small and large letters, primes and subscripts. The NIST (National Institute of Standards and Technology of the USA) adopted a system in 1960 proposed by Young in 1939. In this system the lowest C on the piano is labeled C1. The chromatic scale upwards is then C1, C#1, D1….B1, C2, C#2. Middle C becomes C4 and the open A-string of the violin is labeled A4. This system will be used throughout the study.

[5] Boyden's thorough rendition of this topic renders him the authoritative voice in this regard and as a result he will be referred to many times.

[6] The viol, a bass stringed instrument held between the legs, was brought to Italy from Spain, presumably in the 1490s.

The highlight of the early amalgamation of these instruments is undoubtedly the three-stringed violin manufactured by Andrea Amati (1511-1577) in 1542. He is consequently hailed as the father of the modern violin and was one of the first luthiers of the so-called Cremonese dynasty. Amongst his other contributions are the standardization of both the dimensions of the viola and the cello (Beare et al. 2007). The last major structural change was the adding of a fourth string, E5. The origins of this particular extra is not known but apparently the French was rather pleased with its sound and called it “la Chanterelle” (Boyden 1965:50). By the 1550s the tuning of the four strings and its structural particulars had for all practical purposes been standardized. The oldest four-string violin known today dates back to 1555 from the workshop of Amati and the first formal textual reference of any sort appeared a year later in the *Epitome Musical* of Jambe de Fer (Boyden 1965:35).

2.2.2 Violin music and social position

The success of the subsequent violin making schools of Cremona, Brescia and other towns surrounding the capital of Milan, rendered the craft of violin making almost exclusively an Italian preserve (Boyden and Walls 2007) and soon infiltrated the country’s musical milieu. The violin became an important part of the late Renaissance socio-music environment in the function it served. For the greater part of the 16th century, professional violinists spent most of their working time either entertaining noblemen, working as court musicians, accompanying singers or bowing out rhythms at dance events. Evidence as early as 1523 indicate that the French monarchy, who ruled Savoy at that time, employed a consort of ‘vyollons’ from the town Vercelli, for some evening entertainment. By the 1550s, the violin consort was the most popular choice for musical entertainment, as opposed to wind instruments which were more suited for the humble social classes (Holman 2007).

Boyden (1965:52) reiterates and notes that in the early stages of the century the violin served two principle functions, namely to play for dancing occasions or to double some of the voices in vocal ensembles. There was therefore no need for written violin music since the dancing violinist would have served an improvisatory function and the vocal accompanist one of mere doubling. In this era violin music was of little importance and shadowed by the reigning literature for the mass, motet, madrigal and keyboard. The earliest known violin music in written form therefore only appears in 1582 as two dances that form part of *Ballet comique de la reine*; music written a for a royal wedding festivity during that time. The composer remains unknown (Boyden 1965:51).

2.3 Musical developments that led to the birth of violin vibrato

2.3.1 Secular vocal music in the 16th century

Vocal music dominated the formal music scene in the late-Renaissance in Italy; both in secular and sacred environments. On the secular front, the polyphonic madrigal, which in its essence is a musical setting to secular verse, was the most popular choice of musical composition. Since its origins in the 14th century, up until the 1580s, the madrigal was either a past time or served a more functional role in public or private festivities and was composed in the reigning compositional style of the era and area. Haar (2007) describes madrigals in the early 16th century as "…chamber music performed by cultivated amateurs for their own enjoyment…" The more functional madrigal served as accompaniment to dramatic plays of composers such as Alfonso della Viola Rore. Texts set by Verdelot, produced in Florence in 1525, used madrigals as *intermidi* in his plays *Mandragola* and *Clizia*.

So what did the madrigals sound like? Phillips (1978:196) makes a general comment regarding the textures:

> Throughout the century (up until the last two decades or so) the music seems to rely on a perfectly balanced sound, a sound where no single voice or part should obtrude. This ensures that the counterpoint, where every line is of comparable importance to the whole, is presented without distortion.

Each composer of course had a personalized style and perhaps trademark sound. The madrigal also had no fixed number of vocal parts. A monumental figure in the mid-century madrigal development, Phillip de Monte (1521-1603), for example, produced two books for seven voices, nine for six, nineteen for five, four for four, one for three – a total of over 1000 compositions. Other notable contributors include Willaert (1490-1562), Rore (1516-1565), Nasco (1510-1561), Andrea Gabrielli (1523-1585), and Wert (1535-1596). Haar (2007) notes that nearly every composer in Italy contributed to an explosion in popularity in this genre during the 1550s and 1560s.

The violin, which was still in its infancy during this stage, found an employment haven in the flourishing madrigal market. Burney (1789:434) summarises the acceptance of violins into the vocal genres of the era:

> Instruments (violins) were first admitted into good company for enforcing the voice parts in the performance of madrigals; and soon after, whenever voices were wanting in private music meetings, instruments supplied their place, and the madrigals were played instead of being sung.

The above provide evidence that as far as the social musical circuits were concerned, the violin gradually became a part of daily proceedings and, most importantly, evidence already hints at emancipation in terms of its true voice from the dominating vocal music.

2.3.2 Sacred vocal music in the 16th century

The state of sacred music during the same era, as in the case of the madrigal, relied on the vocal polyphonic tradition of the 16th century. The mass served as the vehicle for sacred musical composition in the late-Renaissance. By the 1520s Josquin and his contemporaries had established two main types of composition for texts used in mass: the older tenor mass and the newer polyphonic paraphrase (Göllner 2007). A gradual decline of these mass structural principles eventually receded into obscurity with the rise of the contrapuntal imitation mass – frequently called the ‘parody mass’. The rise of the ‘new’ style may be due to an increase in composition of a popular form of sacred vocal music, the motet. The first half of 16th century witnessed an increase in composition of motets in an imitative homophonic style which is thought to have had a prominent effect on the mass of the day (Sherr 1986).

If one composer could be singled out as representing the polyphonic vocal mass in the late-Renaissance, it would undoubtedly be Palestrina (1526-1594) (Capwell 1986). His first book of masses appeared in 1554 and 40 years later he had contributed no less than 104 complete mass settings; 53 of which follow the complex polyphonic imitation style. In 1562 the Council of Trent, a body dedicated to the discipline and administration of the Catholic Church in the post Counter-Reformation, issued a law “prohibiting all ‘seductive and impure’ melodies in church use and the primary goal was to see that the mass text was made as intelligible as possible to the congregation” (Lockwood and Kirkman 2007). Palestrina happily abided with the new plea and in a letter in 1568 he asked the cardinal of Mantua to let him know if a certain mass of his proved unsatisfactory and, if it must, he will rework it (against his will) so that the words may be understood.

Perhaps not as a direct result of this event but due to stagnating compositional methods that had been followed for many decades and perhaps due to an over familiarity with the Latin texts, the mass had for all practical purposes plummeted into lifeless unintelligible imitation. Schnoebelen (1990:537) notes that the mass had become the most conservative and least innovative sacred music genre in Italy. Palestrina's legacy also spurred a continuation of the formula-driven vocal style for decades to come.

2.3.3 The rise of *seconda prattica*.

Earlier in section 2.3, a distinction was made between the state of the madrigal and the mass; denoting the reigning secular and sacred vocal compositional genres of the 16th century. By the end of the century both had reached a stage where the traditional polyphonic setting of text no longer suited the artistic ideals of the time. The polyphonic style of the previous century, in the words of Caccini, "stretched out or on the contrary compressed the syllables for the sake of counterpoint and thus destroyed meter and words" (Sachs 1949:206). Sachs adds that with the elimination of polyphony the composer was at last in a position to comply with "humanistic claims" which emphasize the prevalence of words above the music.

Razzi (1980:300) states in more concrete terms that in the older style (*stile antico*), the musical structure is sustained essentially by the interdependence of the lines, which are perceived as part of the whole. The poetic text, though important, is not a primary element. Towards the end of the 16th century, the relation between text and music became the base of musical composition in itself. This new style demanded a "degree of expressive autonomy and declamatory substance, an inner freedom in the utterance of the poetry…" (Razzi 1980:300). The general movement towards these artistic claims became known as the *seconda prattica*.

The madrigal had by the 1580s reached a climax where vocal virtuosity and wide-ranging technically demanding ornamentation was at the order of the day. Marenzio (1553/4-1599) and Andrea Gabrieli (1532/3-1585) were pioneers in the pre-*seconda prattica* madrigal which further included features such as tone-painting, written-out ornamentation and far-reaching harmonic excursions (Newcomb 2007). The flamboyance of this decade was short-lived but the expressive possibilities in both performance and composition became a backbone for the new style. Furthermore, the abolishment of Petrarchian-type texts in favour of more free verse of contemporary poets further rendered the circumstances fit for a new era.

Alessandrini (1999:633) comments on the *seconda prattica* madrigal by saying that the composer is required to translate into music the contents of the poetic text and the performer to translate the synthesis of text and music into sound and emotion.

Of importance to our current study is the performance aspect of the new madrigal in which the early violin had at the time (1580-1600) at least been an ad-hoc 'voice' for the previous thirty years. It is thus appropriate to quote at some length the performance directions for the 'new' music by the Italian, Nicola Vicentino:

> He should sing the words in keeping with the composer's intention, so as to leave the audience satisfied. He should express the melodic lines, matching the words to their passions – now joyful, now sad, now gentle, and now cruel – and adhere to the pronunciation of the words and the notes. Sometimes a composition is performed with a certain method that cannot be written down, such as uttering softly or loudly or fast or slow, or changing the measure in keeping the words, so as to show the effects of the passion and the harmony (Alessandrini 1999:634).

It is argued here that since the early violin was in close association with the vocal styles of the second half of the 16th century due to geographical and social circumstances, it must have in some way adopted the new style of expression emerging from behind the closing curtain of the Renaissance. There is no written evidence of the borrowing of technique at this stage but it is reiterated time and time again by authors on the subject that the two instruments, the violin and the voice, share a highly desirable *cantabile* quality which probably initiated the collaboration in the first place. Of interest in our study of vibrato is whether the voices of the new style did employ the technique and whether it is reasonable to assume that, given the circumstances, the violin directly borrowed this highly expressive technique.

Alessandrini's (1999:635) article provides a humorous account from a German talent scout regarding the state of vocal vibrato use in Rome in the early 17th century. He (the scout, Christoph Bernhard) first states that the *tremolo* in his native country is considered a decoration of the stable note but considers it a vice when used continuously. The Italians use it continuously, he says, but not as an artistic device, rather like that of an "old person singing alone that cannot hold a steady note." From this it can be assumed that it was already in use by the turn of the century and probably before.

The origins of violin vibrato may well have been in the changes in expression in the secular vocal music but the first formal account of this technique stems from the emergence of instruments in sacred

Italian music. There is evidence of a few remaining Venetian prints which indicate that instrument ensembles were already in use in a number of Italian churches in the 1560s. Their duty would mainly have been in doubling the vocal parts of motets which during the second half of the 16th century often replaced parts of the mass Proper. It was not common practice to specify specific instruments that were to be used and it is only in 1597 in Giovanni Gabrieli's first collection of *Sacrae symphonia* that such specifics were mentioned (Alessandrini 1999:636).

The 1580s saw a great increase in the use of musical instruments in church music especially in Northern Italy. It was firstly due to a sharp rise in musicians' salaries during this time; secondly due to the lowering in pitch of the organ in the Duomu at Cremona, specifically for the reason that ensembles could now participate in general liturgical proceedings; and thirdly, due to the popularity of a new type of instrumental composition known as the *ensemble canzona*. This ensemble type was an instrument-only composition and was meant primarily for use in certain parts of the mass (Bonta 1990:521).

The above statements of Bonta (1990) provide evidence that the violin was already accepted into church music by the end of the 16th century. The gradual change in text types and vocal expression already flourishing in secular music due to the emergence of the *seconda prattica* principles was soon incorporated again by North Italian church composers. They adopted the same principles and turned to motets and psalm texts in the vernacular to catalyze more affective expression in the music (Schnoebelen 1990:537), something that would not have been possible in the stagnated Latin-text Palestrinian style.

The breath of fresh air in church music in the early 17th century saw the emergence of amongst other initiatives, the so-called *concertato* style: a mass for soloists and basso continuo, used in contrast to a full chorus. Schnoebelen (1990:537) notes that the new vocal style borrowed from the secular performance found a welcome haven in the new type of work which favoured virtuosic elements such as wider vocal ranges and faster note values. The contrasting solo-chorus variation became an important factor in the new style. The ensemble canzone, often accompanied by organ, added contrast in terms of chorus and instrumental sections. This type of canzone would later become the *sonata da chiesa*.

2.4 The beginnings of violin vibrato

2.4.1 Early violin vibrato

It is at this point in history, and the development of violin and vocal music, in Italy that the first reference to violin vibrato occurs. When Biagio Marini (who was born in Brescia and worked in Venice at the time) wrote *tremolo con l'arco* in the violin parts of his sonata for two violins, *La Foscarina* (Opus 1, 1617), he became the first composer to use the term in a composition for bowed string instruments (Carter 1991:43). A quick terminology check is necessary for the benefit of the remainder of the discussion. Tremolo in this case refers to the modern *portato* or *louré* style of bowing whereby a series of notes of the same pitch are taken in a single stroke without stopping the bow. Boyden (1965:422) calls it "slurred vibrato" in that the pulsating bowing hand "slurs" the notes to create the effect of a single note with added character. Probably the earliest reference can be found in Ganassi's *Regola Rubertina*[7] from 1542. Here he advises players of the viola da gamba: "For melancholy words and music…shake the bow arm and the finger of the hand on the neck of the instrument in order to make the effect conform to melancholy and tormented music" (Gammie 1979:23). Agricola (1545), in Sachs (1949:160) writes:

> Who, while their stopping fingers teeter,
> Produce a melody much sweeter
> Than 'tis on other fiddles done.

The first "shake" of the bow arm is what Marini specified in his score. The left hand "shake" of Ganassi and the "teeter" of Agricola is what we know as vibrato today. The current study is concerned with left hand vibrato only, but it is assumed by Carter (1991) that the two vibrato types may have been used in conjunction. Evidence on this topic is lacking. Whatever the case may be, although Marini's inscription is undoubtedly calling for a *portato* effect, this is the first formal in-manuscript reference to any sort of periodic change in either a note's pitch or amplitude and it is thus considered a pivotal point in the history and development of violin vibrato.

An inscription by Marini on the organ continuo part of this sonata reads *metti il tremolo* ('put [or set] the tremolo'). As Carter (1991:43) notes, the tremolo indications in the bowing parts now become

---

[7] Every effort has been made to get hold of an English translation of this document. Due to its scarcity and apparent complexity, even in its English format, the Journal of the Viola da Gamba Society issued a shortened version in 1979, the version on which this text relies.

clear: the violinists are to imitate the undulations of the organ. Alessandrini (1999:635) casts some light on the subject. He notes that Italian organs at the beginning of the 17th century were equipped with a register known as *fiffaro* and later as *voce humana*. It consisted of a series of Principal-scaled reed pipes tuned slightly higher than the Principle octave. When the slightly detuned reeds sounds together, "the frequency difference produces a regular beat the speed of which is proportional to the degree of discrepancy." The fact that the register is named *voce humana* is obviously a reference to the vocal vibrato of the human voice.

The preceding description of the origins of the violin and then the various states of vocal music in Northern Italy is a necessary cornerstone in understanding the converging elements that may have contributed to this early reference of violin vibrato. The evidence given in the chapter thus far strongly points towards Northern Italian origins. The famous violin making schools of Brescia and Cremona contributed to developing the instrument worthy of a place next to the human voice in musical activities in the 16th century. Early composers of vocal music in their turn welcomed the new instrument in its infancy when it was still searching for its true voice of expression. Church composers followed suit and the violin was soon an important part of the *seconda prattica* mass. Nearly all social and artistic urgency to express what had been suppressed by stagnating forms and structures, contributed to the first formal reference of violin vibrato.

The second part of this chapter traces the use and development of violin vibrato from the early Baroque to post-Romantic 1930s, when the technique was first applied as a continuous device, the way it is still used today, instead of its earlier use as mere embellishment.

2.4.2 Violin vibrato from 1600 – 1930

For all intents and purposes it can be assumed that violin vibrato was now part of formal music composition. In the years following Marini's inscription, other Italian composers followed his example and likewise indicated in their scores that the violin should *tremolo* with the organ. Other composers followed the example of Marini (Carter 1991:44-45). In 1619 Gabriel Usper published a sonata for two violins, bassoon and continuo which contain a tremolo passage. One year later Riccio published two works for two violins, trombone and organ, with the inscription *tremolo con l'arco*. A *canzon* from Giovanni Rovetta with similar effects appeared in 1626 and in 1629 Dario Castello also published a work with tremolo passages. In the preface to Monteverdi's eighth book of madrigals in 1638, he defines three styles or *genere* of emotional states in musical composition: *concitato* ('agitated'), *temperato* ('moderate'), and *molle* ('soft' or 'relaxed'), corresponding respectively to the affections of 'anger', 'moderation', and 'humility' or 'supplication' (Chew 2007). In that same year Monteverdi published a work containing tremolo to express "warlike passions" which, other than Ganassi's association of it with melancholy, is associated with the *concitato*-type (Boyden 1965:129).

These results reflect the fact that the technique gained at least some popularity in the succeeding years of Marini's indications. Based on Monteverdi's association of vibrato with a certain *genere* and Ganassi's earlier reference to its use only for "melancholy" reasons, it can also be deduced that it was primarily used at least as an effect to impart a certain state of feeling. However, as will be seen later on, from this point in the early Baroque onwards the different applications of vibrato passed in and out of fashion. By the 1930s it was no longer a question of which *genere* or state of emotions the performer adhered to, as it became an ever-present organic part of tone production.

The rest of the chapter is mainly concerned with this change in application. Possible reasons as to why this may have occurred are also provided, but first the attention turns to those authors who have contributed to our understanding of the use and application of the technique from its origins to the 1930s.

An exact account of the chronological development of the technique falls outside of the scope of this study. Furthermore, although violin vibrato has received much attention since the 1930s, information on the subject prior to this decade is scarce and, as a consequence, renders such a methodology unfit. Apart from a few references and other snippets of information, what ís available to the modern scholar, and of great worth, are violin tutorials from different eras. These allow the researcher to make broad observations and allow some form of consistency in terms of their diachronic appearance in history. For example, Ganassi's recommendations in *Regola Rubertina* appears in 1542-3 and provides a different approach to the uses of vibrato in Geminiani's tutorial some 200 years later. Leopold Auer's ideas regarding vibrato in 1921 with his *Violin playing as I teach* provides yet another completely different view. Section 2.4.3 provides an overview of the different perspectives of vibrato over approximately the last 400 years.

2.4.3 Authors on violin vibrato

Few sources on vibrato exist from the 17th century. One example is Mersenne's *Harmonie Universelle* from 1638 where he calls the effect *verre cassé*:

> It has a very great charm when it is made quite properly. And one of the reasons that the moderns have rejected it is because the older ones used it almost all the time. But since it is as vicious to use it not at all as to perform it too much, it must be used in moderation (as quoted in Boyden 1965:178).

Mersenne gives further advice on how to perform vibrato and mentions that "the left hand must swing with great violence…when this ornament is performed." He encourages sparing use and, of great importance, refers to it as an ornament; a counter-reaction, it seems, to players that may have abused it in previous years.

A treatise in 1695 by Merck defines two species of vibrato: the normal "shaking" type and the "close shake". The "close shake" is performed by placing one finger firmly on the string and a second finger makes a rapid trill very close to the pressed down one. The theorist Rousseau proposes that "it is used on all notes long enough to permit it, and it must last as long as the note" (as quoted in Boyden 1965:288). This reference advocates some form of continuous vibrato without regard for any emotional connotations.

Geminiani ([1749] 1969:3) describes the vibrato in his *A Treatise of Good Taste in the Art of Music* as a "close shake" and, like Rousseau, favours its continuous use. According to the available sources, he may be the first author to be aware of different types of vibrato. He differentiates between a strong "punching" shake and a "shorter, lower and softer" type; the former denoting "majesty and dignity" and the latter "affliction and fear". Interestingly, he even advises that "when it is made on short notes, it only contributes to make their sound more agreeable, *and for this reason it should be made use of as often as possible.*" [Italics added].

A few years later in 1756 Leopold Mozart replies with his take on vibrato use in his *A Treatise on the Fundamental Principles of Violin Playing*. He calls it "tremolo" but specifically indicates that he refers not to the organ's undulations but to specific left hand oscillations. He says:

> Now because the tremolo does not sound pure as one note but fluctuates, it would be a mistake indeed to play every note with the tremolo. There are already players who use vibrato consistently

> on every note as if they had the palsy. The tremolo must be employed only in such places where Nature herself would produce it (Mozart [1756] 1975:203-204).

Mozart distinguishes between three types of vibrato: the “slow”, “accelerating”, and the “fast”. Other than Geminiani, these types are not linked to emotional states but different uses are approached in a more conscious musical fashion. The varying types are associated with, for example, intensification of notes or in adagio passages where notes are sustained.

From the early classical accounts the discussion commences with two worthy tutorial contributions from the early-Romantic era: Louis Spohr’s *Violinschule* from 1832 and Pierre Baillot’s *L’Art du violon* from 1835. Spohr ([1832] n.d:175-176) directly links the violin vibrato to that of the voice: “The violinist is able to imitate closely this trembling, together with many other peculiarities of the human voice.” The violinist, he says, should take care not to introduce it too often and in unsuitable places. “He should therefore use it only in passionate passages and the string accentuation of all notes marked *fz* or >.” Long notes may be made more “alive and “intense” with this effect. Spohr adds an extra type of vibrato to those of Mozart: the decelerating type.

Baillot ([1835] 1991:239-243) likewise links vibrato to the voice and warns against overuse: “Used with discretion, vibrato gives to the sound of the instrument a similarity to a voice strongly affected by emotion.” Baillot still recognizes the true tremolo (the *poratato* type) as a technique of expression, something that others have rejected. He even proposes simultaneous use of the true tremolo and vibrato. In conclusion he rejects its use in a succession of notes and states that it has a good effect on long notes and repeated notes.

A year before the release of Spohr’s *Violinschule* saw the birth of the violinist, Joseph Joachim, who has been venerated as the “revered high priest of Classical taste” (Brown 1988:116). Throughout his career he has premiered some of the gems of the Romantic violin repertoire, including the Brahms and Schumann violin concertos, and befriended some of the leading composers of the time (Borchard 2007). His collaborative *Violinschule* with Andreas Moser in 1905, however briefly, provides valuable insight into what the high-Romantic would possibly have expected of their flagship violinists. After quoting almost the entirety of Spohr’s vibrato instructions and thereby proclaiming themselves disciples, they conclude:

> The pupil cannot be sufficiently warned against its habitual use, especially in the wrong places. A violinist whose taste is refined and healthy will always recognize the steady tone as the ruling one,

> and will use the vibrato only where the expression seems to demand it (Joachim and Moser 1905:96).

The similarly venerated "priest" of violin pedagogy and student of Joachim, Leopold Auer, released his teaching methods in 1921, titled *Violin playing as I teach.* His account of the current use of the technique can only be described as grumpy and thereby probably takes a final stab at the rapidly looming notion of continuous use. Clauses such as "a plague of inartistic nature", "device for hiding bad intonation", "out and out dishonest artistically", and the current researcher's favourite, "the Tabasco of continuous vibrato", constantly grace his pages.

Brown (1988:112) remarks that by the time that Auer penned his grievances, the use of continuous vibrato was gaining universal sanction, and perhaps a little irony lies in the fact that some of its greatest exponents, notably Heifetz, Elman, and Zimbalist, were his own pupils.

In the same breath, Brown notes that the beauty and nobility in tone at the turn of the 20th century were increasingly linked to a continuously vibrant tone produced by the left hand. Before, beauty in tone was associated with clear and pure sound produced by the bow. Carl Flesch states in his *The Art of Violin playing* from 1924:

> While the right arm (bowing arm) has to solve sharply defined, mentally controllable tasks, namely, the free development of string vibrations, as well as rhythmic and dynamic shading of the tone sequence, the duty of the left hand, besides the most exact verification of the tonal pitch consist of an unconscious merging of the tone with psychic powers slumbering deep within or subconscious. The result makes itself heard as continuous vibrato (Flesch 1924:35).

He further adds that individuality in violin playing is solely determined by the quality and type of vibrato used. Fritz Kreisler observes the trends of vibrato in this age:

> Wieniavsky (1835-80) intensified the vibrato and brought it to heights never before achieved, so that it became known as the 'French vibrato'. Vieuxtemps (1820-81) also took it up and after him Eugene Ysaÿe (1858-1931), who became its greatest exponent, and I. Joseph Joachim, for instance, disdained it (Lochner 1951:19).

A final quote by Flesch in his *Memoires* of 1957 should render our vibrato argument sufficient:

> We must not forget that even in 1880 the great violinists did not yet make use of proper vibrato but employed a kind of *Bebung,* i.e. a finger vibrato in which the pitch was subjected to only quite

> imperceptible oscillations… Ysaÿe was the first to make use of a broader vibrato and already attempted to give life to passing notes, while Kreisler drew the extreme consequences from this revelation of vibrato activity; he not only resorted to a still broader vibrato but even tried to ennoble faster passages, by means of a vibrato which, admittedly, was more latent than manifest (Flesch 1957:120).

The above quotations and points of view show an evolution from an ornamental feature in the opinion of the early Italian vibrato ‘school’ to a continuous “French Vibrato” some three hundred or more years later. Why did this phenomenon occur and why did it take place at this particular time in the history of music?

Katz (2002:174) ruminates on this topic and provides some interesting insights. The shift from the old to the new, he says, may be observed on phonograph recordings of the time. Prior to 1910, only slight vibrato was heard on melodically important notes. The following decade revealed a transitional period where some violinists already experimented with more frequent use. Generally “after 1920, the new vibrato is apparent in the recordings of most violinists.” As to why the trend occurred at this point in history, he points towards the phonograph. “A constant and strong vibrato became increasingly useful for concert violinists for whom recording became a way of life” (2002:174). Firstly it could obscure imperfect intonation which is obviously more noticeable on record than it is in the concert hall and secondly, due to the visual aspect being obsolete on recording, violinists could enforce a greater “sense of performance” and “individuality” by their vibrato use (Katz 2002:179).

Robin Stowell (1994:91) suggests that the change in vibrato was due to the introduction of a new chinrest which transferred the weight of the violin to the shoulder and liberated the left arm to “cultivate a more fluid vibrato movement.” Another argument is that after World War 1, violinists began to replace their gut strings with the more pierce-sounding metal string. String players may have adopted the new style as a way to “mitigate” the quality (Katz 2002:1979).

2.5 The natural sciences and vibrato

Whatever the reasons, the new vibrato was a prominent feature for the leading violinists in the decade of the 1930s and after. The change was almost viewed as a phenomenon amongst musicians and Flesch (1924:40) claimed in 1924 that Kreisler had started a “revolutionary change in the use of violin vibrato." It is exactly at this time that the scientific study of vibrato made its first major contribution. For the remainder of the chapter, we turn to these pioneering scientific studies.

In 1931 the Psychology department of the State University of Iowa headed by the Dean, Carl E. Seashore published a treatise solely devoted to the study of vibrato. He and his colleagues distanced themselves from prevalent vibrato application opinions such as those in the previous sections and focused their research on the purely scientific aspect of the effect. In the introduction to the treatise, Seashore writes:

> As to the vibrato itself, the volume deals in firm and bold strokes with musical history, theory, practice, pedagogy and criticism in that it clears up the historical controversies as to what the vibrato is and should be by laying down objective and verifiable definitions, analysis and principles. It lays a scientific foundation for aesthetic theory to this element of beauty in music (Seashore 1932:9).

He further states that their research aims to simplify, clarify and place the phenomenon under control. The Iowa University research team then essentially proceeded by asking the same questions as those of the tutors, performers and theorists as to really what this "element of beauty" is, but from a scientific point of view. Prior to this specific publication, Seashore coined the term "deviation principle" by which he laid down the principles of scientific study needed for fully investigating vibrato. He argues that all music that is conveyed from the performer to the listener is done through sound waves which are the "material basis for the analysis and clarification of all possible elements in the musical tone as an art object" (Seashore 1947:18). In addition to this he confines the musical sound to four basic elements: *frequency, intensity*, *duration*, and *waveform*. Of the latter elements he states that it is "the only 'plastic media' in terms of which beauty or ugliness may be created in music" (Seashore 1927:141).

In more concrete terms, he says that "beauty consists in deviation from a fixed base such as true pitch, rigid time, uniformity of loudness, or a pure tone" (Seashore 1927:142). A tone presented to any listener with true pitch and uniform loudness etc. will be of little musical significance. Seashore argues that it is the minute changes in pitch and amplitude etc., for example when the violin bow scrapes across the string at the onset of a note, or the 'artistic' timing delays from rigid timing at the end of phrases, that renders certain notes or phrases 'more beautiful' than others. Vibrato, as it will be seen in subsequent chapters, is then essentially the artistic deviation from regular pitch (periodic variations in frequency), uniform loudness (periodic variation in amplitude), pure tone (periodic variation in timbre), all over a continuum of time.

Chapters 3, 4, 5, and 6 approach vibrato from a similar scientific point of view but instead of only measuring and comparing the deviations of violinists (which will constitute chapter 5), it also aims to excavate the core principles of the violin sound (chapter 3), the vibrato as a scientific phenomenon (chapter 4) and in the conclusive chapter 6, the auditory perception and functioning of specialized neuronal centres.

Against the background of the origins and current state of vibrato, chapter 3 describes the active parts and mechanisms involved in violin tone production. The process is explained right from the beginning when the bow sets the string into motion, through the various stages of vibration interpretation in the body, up to the point where the sound is released as an audible acoustic event.

Chapter 3

The sound of the violin

3.1 Introduction

Chapter 2 presented the origins and development of violin vibrato in a diachronic fashion, from the 16th century up to the present. The remainder of the study proceeds to describe the vibrato phenomenon in a predominantly scientific manner. Before the characteristics of violin vibrato itself are discussed in chapter 4, the current chapter documents the sound production process of the violin, right from the moment of string excitation up to the point where the instrument body emits sound waves into the air. The timbre of violin tone is also discussed as a final product of the preceding processes. Figure 3.1 is a graphical representation of the basic chain of events involved in violin sound production and also serves as a rough guide to the structure of the chapter.

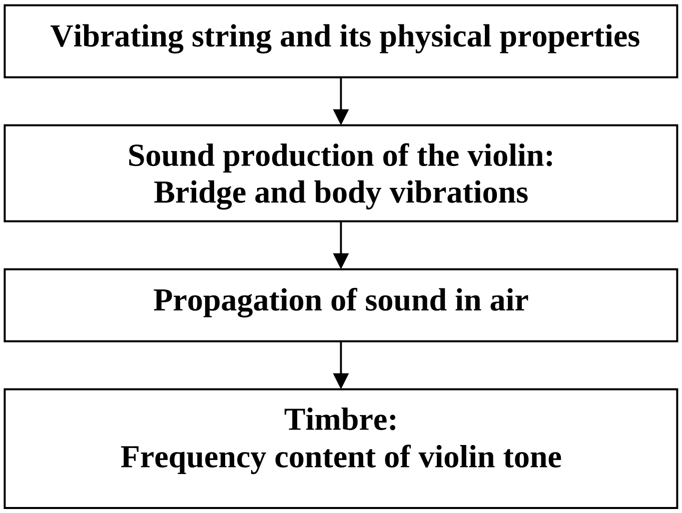


Figure 3.1. The various stages involved in violin sound production, with timbre as an end product.

3.2 Physical properties of a vibrating violin string

3.2.1 Kinematics of the bowed string

What the ear perceives as a continuous sustained sound coming from the violin is in fact a continuous stick-and-slip motion mechanism induced by the frictional relationship between the bow hairs (with resin applied to it to increase sticking) and the string. When a violinist bows the string, before the string slips back for the first time, it sticks to the hair of the bow momentarily. The string is thus removed from its position of rest to a position where it has potential energy (E_p) and therefore the potential to do work. Once the restoring force of the string, due to tension, exceeds the maximum static friction, the string then starts slipping towards its original position. However, the kinetic energy (E_k) induced by the release causes the string upon release to overshoot its normal position of rest when it is caught by the bow to repeat the process. Figure 3.2 is a graphical presentation of the sawtooth-like motion that the string undergoes during the process of bowing.

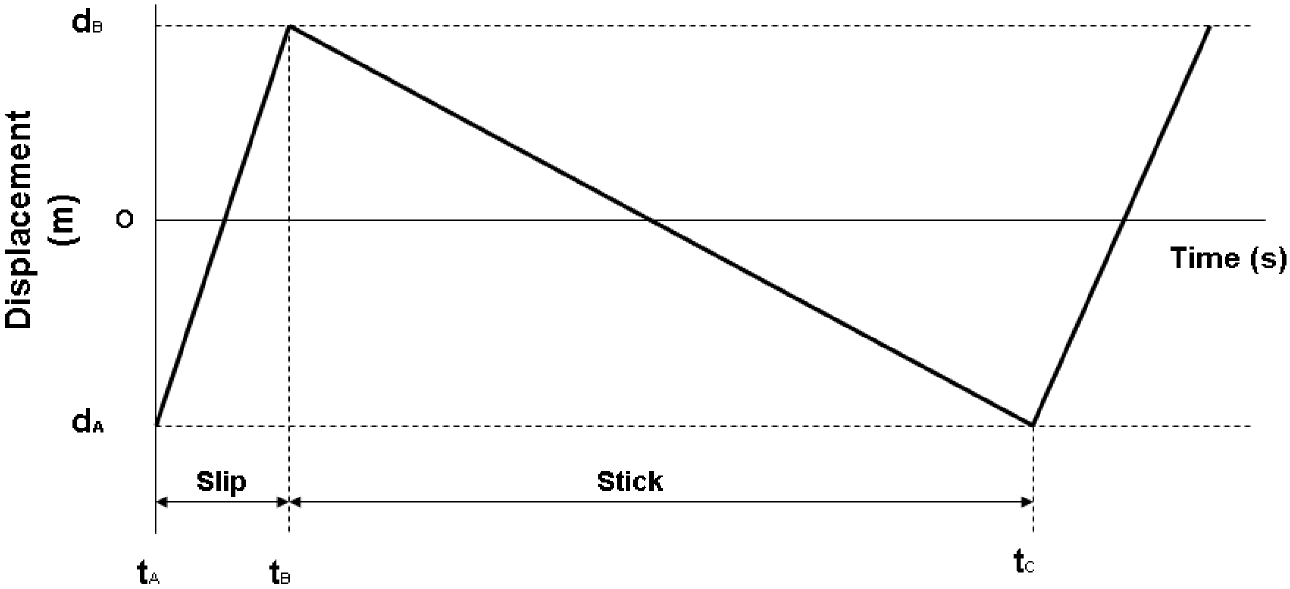


Figure 3.2. Motion of the string during bowing (Adapted from Davis (1908)).

The zero line represents the string's undisturbed position. The dark sawtooth-shaped line represents the string's physical displacement over time. At time t_A, the string is at maximum displacement (d_A) before slipping occurs. From t_A to t_B, the string slips from the bow, overshoots its resting position (zero line) and is caught again by the moving bow at position d_B, (maximum displacement of string in the opposite direction). At time t_B, the string and bow move at the same velocity in the direction of bowing until slipping occurs again at t_C. d_B-d_A = Amplitude of displacement. t_A-t_B = total time of slipping. t_B-t_C = total time of string and bow moving in the same direction. t_A-t_C = time of one period.

The sticking and slipping of the string to the bow during normal bowing is a function of the properties of the two materials, bow hair and string, acting on one another. However, the actual attaching and releasing is governed by a process first observed by Helmholtz (1885)[8]. When the string slips back from its displaced position (t_A-t_B), it does so at a faster velocity than with which it travelled while sticking to the bow. For the sake of simplicity, consider the situation of a single backslap event. Two V-shaped transverse waves are produced and travel in opposite (and perpendicular) directions from the point of disturbance: one towards the bridge and the other along the fingerboard towards the nut. Friction and the "lossy" character of violin strings in general damp out the latter wave so that only the wave going towards the bridge is of real importance in this circumstance (Fletcher and Rossing 1998:50). The remaining wave (the one travelling towards the bridge) induced by the "backslap" of the string is reflected off the bridge and passes through the bow. During this passing the V-shaped wave triggers a stick-action so that the bow and string now move together once again in the direction of the bowing. The wave still travels in the direction of the nut but in an inverted state compared to its initial state at the moment of excitation. Consistent with Newton's action-reaction law (Cutnell and Johnson 1995:533), the nut (or finger) at the far end of the bridge "pulls" at the string and the V-shaped wave is returned to the bow and in its original phase.

As soon as the travelling wave moves under the bow it causes slipping. The process then repeats itself with a newly formed wave travelling towards the bridge. Figure 3.3, adapted from Campbell and Greated (1987:214), is a presentation in time of the so-called "Helmholtz corner" travelling back and forth along the string.

In practice, however, the situation is slightly more complex than a single wave travelling along the string. During the process of bowing, many consecutive waves are produced which race from the bow to the bridge, all the way to the stopping finger and back. These superimpose on one another to ultimately create a complex vibration pattern. The remainder of the discussion on string vibrations will, for ease of explanation, assume the simplified situation. Where necessary, reference will be made to where the situation moves from the simplified theoretical version to the complex practical reality.

---

[8] The description of the motion of the string appears in chapter 5, pp, 80-87.

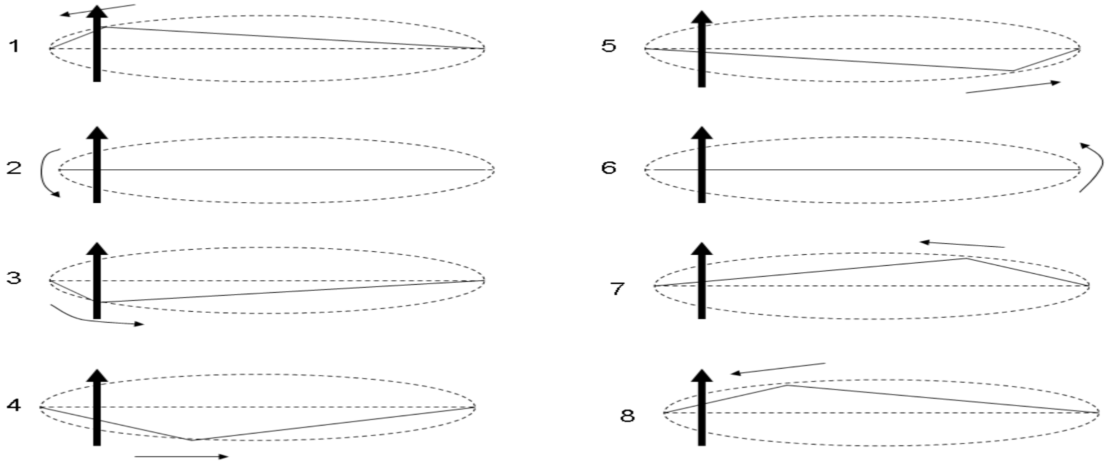


Figure 3.3. Time analysis of the motion of the Helmholtz corner, showing the shape of the string at eight successive times during one cycle. The thick black arrows represent the bow and the direction of movement (Adapted from Campbell and Greated (1987)).

3.2.2 The speed of a wave on a string

The speed at which the V-shaped wave travels along the string determines the perceived note's frequency. If a violinist bows the open E-string the listener perceives a fundamental frequency of 660 Hz. This implies that one slip and one stick action occurs during a wave length, which repeats 660 times in one second. Or stated otherwise: in one second the travelling wave completes 660 round trips from the bow to the bridge, to where the string is stopped and back to the bow again. In yet other words, one round trip lasts 0.0015 seconds in total, during which one stick and one slip action occurs. It can be deduced then that the speed of the wave determines the frequency of the note and not the speed of the bow as is often believed. If the latter were the case, intonation would prove to be an even greater challenge on the violin than it already is. The velocity of a wave on a string is determined by a few factors and can be expressed as follows:

$$v = \sqrt{\frac{F}{m/L}} \tag{3.1}$$

where F is the tension measured in Newton (N) and m/L (kg/m) is the mass per unit length. This leads to the conclusion that the greater the tension between the particles of the string, the more responsive they will be to an energy wave passing through them. Therefore, the higher the tension, the faster the wave travels on the string. The mass of a particle also has an effect on the speed of a wave. Newton's second law of motion states that for a given net force, the magnitude of the acceleration is inversely proportional to the mass. In other words, for a given net pulling force, a smaller mass has a greater acceleration than a larger mass (Cutnell and Johnson 1995:487). When a violinist plays two consecutive notes on the same string but the second one in a higher position (closer to the bridge), the tension of the string remains the same, but the string is shortened (causing lower mass) which renders a faster moving wave and quicker revolutions. This renders faster alternation between slipping and sticking, which shortens the time period of each wave cycle so that the listener ultimately perceives a higher pitch.

3.2.3 Standing waves on a string

The cyclic behaviour of the wave just described causes what is known as a *transverse standing wave*. As the bowing-induced waves travel back and forth along the string they will inevitably meet and pass one another at a certain point. The resultant string displacement at this particular point will be the sum of the travelling waves working in on the point. However, an instant later, once two waves have passed the same point they both emerge on either side with their original identities. The *principle of linear superposition* describes this behaviour (Rossing 1982:36). The vibrating pattern of a string at any moment can therefore be described as a sum total of all the different waves that travel on the string in their opposite phases.

The addition of all travelling waves gives rise to what is known as a *standing wave* on a string because the wave does not appear to move in either direction. Cutnell and Johnson (1995:541) define it as "the pattern of disturbance that results when oppositely travelling waves of the same frequency and amplitude pass through each other."

3.2.4 Description of modes of vibration on a string

> It is this mathematical superposition of (string) shapes, in particular, the proportion of their amplitudes and phases, which defines the physical superposition of harmonics with which the string will actually vibrate (Roeder 1994:105).

It is in this view that we proceed to the idea of vibrating modes on the string. The properties of a vibrating string give rise to a standing wave. However, this pattern of vibration is made up of many smaller standing waves. The back and forth travelling of the transverse waves bouncing from the bridge and from the nut-end superimpose on top of one another during the period of excitation (bowing). When two v-shaped waves meet from opposite directions on the string they will add if their “V’s” are both positive or ‘pointing’ in the same direction. Their relationship is referred to as *constructive interference*. When two waves meet of opposite sign (“V’s” pointing in different directions), they subtract. This is known as *destructive interference* (Rossing 1982:36). The many smaller standing waves that make up the total vibration of the string are a result of continuous constructive and destructive interferences during bowing. These are also referred to as *modes of vibration*. The modes of vibration all occur at different frequencies (and therefore different tones) to make up the harmonic series. The first mode of vibration is known as the fundamental, f, and vibrates at the lowest frequency of the series. The other modes of vibration occur at integer multiples of f so that when the fundamental is 440 Hz, the next mode, $2f$, will have a frequency of 880 Hz. The third mode of vibration in the series, $3f$, will be sounding at 1320 Hz and so forth. Table 3.1 shows the first five modes of vibration and corresponding frequencies of a vibrating open A violin string.

Mode of vibration	**Frequency (Hz)**
f (fundamental)	440
2*f*	880
3*f*	1320
4*f*	1760
5*f*	2200

Table 3.1. Modes of vibration and the corresponding frequencies of the fundamental and first four harmonics of a vibrating A violin string.

3.3 Sound production on the violin

3.3.1 Bridge vibrations

From the above table and description it can be concluded that the string vibrates in a very complex manner, accommodating many different frequencies at any particular point in time, all of which are integer multiples of the fundamental mode of vibration. The sound of the violin is however not produced by the vibrating strings as such. These merely act as the *excitation force* for the sound-producing components of the violin. The role of the body of the instrument is then to convert these string vibrations into sound waves for the listener to perceive. Before the body can perform this necessary task, the bridge has to relay the information from the string to the top plate of the instrument. This process is described below.

Each mode of vibration in the vibrating string “rocks” the bridge to and fro, the extent of which depends on its frequency. The fundamental mode excites the bridge, in the case of an open A-string, 440 times every second. The feet of the bridge relay these tiny vibrations to the body of the instrument. By the same principle, the second mode of vibration (2*f*) obviously excites the bridge twice in the time that the fundamental relays its energy. In this way the entire vibration ‘recipe’ of the string is transmitted to the violin body through the propagation of the energy impulses in the wood of the bridge. These side-to-side oscillations, which are parallel to the direction of the bow, are known collectively as *direct excitation* since the string directly causes a lever-like action of the bridge on the body of the instrument.

Benade (1990:529) defines a second more subtle means by which the string vibrations are able to excite the top plate[9]. The tension of the string goes through two variations of tension during each cycle of the stick-and-slip motion. Now, since there already exists a substantial downward force on the wood due to the string tension, the oscillatory variations of the strings' tension during these cycles cause variation in the downward force. This is known as *indirect excitation*. It must be noted that the indirect way of excitation occurs at twice the frequency of the corresponding direct excitation because of the tension variations occurring twice in each cycle. Therefore, if the first mode of vibration were to act alone on a bridge during normal bowing, the vibration recipe would comprise of both 440 Hz vibrations (direct excitation) and 880 Hz vibrations from the indirect excitation mechanism (Benade 1990:529). The same applies to higher modes of vibration.

The next section describes the processes by which the violin body reworks the vibrations from the bridge into audible sound waves.

3.3.2 Vibration of the violin body: air modes

The way in which the violin body responds to the vibration frequencies relayed from the strings through the bridge is a complicated process. In the ideal case, namely, that of a vibrating string fixed at both ends, vibration modes are present at all the possible frequencies which are allowed for the string length. That is at f (fundamental), $2f$, $3f$, $4f$ etc. with the resulting amplitudes varying as $1/n$, where, n is the vibration mode number. For example, the amplitude of the fourth harmonic would stand in a 1:4 ratio with the fundamental (Rossing 1982:175). The violin string modes appear in the same ratio as in the above case but the various amplitudes are altered by many external factors such as damping and other mechanical variables. The violin body receives these amplitude-altered vibrations and reworks them into sound waves.

---

[9] Structurally, the violin consists of a top plate, back plate, neck, fingerboard and scroll. The bridge relays string vibrations to the body via the top plate.

The body of the violin also vibrates in modes, that is, certain parts vibrate at a certain frequency. Two different systems of vibration are present at all times to produce a complex pattern of air movement that relates to the sound that the violin produces. The first method of vibration is that of air inside the body of the instrument, referred to as *air modes*. The volume, shape and hardness of wood determine the way in which air will behave inside the body of the instrument at a specific frequency. Saunders (1953) documented her findings regarding these modes and arrived at a graphical representation in the form of the so-called *loudness curve*. She found that certain frequency areas are louder in comparison to others if all other conditions, such as bowing, are constant. This is due to a complex set of air vibrating patterns within the violin body. The main air resonance (A^0) or “Helmholtz resonance” occurs at a frequency between C4 (261 Hz) and D4 (293 Hz). At this frequency the top and back plates move out of phase with each other and thereby expand and contract in support of the motion of the air (Marshall 1984:705). Air moves in and out of the f-holes.

The next mode of vibration, A^1, involves end-to-end movement of air between the back and front areas of the body. This implies a horizontal nodal line near the f-holes. This particular mode amplifies a note played near the frequency of 480 Hz. Higher air modes are described by Hutchins (1990). The first seven air modes were found to lie near to the following frequencies: A^0: 284 Hz; A^1: 499 Hz; A^2: 1077 Hz; A^3:1190 Hz; A^4:1340 Hz; A^5:1646 Hz; A^6:1887 Hz (Fletcher and Rossing 1998:292). The fact that certain frequency bands are accentuated by the natural air resonances of the body is of importance to the present study.

3.3.3 Vibration of the violin body: wood modes

In the same way that the air responds to certain frequencies, certain parts of the wood resonate at specific frequency bands. This is not to say that only a small section of wood will be active for a certain played note but rather that the violin plates vibrate in a different way for each frequency. “At a given resonance frequency, different points on the plate vibrate with different magnitudes varying between a maximum and no vibrations” (Jannson 2002:5.4). This occurs as a function of mass, stiffness and internal friction (Jannson 2002:5.11). The main wood resonance (W^1) is found between 440 Hz and 480 Hz, depending on the violin examined. Saunders (1953) is of opinion that this W^1 resonance area causes a significant rise in amplitude for nearly all violins. Although the top plate is primarily responsible for the excitation of the air particles, the back plate is always part of the vibration process, even though the two do not necessarily vibrate in symmetrical sympathy (Marshall 1984:707).

The first four vibration modes of the top plate were found to be in the vicinity of the following frequencies: W^1: 540 Hz; W^2: 775 Hz; W^3: 880 Hz; W^4: 980 Hz (Jannson et al. 1970 in Roeder 1979:111). Benade (1990:533) estimated W^1 to be around 440 Hz and Saunders (1953:495) measured the first wood resonance closer to 480 Hz. It must be added that the measurements of Jannson et al. were performed with the body of the violin only and the neck detached. It is therefore expected that in normal conditions, Jannson's figures would be closer to those of Fletcher and Rossing (1998) and Saunders (1953).

Most of the low register frequencies of the violin playing range are brought about by single resonant properties of either wood or air modes. But, as "the excitation frequency applied to the body by the strings rises, it excites the plates (and air inside the body) into increasingly complicated vibration modes, each one having more modal lines than the one before" (Benade 1990:536). Add to this the collaborative behaviour of wood and air modes at certain frequencies, one is faced with a rather intricate mechanical system of vibration. The exact mathematics of this system is beyond the scope of this study. For the present purpose, it should suffice to understand that the vibration characteristics of the violin are governed by two distinct but interrelated systems, wood vibrations and air vibrations.

3.4 Propagation of sound in air

Sound quality of the violin is governed by the interaction of the instrument's resonating sound board and air flow out of the f-holes, into the surrounding air. Depending on the frequency supplied by the string, the violin body will react with the appropriate vibrations. Hypothetically, if a violin string is excited and all the harmonics are damped except the fundamental mode, the resulting vibration will only be that of the fundamental frequency. Since the properties of a string excited by a bow determine that both even and odd numbered vibration modes are present, we expect the violin to vibrate at those frequencies too, as indicated by table 3.1. To take a practical example, if an open A-string with a frequency of 440 Hz is bowed, we can expect the vibration modes of the string to excite certain parts in the violin body which in turn induce pulsations in the air at that frequency. Thus, according to table 3.1, pulsations in the air should be present not only at 440 Hz but also at frequencies 880 Hz, 1320 Hz, 1760 Hz etc.

The pulsations of the wood during vibration on the outside air bring about variations of pressure. When the vibrating wood bulges outwards, the layer of air in contact with it will also be forced in the direction of motion. This layer of air cannot move freely as it is inhibited by the layer of air right in front of it. After a while of pushing between these two layers, the next layer is also compressed against the next etc. In the meantime, the wood has moved backwards. The air right next to it now has a larger volume to fill and causes the air pressure to drop below normal atmospheric levels (Campbell and Greated 1987:23). The next layer of air rushes back to the reduced pressure area which ultimately causes a pulse of decompression to follow that of the compressed pulse. As the wood of the violin moves inwards and outwards a series of pulses are transmitted into the outside air. These pressure variations are known as sound waves or *longitudinal wave motion.*

In section 3.2 it was stated that when a string is displaced from its position of rest, a "restoring" force acts in the opposite direction towards its position of rest. The same force is present in the vibrating body. When it moves outwards, it reaches a distance of maximum displacement from where it moves back past the point of rest to repeat the process. When the restoring force of a vibrating object is proportional to its displacement, as in this particular case, the object is said to be in *simple harmonic motion* (Rossing 1982:18). The resulting longitudinal air wave gives rise to a pure tone (Wood 1962:5).

For a particular point on the body of the violin, such motion is known as sinusoidal and can be graphically presented by a displacement-time graph.

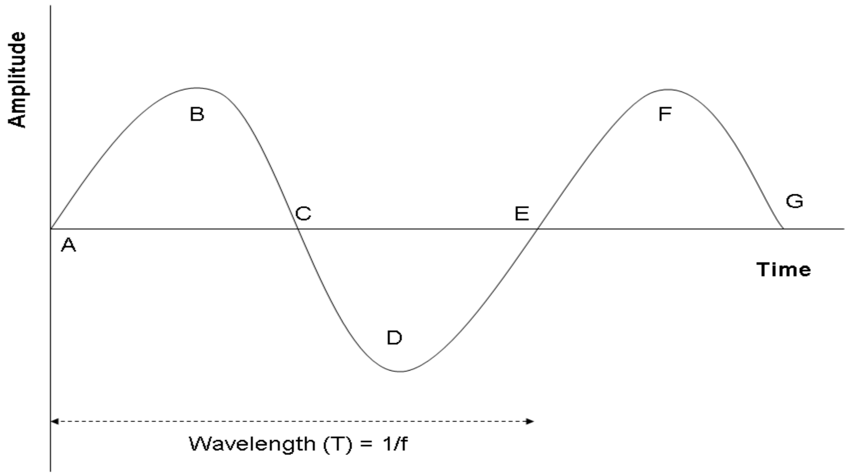


Figure 3.4. Presentation of sinusoidal motion of air waves.

When a body is in simple harmonic motion the resulting displacement curve is sinusoidal as seen in the figure 3.4. *ACEG* represents the undisturbed state of the wooden plate. *BDF* represents areas of maximum displacement. *B* and *F* are crests, outward bulging of the surface and, *D* is a trough and maximum backward displacement. Two important qualities of the sound wave can be deduced from the above graph. Firstly, the amplitude, which is the "maximum excursion of a particle of the medium from the particle's undisturbed position" (Cutnell and Johnson 1995:484). This is represented by the perpendicular distance between *A* and *B*, *C* and *D* and *E* and *F*. The next bit of information that can be deduced from the graph is that of the frequency of the wave, or how many times per second a wavelength repeats itself. A wavelength is the horizontal length of one cycle of the wave as indicated by *AE* in the graph. The period *T* is the time required for one complete up and down cycle. The period T is related to frequency in the following way:

$$f = 1/\mathrm{T} \tag{3.2}$$

so that when the time required for one up and down cycle is 0,00227 seconds, the frequency of the wave will be 440,53 Hz. The sound emitted by the violin is however significantly more complex than the simple harmonic motion just described. It was stated in section 3.2.4 that during normal string vibration, certain modes of vibration on the violin body is excited simultaneously to reproduce the vibration recipe passed on from the string. This implies that the modes of vibration in the string recipe will excite only the wood modes and air modes whose resonant frequency matches those present in the string, each mode having its own frequency and amplitude.

3.5 Frequency content of a violin tone

In the 18th century, the French mathematician J.B. Fourier (1768-1830) showed that any signal that can be generated can alternately be expressed as a sum of sine waves of various frequencies, each having its own amplitude and phase (which will be addressed in a later section) (Brice 2001:14). His theorem states that:

> Any periodic vibration, however complicated, can be built up from a series of simple vibrations, whose frequencies are harmonics of a fundamental frequency, by choosing the proper amplitudes and phases of these harmonics (Rossing 1982:115).

Figure 3.5 demonstrates how a sawtooth wave is constructed by the addition of sine waves according to formula 3.3. Formula 3.3 is known as the Fourier[10] series representation of a sawtooth wave.

$$x(t) = \frac{2}{\Pi}\sum_{k=1}^{N}\left(\frac{\sin(2\Pi kft)}{k}\right) \tag{3.3}$$

The violin sound signal also adheres to this theorem. The change in wave shape (in Figure 3.5) is accompanied by a change in timbre; from a pure-sounding tone to a harsh-sounding one when it has turned into a sawtooth shape.

To further demonstrate the theorem of Fourier, a pure sine wave and a saw tooth wave of 440 Hz was generated[11] in Csound[12] at a sample rate of 44.1 kHz and 16-bit resolution. Figure 3.6 shows a displacement-time graph of a sine tone with an accompanying FFT (Fast Fourier Transform) spectrum. Figure 3.7 shows the same for a sawtooth wave.

---

[10] For a description and further reference to the Fourier formula, see Sethares (2005: 333-341).

[11] A track list and accompanying audio CD of the sounds generated, recorded, or sampled for the purpose of the thesis is available in Appendix A.

[12] For more information visit: http://www.csounds.com/. Coding for all synthesis, calculations etc. performed in Csound and Matlab throughout the project is available in print in Appendix B.

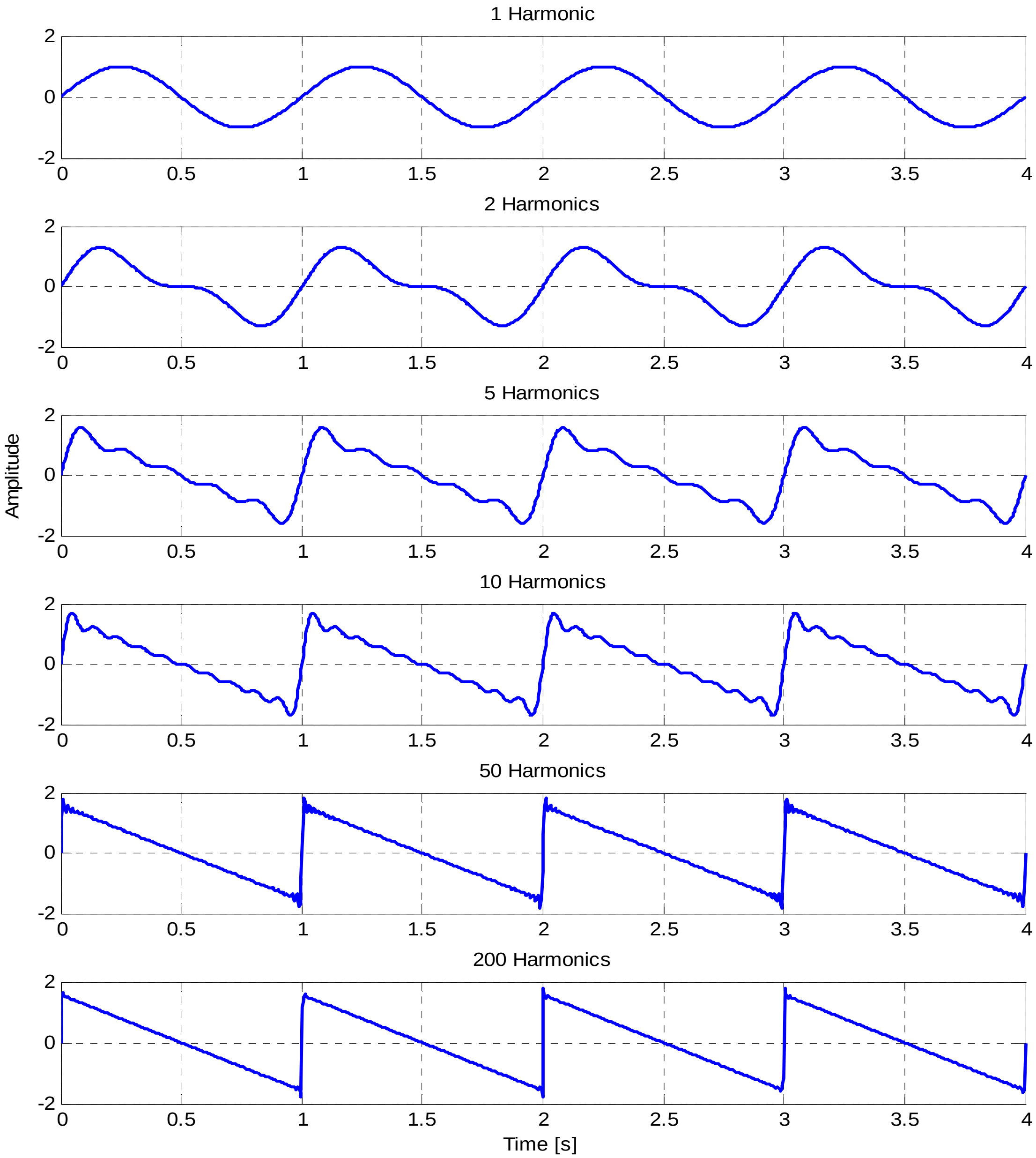


Figure 3.5. Demonstration of how the addition of sine waves according to formula 3.3, results in a sawtooth wave.

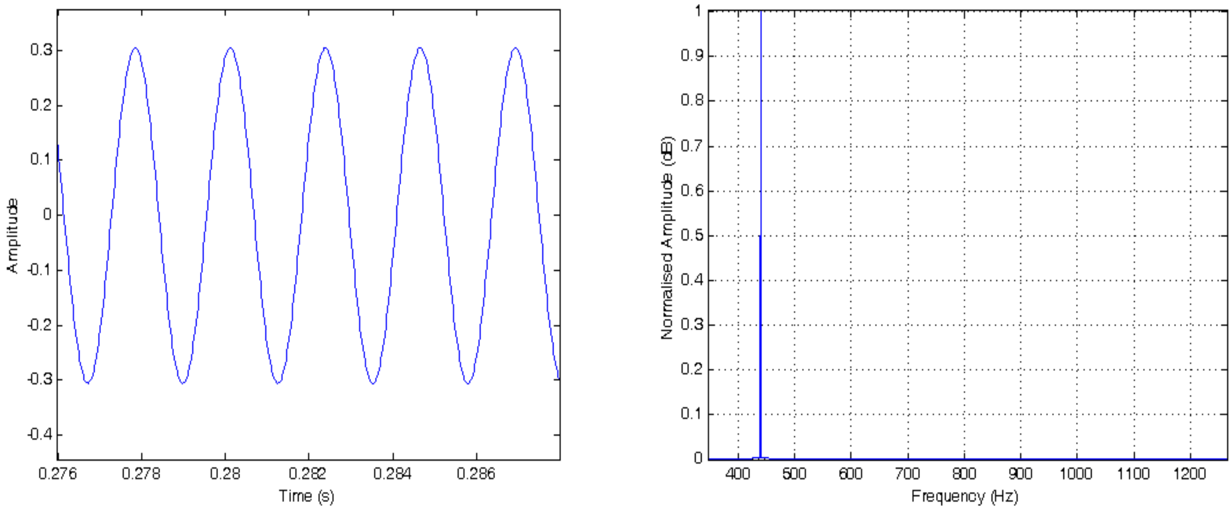


Figure 3.6. Presentation of a Csound 440 Hz sine tone. Left: Amplitude-time domain Right: Fourier domain.

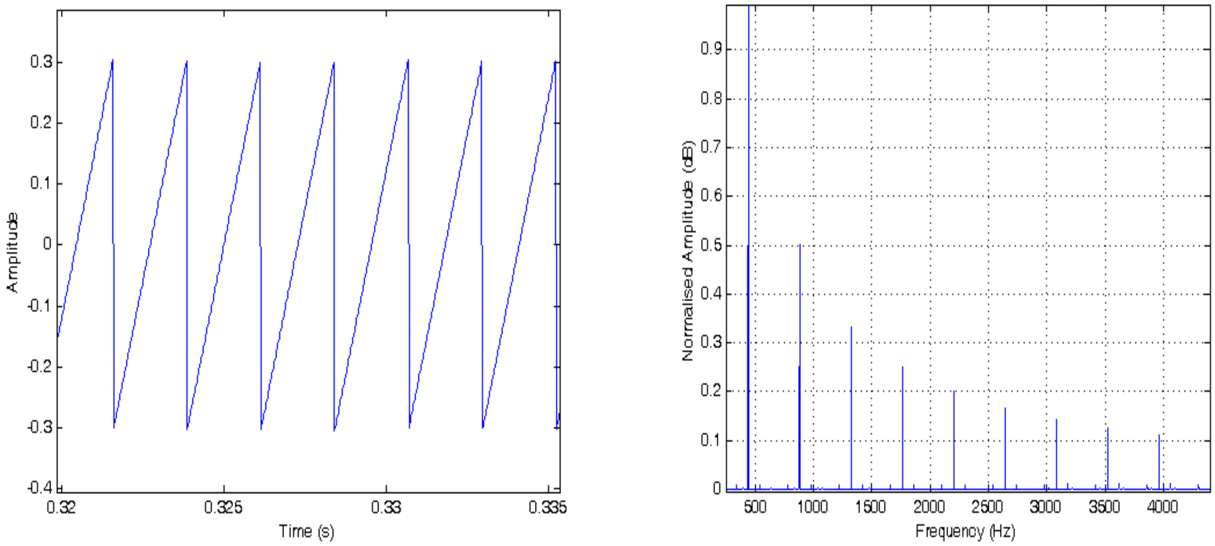


Figure 3.7. Presentation of a Csound 440 Hz sawtooth tone. Left: Amplitude-time domain Right: Fourier domain.

If we analyze a violin tone, we note that the displacement curve of a few cycles represents that of a sawtooth as in figure 3.7. However, the shapes of the above figures differ somewhat from that of the real violin tone (see figure 3.8). The difference between the real and synthesized tone is due to the 'non-ideal' properties of the strings and other factors such as bowing and type of wood used for the instrument etc. In a way, the violin body acts as a filter that either amplifies or attenuates certain components of the sawtooth wave, depending on which modes of vibration are activated or not.

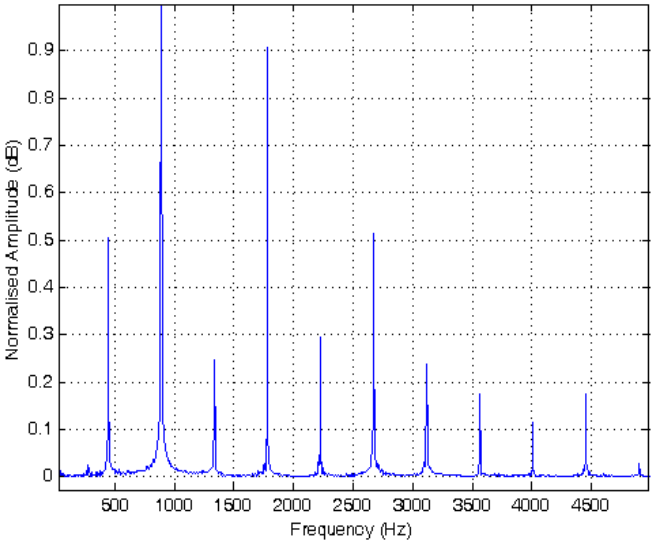


Figure 3.8.Presentation of a 440 Hz violin tone.[13]

It must be added here that a different violinist playing a different instrument would yield a completely different spectrum. The timbre of an instrument is determined by many other variables and these are described below.

3.6 Timbre

The filtering characteristic of the violin, to a large extent, determines its *timbre* or tone quality. The definition of timbre is problematic since it does not only depend on the filtering of the various harmonics but on a few other variables present in a natural occurring musical note. Authors therefore generally describe timbre as the "multidimensional" attribute of a musical sound as opposed to its duration, frequency and amplitude that can be represented with a single figure. "It (timbre) is the perceptual attribute that enables us to distinguish among orchestral instruments that are playing the same pitch and are equally loud" (Risset and Wessel 1999:113). The determinant variables of timbre

---

[13] All the notes used for analysis in the third and fourth chapters of this thesis were performed by Renate Riedemann. For the recording she played on a Kotie van Soelen violin. The date of construction is unknown. The recording and analysis of the samples were performed by the present researcher in August 2007 at the Konservatorium of the University of Stellenbosch.

have been researched by Grey (1977), Campbell and Greated (1987), Butler (1992) and Sethares (1992), etc. From these authors we conclude that the perception of timbre is influenced by five variables: the behaviour of onset transients, spectral energy distribution or formant regions, the change of energy distribution over time, noise and artefacts and directional radiation properties. These variables are discussed below.

3.6.1 Onset transients

When the string of a violin is excited it does not reach its full volume straight away. The different harmonics present in the vibration recipe of the string are turned into audible sound at different rates and volumes over the duration of the attack time, otherwise known as the *onset transient* of the vibration (Campbell and Greated 1987:157). The different harmonics swell and decrease in an arbitrary manner until it settles into the sustain portion of the musical sound. These transients have been found to be “intrinsically complex and they are not reproducible from one tone to another even if they sound very similar” (Risset and Wessel 1999:117). Musical instrument families have unique characteristics concealed in these attack times which influence the identification of the instruments. It has been found that instrumental tones sound confusingly alike when the attack portion of instruments’ tones is removed (Butler 1992:74).

3.6.2 Formants

The classical view of timbre has been that the steady state portion (after the attack) was the sole determinant of an instrument’s timbre. The view was supported by Helmholtz (1885), one of its main proponents, and he was aware that certain peculiarities of the musical tone was present in the attack and decay portions but still only studied the tones that continue uniformly. Of course no human-produced acoustical instrument tone is perfectly steady-state but changes from one millisecond to the next. Helmholtz recognized in his slightly erroneous study of timbre, certain areas of resonance which amplify certain frequency areas. These are known as *formant regions* and are caused by the distinctive size and shape of the instrument in question. “The number, breadth, and relative strengths of these formant regions help to shape the distinctive waveform that makes the tone colours of voices and instruments identifiable" (Butler 1992:74). A formant is therefore a special resonance area in the frequency spectrum of a musical tone that adds to its unique timbre.

3.6.3 The envelope

The envelope of a sound is a representation of how a tone evolves over time and consists in theory of four time intervals: attack, decay, sustain, and release, otherwise known as the ADSR or dynamic envelope of a sound (White 2002:9). Our perception of timbre is influenced by the way in which the overall amplitude of a sound evolves over time. Grey (1977) refers to this as the "spectral fluctuation" of a tone and George (1954) demonstrated its importance in timbre recognition by time-reversing a piano tone. The reversed sound sounded nothing like a piano although the spectra of the sound remained the same. Figure 3.9 is a graphical representation of the typical dynamic envelope of an instrumental tone.

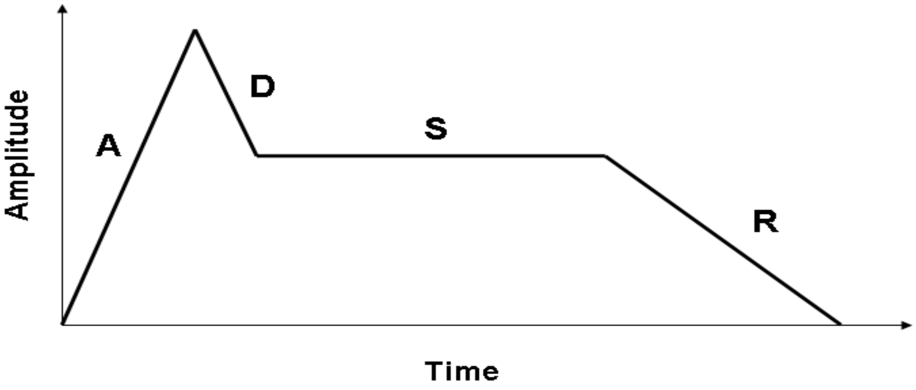


Figure 3.9. Graphical presentation of the ADSR of a typical instrumental tone.

3.6.4 Noise and artefacts

Upon close inspection of the sound spectrum of the violin tone in figure 3.8 the reader will notice that there is often some low level energy present at almost all the frequencies visible on the graph. Two sources are responsible for this visible (and audible) departure from the idealized spectra: noise and artefacts (Sethares 2005:11). The noise could be caused by mechanical irregularities such as bowing, picking, finger noise on the strings, and electronic noise from the recording equipment, etc. which manifests in the sound spectrum. Artefacts are visible-only “edge effects” created by computational errors in “windowing” that causes spectral representation of sounds to “smear out” to other frequencies (Sethares 2005:334).[14] The noise caused by the mechanical action of sound production adds to the timbre of specific instrument families. The noise of the violin bow, the puff of air when the flautist starts a note, etc. all add to the unique timbre of each instrument.

3.6.5 Directional radiation

The term “directional tone colour” or “directional timbre” refers to that property of violin sound production which determines that the same played note will have a different timbre depending on which direction relative to the performer it is perceived from. This idea was put forward by Weinreich (1997) who studied the radiation properties of violins. Weinreich found that frequencies below ± 880 Hz radiate omni-directionally from the instrument body and frequencies above that are projected directionally in “wildly irregular” angles into the surrounding air. This is a result of the various wood vibration modes positioned at different places on the instrument body (discussed in section 3.3.3) and due to the vibration properties of the asymmetrical internal structure of a typical violin. These results are confirmed by Wang and Burroughs (2001).

The “directional” description of frequency behaviour above 1 kHz could be misleading. This does not imply that frequencies not directly travelling towards the listener are lost in the surrounding air and not heard at all. The listener is still very much aware of these frequencies but not at their optimal amplitudes. The “direction” in which a specific frequency radiates is thus more a description of the angle at which that frequency propagates from the instrument at its *optimal* amplitude.

Now, the fact that it is only frequencies above 880 Hz that are radiated in different directions means that it is mostly the upper harmonics (see section 3.2.4) of any violin note that are scattered about. The timbre of violin tone, and any instrument for that matter, is to a large extent determined by the relative amplitudes of these upper harmonics. Therefore, if a violinist for example calmly bows a single note and another person would walk around the instrumentalist, he/she would experience a constant change in timbre. The listener will still constantly hear the same note but pass through areas where some

---

[14] This is of course not audible as in the noise effects and only visible in the resulting spectrum. For further reading on this topic consult Sethares (2005:333-341).

harmonics radiate “directly” towards the ear, while at other times they would be suppressed and others will sound louder.

Consider the situation from a different perspective, with a violinist on stage and a stationary audience member. The listener will still hear the unmistakable timbre of a violin as the performer plays along, and possibly the unique timbre of that specific instrument but the scattering harmonics determines that every note’s composition will differ slightly and thus create a rich and “mysteriously fascinating” sound (Weinreich 1997:2344).

This aspect of violin sound has important implications for the appreciation of vibrato. The slight movements of the vibrato finger on the string causes periodic “wildly irregular” frequency ‘beaming’, which according to Wang and Burroughs (2001) may be a reason why vibrato is such a captivating element of violin performance.

3.7 Conclusion

This chapter discussed the principles of violin sound production. It started off with the description of how the bowing mechanism induces various modes of vibration on the string that are subsequently relayed through the bridge into the body of the instrument. The processes involved in converting the vibration information from the string and bridge into audible sound waves were presented. It was also illustrated that the violin tone consists of not only a single frequency but of many specially arranged harmonics which to a large extent determines the sound quality or timbre of the instrument. Following on chapter 3’s basic description of the violin sound as a steady acoustic event, chapter 4 continues the exploration of the nature of vibrato by describing the sound when it is periodically changed by the action of vibrato.

Chapter 4

Fundamentals of violin vibrato

4.1 Introduction

Violin vibrato is the action by which a violinist periodically changes the frequency of a sustained note by moving the stopping finger rapidly backwards and forwards[15] along the string. The current chapter builds upon the foundations laid in chapter 3 for the steady-state violin sound and explores the science of the *changing* sound brought about by the moving finger.

This chapter comprises of three main sections. Section 4.2 discusses the basic fluctuating qualities of vibrato and provides the cornerstone for the rest of the chapter. Section 4.3, which is more experimental in approach, documents first-hand and in-depth research on the frequency content of various synthesized sounds with vibrato. This provides a ‘sterile’ environment where vibrato parameters can be turned on, off, enlarged, exaggerated etc. in order to better understand the rather complicated real-sound situation. Section 4.4 discusses the real violin vibrato tone. All the graphs presented in this chapter were generated by the current researcher.

Before we uncover further technical detail it is important to understand the principles of scientific vibrato-study laid down by one of its pioneers, Carl E. Seashore. Firstly, all that is conveyed from the performer to the listener is conveyed through sound waves (Seashore 1947:18). All emotions, feelings, musical ideas, etc. are properties of the successive sound waves leaving the instrument and reaching the listener’s ear. Secondly, he states that the sound wave can be defined by its four basic properties: frequency, intensity, duration, and timbre. Frequency in this case refers to the subjective perception of the fundamental pitch of the sound wave, intensity denotes the perceived loudness of the sound wave, duration is the continuum of time in which the acoustic event is active, and timbre[16] refers to the subjective tone quality of the wave.

---

[15] Refer to Chapter 1.1 for a description of this action. This type of “rolling” vibrato is different from the “bending”-type used by electric guitar players where the finger does not roll on the string but remains in one position and bends the string up and down to induce a change in frequency.

[16] It seems that Seashore’s description of timbre only refers to the relative strengths of the harmonics present in the sound wave and thus neglects the other factors mentioned in chapter 3 which also contribute to this quality.

One of Seashore’s memorable contributions to aesthetics in the scientific study of music is his so-called “principle of deviation”. He argues that beauty in music and individuality is governed by a performer’s artistic deviation from the regular. An exact note-for-note rendition of a musical score with perfect pitch, uniform amplitude, metronomic timing and, timbre-wise, a pure tone, would yield a rather boring performance. Artists therefore “deviate” from the regular for the reasons given above. Seashore (1937) proved the worth of his principle by scientifically measuring a performance of “Tzigane” by Ravel played by Yehudi Menuhin, amongst other performances. The artist’s performance is documented on a “performance score” which is “a graphical representation showing the character of the performance in minute detail” (Seashore 1937:28). Seashore proved that during performance, the artist indeed deviates from the four elements of the sound wave for artistic purposes. Frequency is measured in terms of Hertz deviation from the note indicated in the score; dynamic deviations are measured in decibel deviation from a standard reference amplitude; timing variations are measured as the number of milliseconds deviated from metronomic time, and the timbre deviations are measured in terms of the distribution of energy amongst the various harmonics in the spectrum (Seashore 1947:74).

The present discussion regarding the physical nature of vibrato is closely related to the pioneering initiative of Seashore. Vibrato on the violin is interwoven in the sound wave presented by the performer to the listener and deviates from the “real tone” in three of the four elements of the sound wave over a continuum of time: frequency, intensity and timbre, producing a complex and “breathing” sound event with added musical life and warmth.

4.2 The physical nature of violin vibrato

Violin vibrato has been found to oscillate in three different ways, not only in frequency as it is often believed (Fletcher and Sanders 1967; Seashore 1931). Violin vibrato (and singing voice as documented by Seashore) induces intensity as well as timbre variations in addition to the obvious frequency variations. The three varying quantities oscillate periodically as a function of vibrato rate and extent but not necessarily in phase. That is to say that as the frequency increases with the roll of the finger forward during a vibrato cycle, the intensity will also change but not always in an increasing manner such as the frequency. It might very well be that a rise in frequency is accompanied by a decrease in intensity. The same applies to timbre which changes periodically as the various intensities of the harmonics present in the waveform change arbitrarily relative to one another. Perceptually it is difficult to separate these changes as they fuse during the auditory process into a single acoustic event. It is however possible to study the three oscillating quantities separately and rather thoroughly at that, with the aid of some specialized computer analysis programs. Sections 4.2.1 to 4.2.3 describe the nature and basic principles of each of the three observed oscillating quantities and follow the description of Fletcher and Sanders (1967).

4.2.1 Pitch vibrato

Let's first consider what physically happens on the violin string during vibrato. When the finger stopping the string moves forwards (or backwards), it changes two properties of the string: its mass (for the vibrating length) and the length. We know from equation 3.1 in chapter 3 (stated again below for convenience) that the velocity of a wave on a string is determined by three factors: tension, length and mass.

$$v = \sqrt{\frac{F}{m/L}} \qquad (3.1)$$

The tension is obviously not changed but the mass and length is. The slip-and-stick motion of the bow is caused by waves running back and forth along the string and because these waves now have a shorter travelling distance than before, it causes a more rapid exchange between kinetic and potential energies. The result is quicker slip-and-stick variations. Consequently there is now a higher fundamental frequency which induces its own set of harmonics that are integers of the new played note. Pitch vibrato is thus the periodic change in frequency by way of the process described above.

Violin vibrato involves a continuous rolling of the finger backwards and forwards across a centre position. It was found that the pitch perceived by the listener is the mean of the vibrato extent for a specific note (Brown and Vaughn 1996:1733) or then the centre position. The perceived pitch is then really an aural illusion. On closer inspection it can be observed that pitch vibrato involves the oscillation of the fundamental frequency continuously and only very briefly passes the position on the string that would in non-vibrato conditions produce the same pitch.

Figure 4.1 illustrates the latter statement. The mean pitch of 371.60 Hz is only heard for a fraction of each cycle, yet produces a clear perceptible pitch.

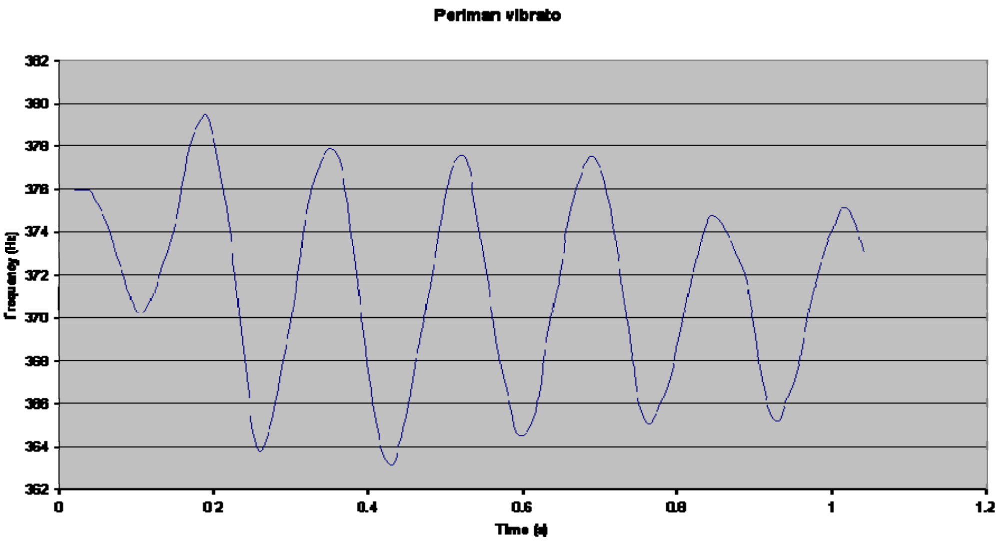


Figure 4.1. Pitch contour graph of Perlman playing an F#4 (bar 60) of Brahms violin Sonata Op. 78. Minimum pitch: 363.16 Hz. Maximum pitch: 379.43 Hz. Mean pitch: 371.60. Pitch contour extraction performed in Praat, version 5.0.05 (Sound source: Bach, J. 1988. *Sonaten und partiten*. Itzhak Perlman. 0772 749455 24 DP. Holland: EMI Classics).

Figure 4.1 presents the change in pitch over time. The graph shows six maxima and six minima which indicate an approximate vibrato *rate* of 6 Hz. The vibrato *extent* is the difference in cents[17] between the maximum and minimum frequency excursions[18].

4.2.2 Intensity vibrato

There are two prevailing theories regarding the existence of intensity vibrato. The first presumption is that fluctuations in intensity during pitch vibrato are caused by mechanical means, namely between the intentional moving of the finger on the string and the unintentional behaviour of the bowing mechanism (Reger 1931). As the finger moves backwards and forwards on the string it changes the mass and length of the vibrating part of the string. This not only alters the pitch but also the friction between the bow and the string which, during the rising section, now slips back to its resting position

---

[17] One cent is equal to 0.01 of an equal tempered semitone.
[18] Consult section 5.3.2 for the method of analysis in this example.

and beyond with greater speed than during bowing with steady intonation. Reger explains that this has the same effect as drawing the bow across the string with greater speed which may result in an increase in intensity. This claim is confirmed by Askenfelt (1989). Reger (1931:331) further suspects that the finger and bow movements are accompanied by pressure variations in the bow arm. These movements, whether intentional or unintentional, somehow synchronize in a periodic fluctuation of intensity. The fact that the periodicity is sometimes in phase with the pitch changes, and at other times not, is governed by “antagonistic or summative effects of the various types of movements at the point of contact between the bow and the string” (Reger 1931:331).

Reger is unable to explain exactly why these amplitude changes occur and his views are speculative. A more plausible explanation for the occurrence of amplitude modulations is governed by the theory that the various harmonics of each newly found fundamental frequency during pitch vibrato vary in their collective intensities. In other words, as the vibrato finger moves from one position to the next, it is not only the fundamental frequency that changes but also the various intensities of each of the harmonics within the spectrum of these fundamentals. The amplitude of the sound wave at any given point on the time abscissa is the sum of the various harmonics. What is observed between a trough and a crest during intensity vibrato, therefore, are two different ‘amounts’ of harmonic amplitudes added together.

The unpredictability of the phase of the intensity modulation as compared to that of pitch modulation is better explained by the latter theory. In section 3.3, it was stated that the violin produces sound fairly unpredictably by the occurrence of body and air vibration modes. These modes enhance frequencies which are excited near or at their natural resonance frequency. Frequencies that do not fall in a range where a vibration mode is active would yield a lower intensity. Therefore, the rolling finger ‘switches’ as such between areas of resonance. Instruments’ resonance areas differ from one another and so does the vibrato extent of each player. Also, in a certain playing position, the upper frequency area of the vibrato cycle may lie in a ‘dead’ area and the lower frequency may be positioned on an active resonance spot and vice versa. This explains the unpredictability factor observed by Reger (1931). It is also possible that Reger’s mechanical theory and the latter theory could interact to produce the observed results. Figure 4.2 demonstrates the amplitude variations present during violin vibrato. The figure presents the amplitude domain of the note played in figure 4.1.

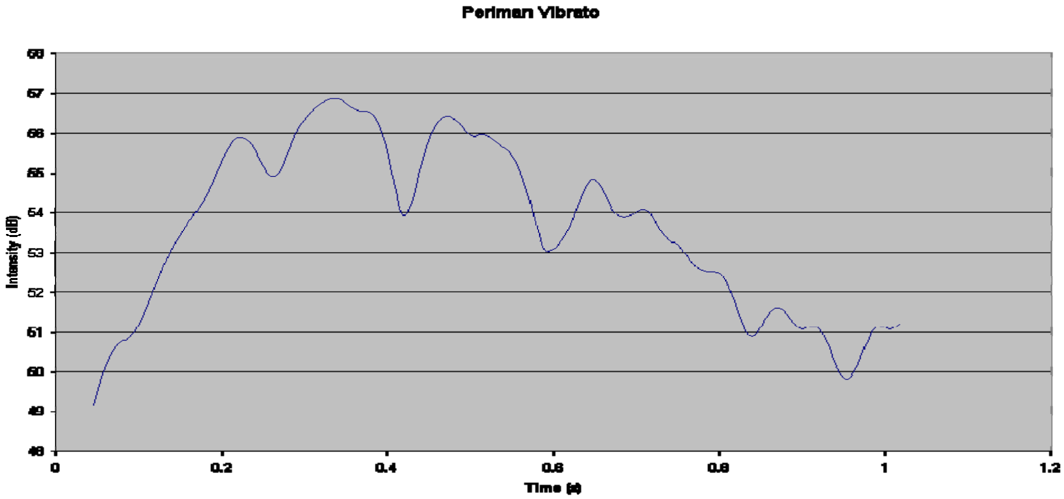


Figure 4.2. Amplitude contour graph of Perlman playing an F#4 (bar 60) of Brahms violin Sonata Op. 78. Minimum Intensity: 49.15 dB. Maximum intensity: 56.86 dB. Overall contour is determined by mechanical means such as bowing pressure and speed etc. Finer contour lines are thought to be a result of the different closely-spaced resonant regions present in the violin body. Pitch contour extraction performed in Praat, version 5.0.05 (Sound source: Bach, J. 1988. *Sonaten und partiten*. Itzhak Perlman. 0772 749455 24 DP. Holland: EMI Classics).

4.2.3 Timbre vibrato

Timbre is a "multidimensional" attribute of sound. It is determined by a few variables changing constantly within the duration of the played note and from one note to the next, even when it is played by the same violinist on the same instrument. Amongst all the changing variables, the relative strengths and positioning of the harmonics of a tone also influence the way in which an instrument sounds. Timbre vibrato refers specifically to the changing of the harmonics during the rolling motion of the finger on the string. Figure 4.3 is the spectrogram of the same note discussed in sections 4.2.1 and 4.2.2. The darker areas present frequencies with a higher intensity than the lighter shaded areas. Notice the periodic strengthening and weakening of certain frequency bands which produce the change in timbre.

Any note played on the violin consists of not only the fundamental or the actual note in the score, but also of a series of accompanying harmonics. Since the pitch changes continuously during vibrato, it can be expected that the harmonic series will behave in the same manner. The kinematical principles of the bowed string determines that of all the possible standing waves, only those that have nodes at the bridge and stopping finger are "permitted" to exist (Roeder 1979:94). For example, when the pitch of

A, 440 Hz, is increased by a semi-tone (by the rolling of the finger upwards) to Bb, 466.16 Hz, the harmonics ‘permitted’ to vibrate with that frequency will also be integer multiples of the fundamental as in the case of the A 440 Hz in table 3.1 in chapter 3. The integer multiples will then be $2f = 932.32$, $3f = 1398.48$, etc. When the finger of the player moves down the neck of the violin from the initial 440 Hz position to G# = 415.31 Hz, the process remains the same with the related upper harmonics changing to: $2f = 830.62$ Hz, $3f = 1245.93$ Hz etc.

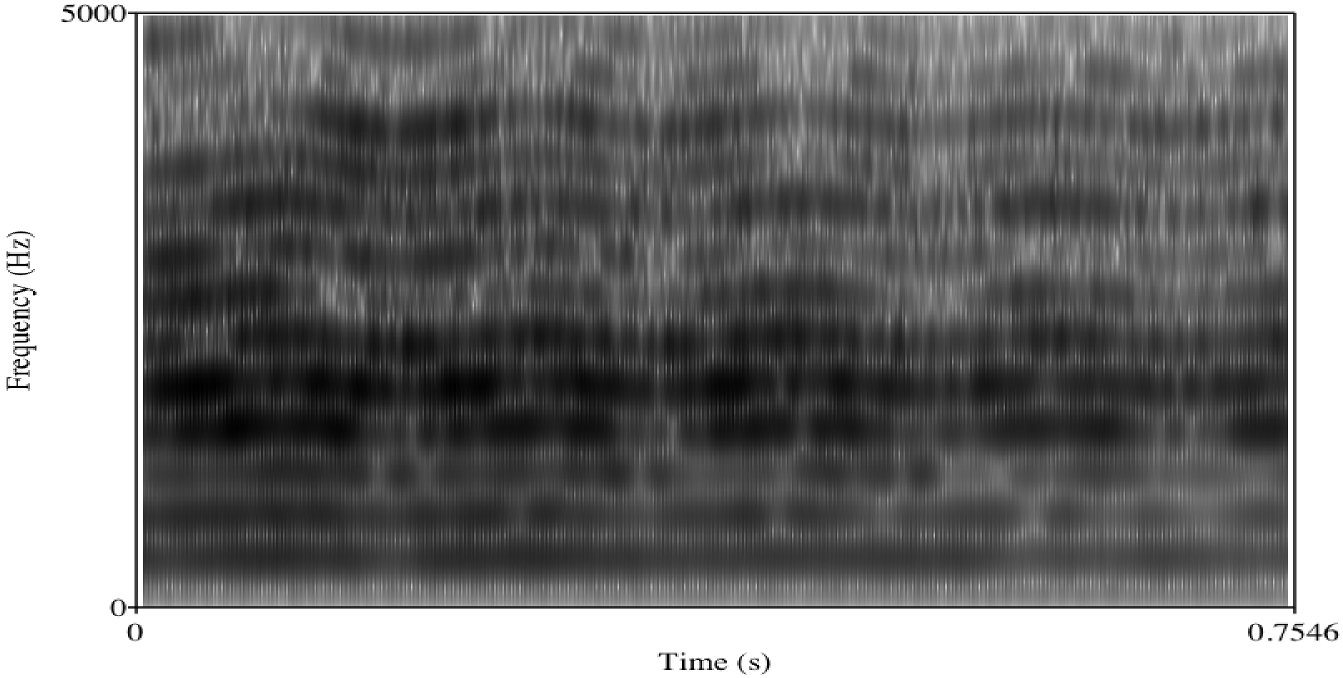


Figure 4.3. Spectrogram of Perlman playing an F#4 (bar 60) of Brahms violin Sonata Op. 78. Spetrogram extraction performed in Praat, version 5.0.05 (Sound source: Bach, J. 1988. *Sonaten und partiten*. Itzhak Perlman. 0772 749455 24 DP. Holland: EMI Classics).

Now, intensity vibrato and timbre vibrato are closely linked. At any given time corresponding to a common point on the time abscissa, a note played with vibrato has both a relative intensity level (in decibels, dB’s) and an accompanying spectrum. The intensity level at that point is the sum of all the intensities in the spectrum. Timbre vibrato is concerned with the variation of the *individual* harmonics since it is that arrangement that alters the timbre. Fletcher and Sanders (1967) studied the changing timbre during vibrato and found that the harmonic spectrum corresponding to the maxima of the frequency level (the upper position of the finger during vibrato) were similar and those corresponding to the minima were also similar. The two sets were however very different. This statement is confirmed by figure 4.3 with the visible repeating patterns of energy distribution.

The harmonics of a violin tone will always be integer multiples. For all practical purposes it can be assumed that every tone will have a fixed harmonic structure. The intensities are however not fixed as found by Fletcher and Sanders (1967). The reason lies in the vibration properties of the instrument. The harmonics of any fundamental is spread out over a wide range of frequencies that may lie in the already mentioned resonance areas. Some may be more enhancing than others. As the frequency changes periodically, so does the frequency enhancing (or reducing), all in phase with pitch vibrato. Weinreich (1997) found that above ± 800Hz the radiation of the violin becomes directional and irregular which implies that it is possible for every harmonic to be radiated in a different direction. Weinreich (1997:2344) says that "the effect (of the changing timbre) can be visualized in terms of a number of highly specialized sound beacons, all of which the vibrato causes to undulate back and forth in a highly organized fashion." These "sound beacons" are of course specialized in both their selectivity in terms of which frequencies they enhance and in which direction the favoured frequencies are emitted. This claim is supported by Wang and Burroughs (2001).

4.3 Principles of frequency and amplitude modulation

The discussion above broadly defined the three types of vibrato that were found to oscillate periodically during a note where vibrato is present. It described the rise and fall of pitch, intensity and timbre from a moment-to-moment point of view. Vibrato is as such not perceived as a moment-to-moment change of three types of simultaneous oscillations but as a single auditory event with added life and character. The perception of vibrato will be described in a later section but for now it aids in our understanding to view theses changes over time as a single event and demonstrate graphically what we hear as violin vibrato.

A Fourier presentation of a violin tone played with vibrato is noticeably more complex compared to the similarly presented sawtooth wave spectrum described in chapter 3. There are many more frequencies present which are not necessarily related to the fundamental frequency (as was the case with steady-state violin tones). In order to make sense and understand the extra information present in the spectrum we turn to the fields of telecommunication and sound synthesis for some applications that may clarify this.

Before doing so, it must be clarified that the current discussion concerns the overall timbre or entire duration of the vibrato note (assuming that the note is steady-state and the vibrato rate and extent remains constant) and not the changing timbre from moment to moment. This is not unlike standing back from a painting and grasping its true meaning as opposed to being too close and only observing individual brush strokes. In order to explain the “new” perspective it is important to understand the overall effect of frequency modulation and amplitude modulation, to which the discussion now turns.

4.3.1 Frequency modulation (FM)

Frequency modulation refers to the normal pitch fluctuation induced by the backward and forward movements of the finger on the string. In synthesis and communication terminology the pitch played (before vibrato) is known as the *carrier wave* and the superimposed wave caused by the moving finger is the *modulating wave*, each having its own frequency and amplitude. “Frequency modulation is when the frequency of the carrier wave (F_c) is varied above and below its unmodulated value by an amount proportional to the amplitude of the signal wave (A_m) and at a frequency of the modulating signal (F_m), the amplitude of the carrier wave (A_c) remaining constant” (Illingworth 1998:228). This is exactly what happens during frequency vibrato: The carrier wave is modulated by an extent equal to the amplitude of the modulating wave and the rate at which these fluctuations occur are equal to the frequency of the modulator. In practical terms, the modulator is the rolling finger: the wider its movement from the pitch centre, the wider the extent of the modulation. The faster the finger moves, the more rapid the rate at which the modulation occurs. Note that it is *only* the frequency of the carrier that changes and not the amplitude. Figure 4.3 is a graphical presentation of the FM synthesizer designed for the purpose of the study in Csound.

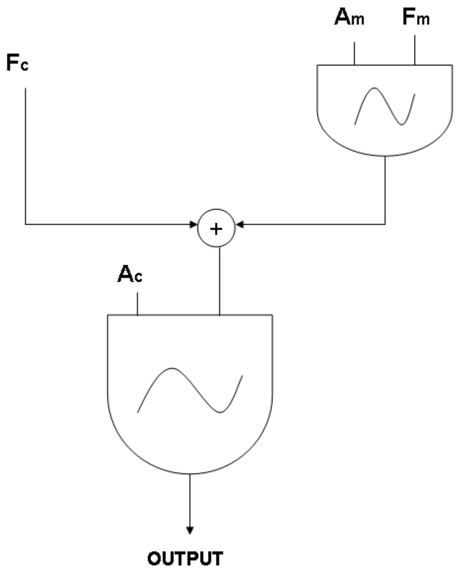


Figure 4.4. Simulation of simple frequency modulation (Adapted from Boulanger (2001)).

The parameters present in simple frequency modulation are as follows:

- Carrier frequency = F_c
- Carrier amplitude = A_c
- Modulator amplitude (frequency deviation of carrier) = A_m
- Modulator frequency (frequency of carrier deviation) = F_m

In the case of a pure sine tone frequency modulated by another pure tone signal[19], the spectrum comprises the carrier signal and a number of partials (known as "sidebands") on either side of it, as shown in figure 4.5. The sidebands are spaced at a distance equal to the modulating frequency, or F_m. The frequencies of the various sidebands in a simple FM spectrum are denoted by the formula:

$$F_c \pm kF_m \tag{4.1}$$

---

[19] See Appendix D for mathematical representation of FM. Alternatively consult Ziemer and Trantner (2002).

where k is an integer which can have any value bigger than or equal to 0. The carrier component is indicated when k=0 (Dodge and Jerse 1985:107). For example, a carrier wave of 440 Hz, frequency modulated by a 5 Hz signal, will have a third partial above the carrier at, 440 Hz + 3(5Hz) = 455 Hz.

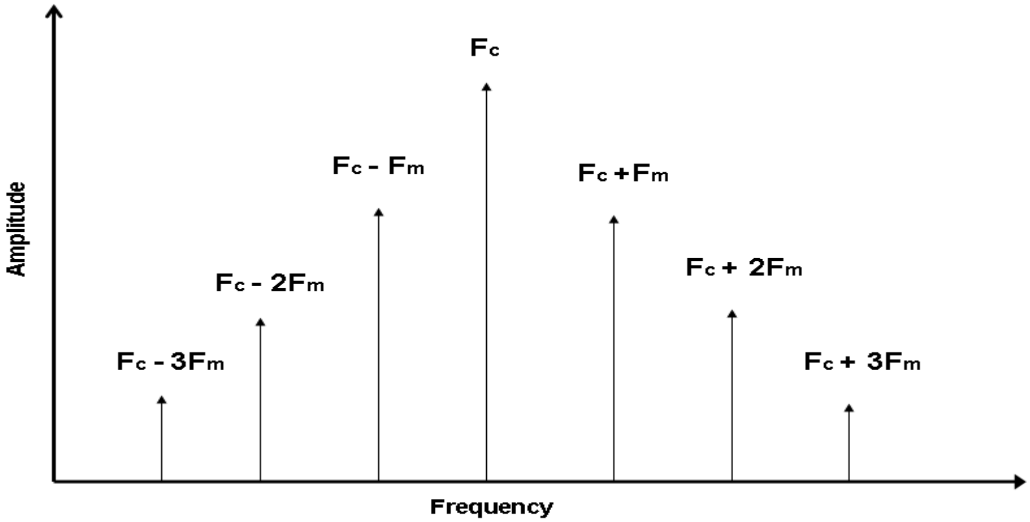


Figure 4.5. Presentation of a frequency modulated sinusoid and its various sidebands.

The spacing of the sidebands is directly related to F_m. The amplitude and number of these sidebands vary with what is known as the *modulation index*: a measure of how much a signal is modulated. It is defined as follows:

$$I = A_m/F_m \tag{4.2}$$

where I is the modulation index. A signal with a deviation of 60 Hz at a frequency of 10 Hz will have a modulation index of 6. A rough approximation is that there will be two more sidebands on either side of the carrier than the modulation index (Russ 1996:222). Now assuming that F_m remains constant, altering A_m gives some interesting results. “Increasing the deviation causes the sidebands to acquire more power at the expense of the carrier frequency. The wider the deviation, the more widely distributed is the power among the sidebands and the greater the number of sidebands that have significant amplitudes[20]" (Dodge and Jerse 1985:107). Decreasing the modulation frequency also increases I and yields similar effects. The deviation of a modulator signal is thus a way in which the bandwidth of the spectrum can be controlled. This is a very important concept in understanding the violin vibrato. The 'modulator signal' in real violin playing is of course the moving finger. Thus, the amount of sidebands is in fact directly under the control of the instrumentalist.

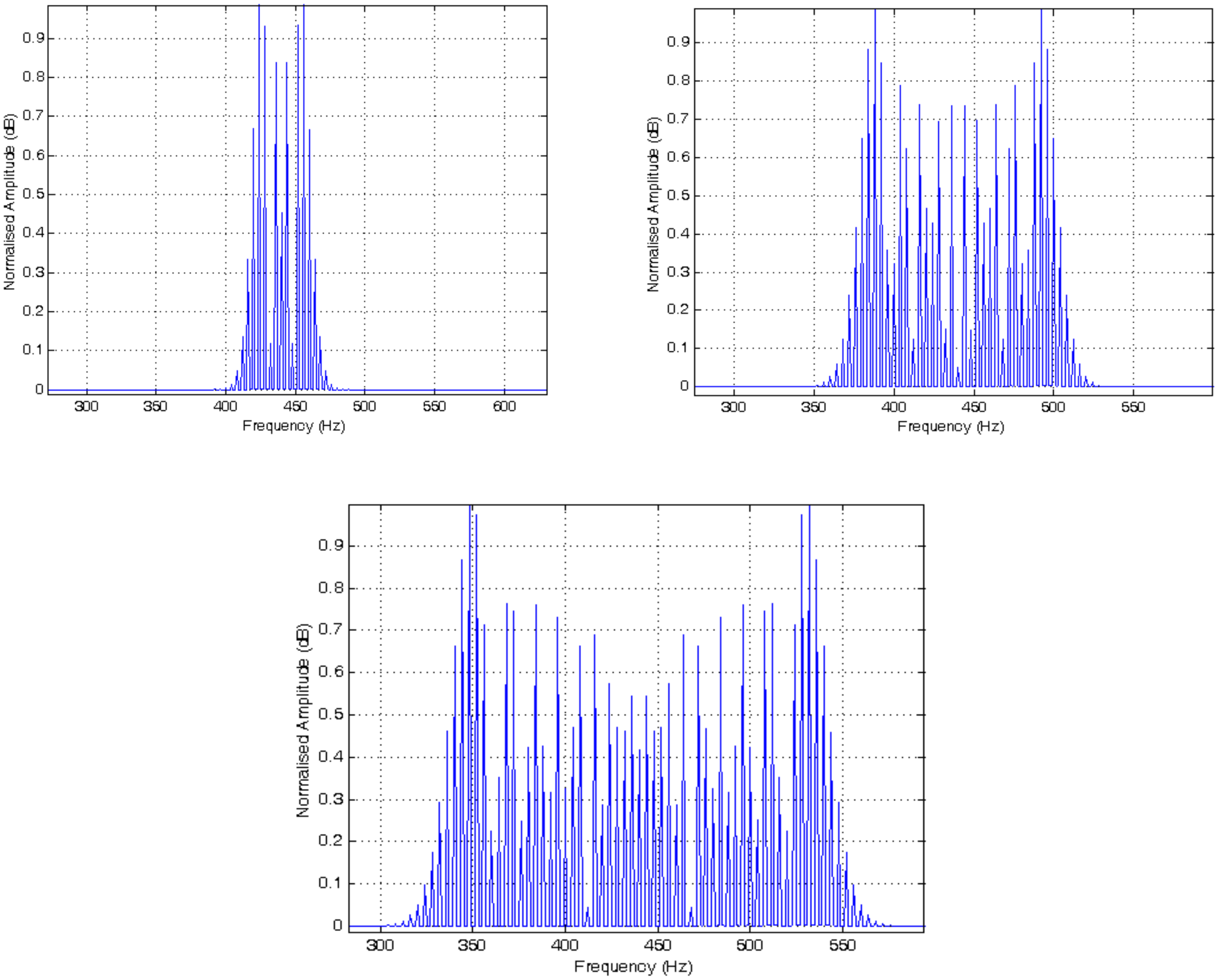


Figure 4.6. Spectra of a single sinusoid frequency modulated with a rate of 4Hz, and increasing extent (A_m). Top left: 20 Hz; Top right: 60 Hz; Bottom: 100 Hz.

---

[20] The amplitudes of the sideband frequencies are determined by a set of curves known as Bessel functions. For further reading consult Chowning and Bristow (1986).

The graphs in figure 4.6 show the effect of increasing A_m whilst keeping F_m constant. Notice the decrease in power of the carrier and a definite ‘fanning-out’ of energy towards the extreme ends of the bandwidth.

In the case of modulating a complex tone, such as a sawtooth wave with a sinusoidal modulator, the same principles apply as before. Only this time each harmonic component of the fundamental acts as a carrier signal itself. The same set of sidebands seen in figure 4.5, and possibly more, will now be present around each harmonic. The amplitudes of the various sidebands will change relative to the amplitudes of the harmonic to which they belong so that a repeating sideband-shape will be observed from one harmonic to the next.

One may rightfully wonder at this point if all these extra sidebands are audible and if they really matter in vibrato perception. Human physiology restricts the hand to move no faster than say 10 Hz and possibly to a width of a semi-tone, perhaps a little more. Therefore, one will never in real violin playing hear the sound associated with the extreme graphs in figure 4.6 but, the sound of real vibrato *is* all the sidebands, all the extra frequencies, all heard as a single sound event. Chapter 6 deals with human perception of vibrato and it is shown how this mechanism is ‘designed’ to incorporate and mould a limited amount of extra information into an acoustic event with added warmth and character.

4.3.2 Amplitude modulation (AM)

Frequency modulation in violin vibrato is necessarily accompanied by amplitude modulation. The harmonics and extra sidebands (created by the process of FM) that accompany the fundamental during this action, fall in different resonance regions which affect the overall moment-to-moment intensity of the played note. The amplitude modulates at the same rate as the frequency but they are not necessarily in phase due to the above phenomenon and other factors. Reger (1931), after an intensive study of string instrument vibrato, found that vibrato in which the intensity crest coincides with the maxima of pitch occurs 40% of the time. The so-called “opposite vibrato” in which the trough of the intensity vibrato coincides with the peak of the pitch occurs 30% of the time. In about 20% of the cases, the crest of the pitch coincides with the upward glides of the intensity curves. For the remaining 10%, there is either no intensity vibrato or the maxima of the pitch correlate with the downward glide of the intensity curve.

Amplitude modulation[21] shares a couple of similarities with its frequency counterpart. To begin with, both need a carrier and a modulating wave (see figure 4.7 below).

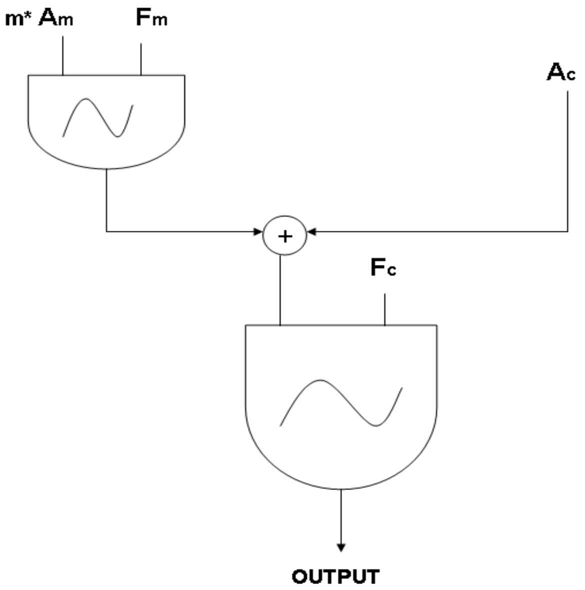


Figure 4.7. Simulation of simple amplitude modulation (Adapted from Boulanger (2001)).

The following parameters are present in amplitude modulation:

- Carrier frequency = F_c
- Carrier amplitude = A_c
- Modulator amplitude (amplitude deviation of carrier) = A_m
- Modulator frequency (frequency of carrier deviation) = F_m

It can be observed in the above diagram that the output of the modulating oscillator is added to a value that expresses the amplitude of the carrier signal (the note being played). The amplitude of the

---

[21] See Appendix D for mathematical representation of AM. Alternatively consult Ziemer and Trantner (2002).

modulating signal is expressed as a proportion of the amplitude of the carrier. The proportion is denoted by the variable m, which is the amplitude *modulation index (m)* (Dodge and Jerse 1985:81). The modulation index is thus not a determinant of the frequency at which modulation occurs, as is the case in frequency modulation. When $m = 0$ there is no modulation and the carrier signal will be a tone with constant amplitude. When $m = 1$, the modulating signal's amplitude matches that of the carrier and 100% modulation takes place. The relevance and importance of this will be discussed later on.

The resulting spectrum of an amplitude modulated carrier shares sideband characteristics with a frequency modulated carrier. In this case, however, there is only the carrier, F_c (in the case of a sine tone) and two sidebands: $F_c + F_m$ and $F_c - F_m$. Concerning the amplitudes, the carrier frequency remains unchanged at all times. The sidebands' amplitudes are calculated by multiplying the amplitude of the carrier by ½ of the modulation index.

$$A_m = A_c.(\tfrac{1}{2} m) \tag{4.3}$$

For example, if A_c has an arbitrary value of 6 with a $m = 1$, the sidebands will have a value of three, indicating that the modulation process splits the energy between upper and lower sidebands (Dodge and Jerse 1985:81). Figure 4.8 shows the components present in the amplitude modulation of a single sinusoid.

Figure 4.9 shows the effect of increasing the modulation index. Notice that only the intensity of the sidebands increases as the index increases. The carrier remains constant and also the spacing of the partials which is governed by the modulation frequency.

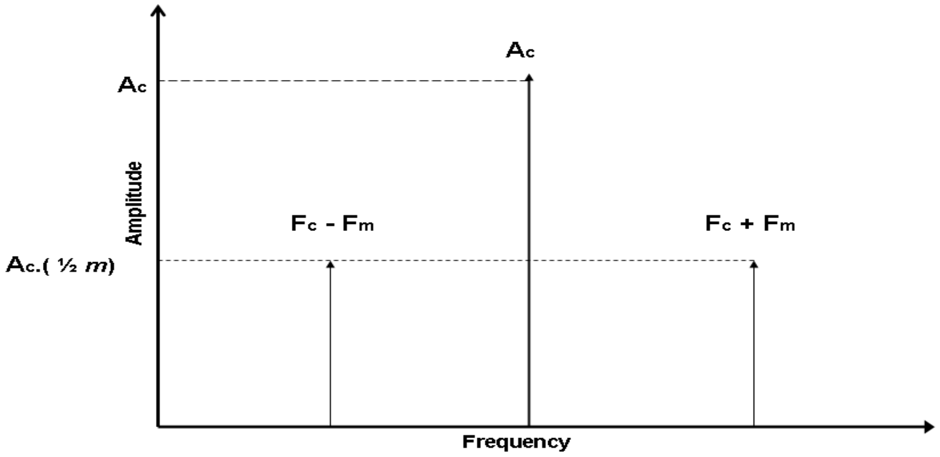
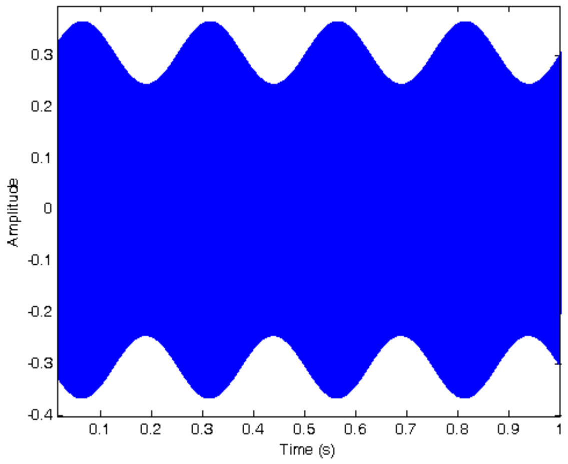
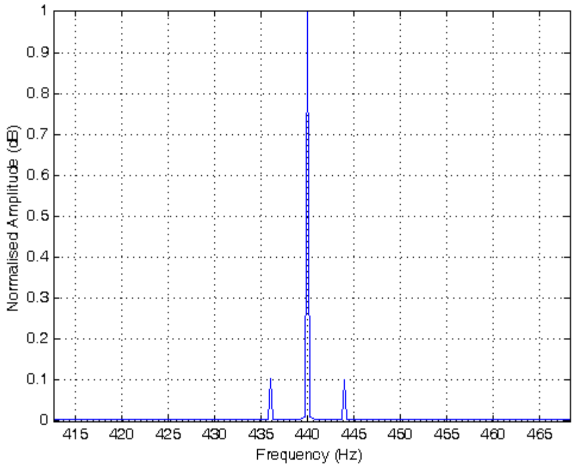


Figure 4.8. Presentation of an amplitude modulated sinusoid and its various sidebands.





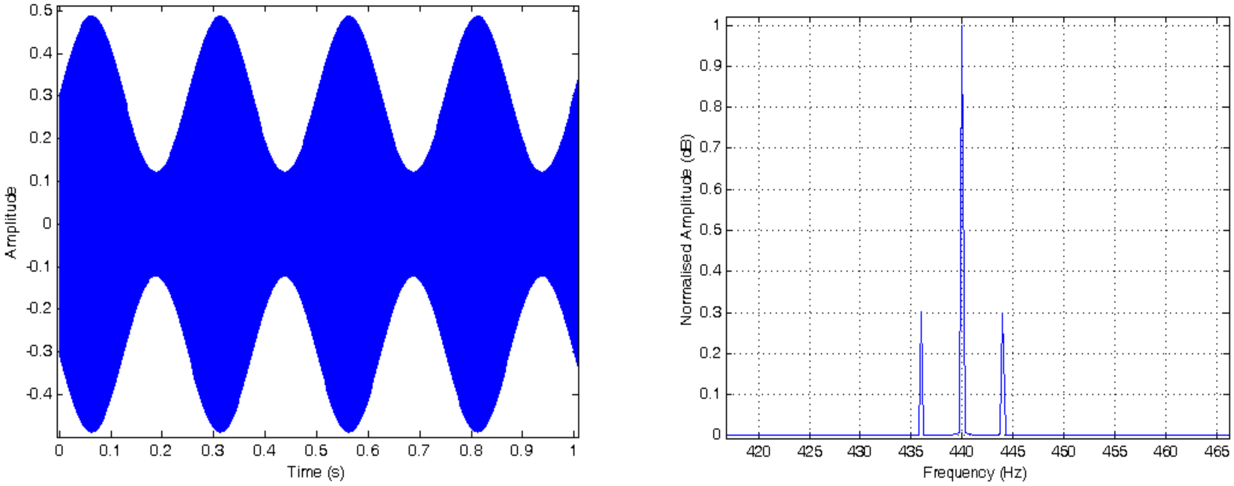


Figure 4.9. Waveform and spectra of a single sinusoid frequency modulated at a rate of 4 Hz, and increasing modulation index (m). Top: 20% modulation. Bottom: 60% modulation.

Of course the violin vibrato tone is not a pure sine tone but a complex one approximating a sawtooth wave. Amplitude modulation creates sidebands around not only the carrier but also the various harmonics in the spectrum. The amplitudes of the sidebands around the harmonics are determined by the same ratio-to-sideband as in equation 4.3.

4.3.3 Simultaneous FM and AM modulation

4.3.3.1 Background

The various modulation types have been described and also the way in which the various spectra are altered by changes in the modulator parameters. In each case the description of modulation started off with its occurrence in the simplest form, that of a sine wave carrier modulated by another sine wave. The sawtooth was also treated with a sinusoidal modulation as its unmodulated spectrum approximates that of the violin tone, i.e. a tone containing both odd and even harmonics. The real violin tone has thus far been kept out of the equation for good reason. In the first place, in the synthesized tone its parameters can be finely adjusted so that the nature of the different modulation types can be studied in a trial and error fashion. The two types can also be kept separate so that each modulation's individual effect may be carefully studied.

Since violin vibrato contains simultaneous amplitude and frequency modulation, it is not possible to study them separately with real tones. Thus, a reasoning leap has to be taken between the spectrum of a violin tone, plus the knowledge of laboratory-modulated tones, to a violin vibrato tone spectrum containing both frequency and amplitude modulation. None of the available literature discuss the combination effect of frequency and amplitude modulation on the spectrum of a violin tone. The telecommunication literature describes low level frequency interference with amplitude modulated radio signals but they are not discussed as two separate varying quantities affecting one another. Synthesis literature deals with both subjects in detail but a spectrum description and the influence of one on the other is yet to be found. The reason for the absence is that it is not a naturally occurring phenomenon, except in the case of certain instruments' vibrato.

The current study aims to describe the spectrum of a violin tone with vibrato in a quantitative manner but distances itself from the complex mathematics involved. The process will commence as in the previous sections, with the simplest case of a sinusoid being modulated with one and then the other, all in the stable synthesis environment.

4.3.3.2 Constant FM, changing AM

What we know so far is that FM and AM are always present and both modulation types produce sidebands or "extra" frequencies. Amplitude modulation produces only a single pair and frequency modulation produces multiple pairs in varying strengths, depending on the modulation index amongst other things. To illustrate again, take a synthesized pure tone with a frequency of 440 Hz, frequency modulated with a deviation of 30 Hz and at a rate of 11 Hz. This yields a modulation index of 2.72. The spacing of the sidebands is determined by the rate (11 Hz) and their relative strengths by the Bessel functions. The resulting spectrum is shown in figure 4.10.

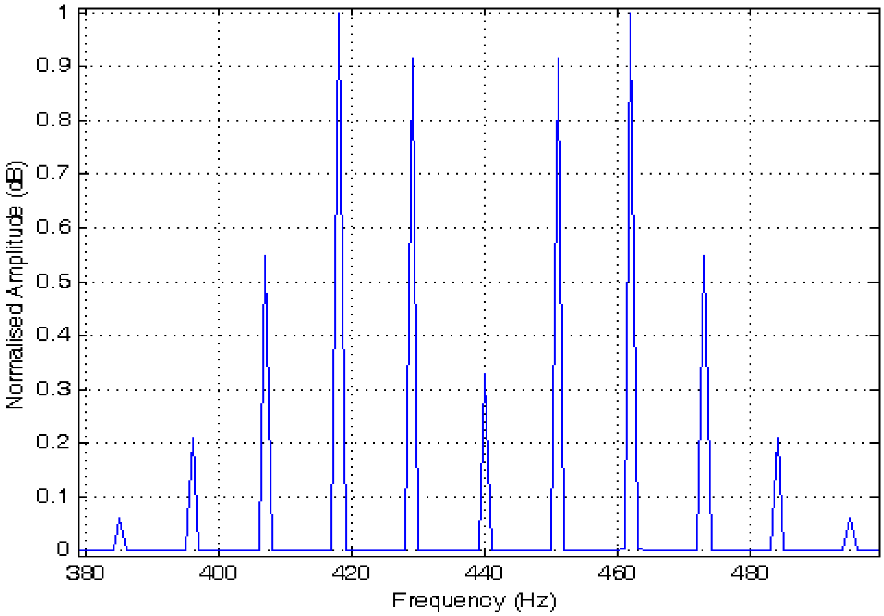
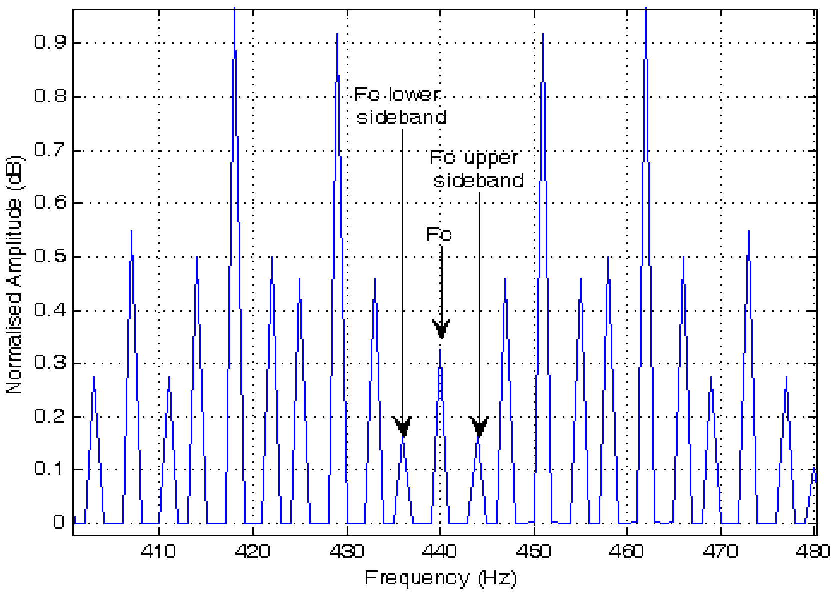


Figure 4.10. Spectrum of frequency modulated pure tone with a carrier of 440 Hz., 30 Hz deviation and rate of 11 Hz. Waveform not included as FM has no effect on the amplitude and thus produces a steady wave form.

We know pitch vibrato (FM) and intensity vibrato (AM) occur simultaneously and at a 1:1 ratio but for clarity purposes lets see what happens when the same signal as in the above case is amplitude modulated in a way that the effect can be more clearly seen. The above signal was modulated with a 100% modulation index at a rate of 4 Hz. The latter rate was chosen so that the sidebands of the AM signal may be clearly distinguished from the FM sidebands. The resultant graph is seen in figure 4.11.



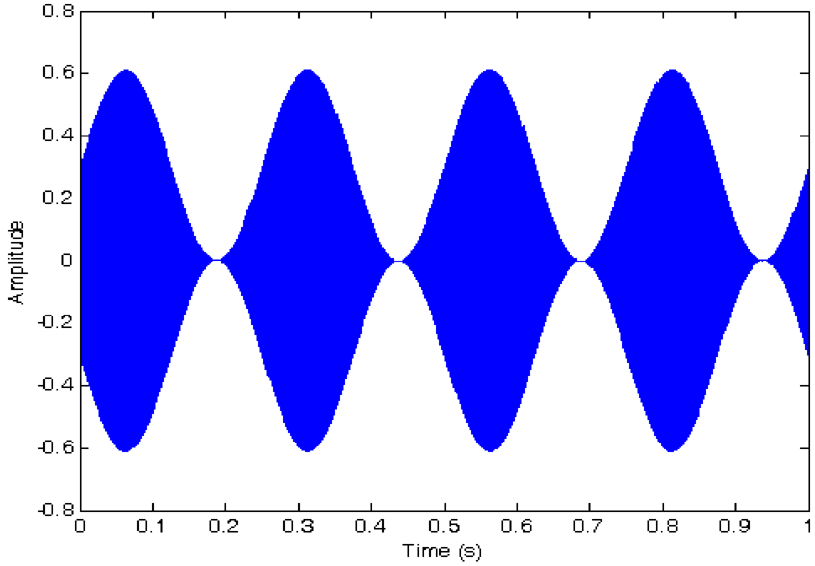


Figure 4.11. Waveform and more focused spectrum view of the same frequency modulated signal as in figure 4.10, with added amplitude modulation: 100% modulation index and at a rate of 4 Hz. The arrows indicate the carrier, and its lower and upper AM-induced sidebands.

It can be seen in figure 4.11 that each sideband now has its own pair of AM sidebands. The original FM sidebands remain unchanged. When the AM rate is increased to match that of the FM rate (11 Hz), as in the case of real violin vibrato, each FM produced sideband becomes a meeting place for three signals: the original sideband, the lower AM produced sideband of the upper-adjacent FM sideband, and the upper AM sideband of the lower-adjacent FM sideband. This could be rather confusing. More simply stated: the AM sidebands of, for example, the carrier (indicated by the arrows in figure 4.11), move outwards and meet the adjacent FM sidebands at their original frequencies. The same applies to, for example, the first FM sideband on the side of the higher frequencies. Its AM sidebands, if extended to 11 Hz to match that of the FM rate, will meet the carrier on the lower side and the second sideband of the FM series on the higher frequency side.

4.3.3.2 Amplitude of combined FM and AM sidebands.

The amplitudes of these combined tones depend not only on the amplitude of the components but also on their different phases[22] (Rossing 1982:128). Reger (1931) describes four different intensity and pitch vibrato combinations (see section 4.3.2). What he described in actual fact is the phenomenon of relative phases between pitch and amplitude vibrato. The four different scenarios were synthesized to view the effect of each. The tone used in all four experiments is a 440 Hz sine wave, with FM: deviation = 60 Hz, rate = 11 Hz and AM: m = 50%, rate = 11 Hz. The resultant graphs are shown in figure 4.12.

The first instance is that of synchrony between pitch and intensity where the crest of one coincides with the crest of the other. Pitch and intensity variation is then said to be *in phase*. The higher sidebands are, as expected, accentuated and the fundamental is barely visible (or audible). The ‘leaning’ effect becomes more pronounced with a higher AM rate. Increasing FM deviation adds more sidebands, i.e. a wider bandwidth and therefore a wider distribution of energy.

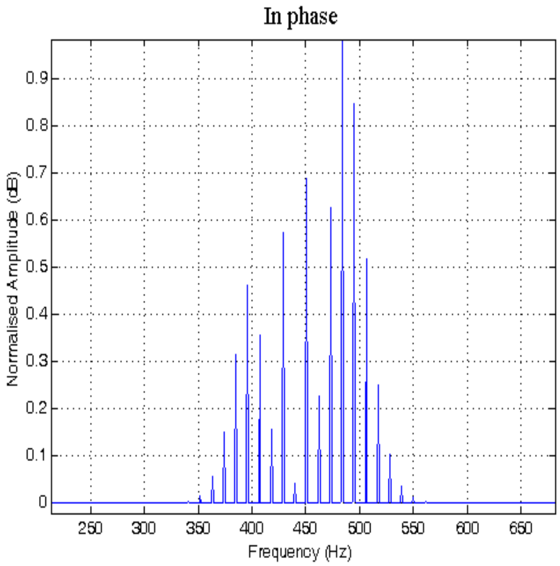
The second scenario is the so-called “opposite vibrato” where the crest of the pitch deviation coincides with the trough of the intensity. The two varying parameters are 180 degrees out of phase and the spectrum is almost a mirror image of the in-phase vibrato. This is expected since the lower frequencies are now accentuated by the same amount as the higher frequencies were before. The effect is audible in that the lower frequencies are heard at the expense of the fundamental which is also suppressed.

---

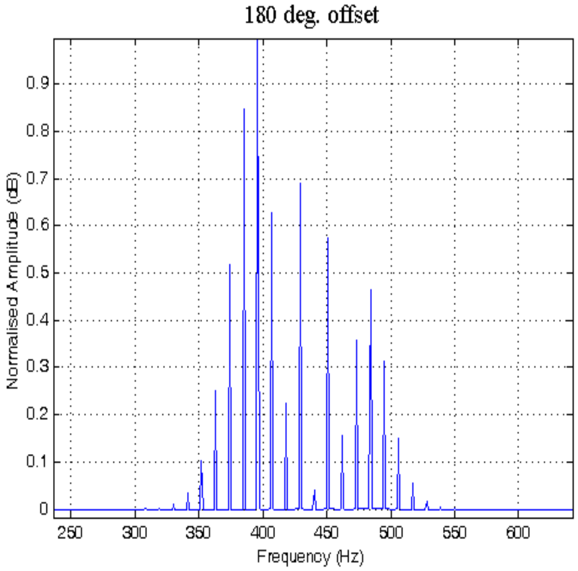
[22] Suppose one complete cycle of a sine wave is equal to 360 degrees, the phase of a wave is an expression (in degrees) of a particular point on the wave cycle.

When pitch and intensity is shifted to be 90 degrees out of phase, it relates to a vibrato where the maximum pitch height agrees with an upward gliding of intensity. Or stated in violin playing terms, when the finger is at the middle position (the note at which vibrato is executed), intensity is at its maximum. The spectrum for this scenario is therefore symmetrical since upper and lower frequencies are suppressed by the same amount.

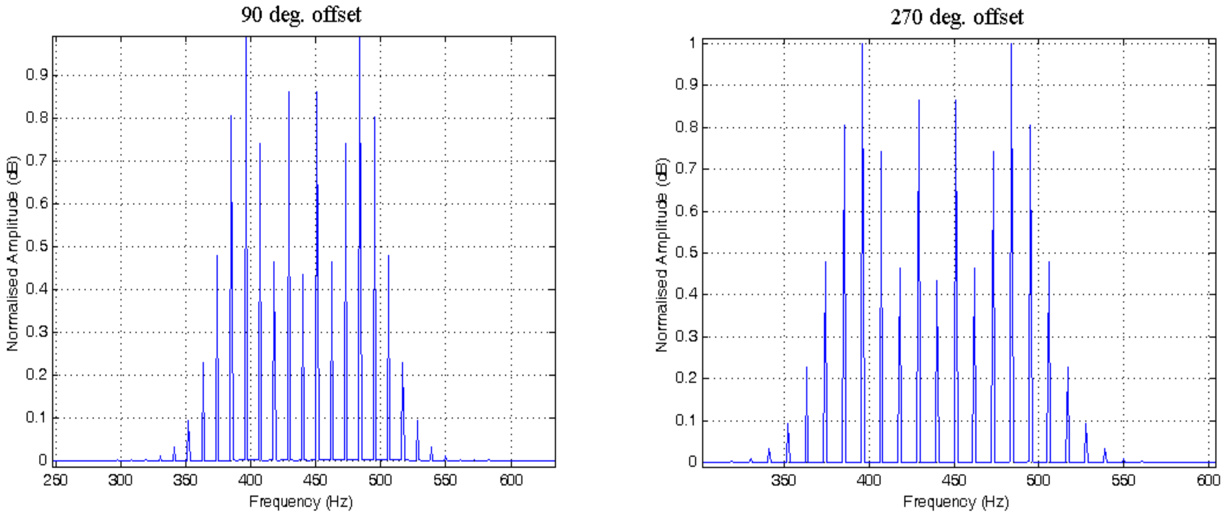
Off-setting the intensity fluctuation by 270 degrees renders a maximum in pitch to coincide with a downward gliding of intensity and yields the same symmetrical spectrum as in the previous case. This is because the middle position of the pitch vibrato cycle, once again, meets the peak of the intensity fluctuation.



In phase



180 deg. offset



90 deg. offset

270 deg. offset

Figure 4.12. Spectra of single sinusoid with simultaneous frequency and amplitude modulation varying in phase. The degrees of offset are indicated.

To conclude the stepwise reasoning towards the spectrum of a real violin vibrato tone, modulating a sawtooth wave (with the same modulation specifications as above, only altering the frequency deviation for a narrower bandwidth) in the same way yields the expected results regarding phase relationships and sidebands etc. In figure 4.13 it can be seen that each harmonic now becomes an isolated system in which frequency and amplitude modulation occurs. The same behaviour of the sidebands observable around the fundamental frequency manifests in the upper harmonics so that a visible repeating pattern is established. The signal used to generate the figure in figure 4.13 also indicates that the FM and AM are in phase due to the 'leaning' characteristic of the sidebands.

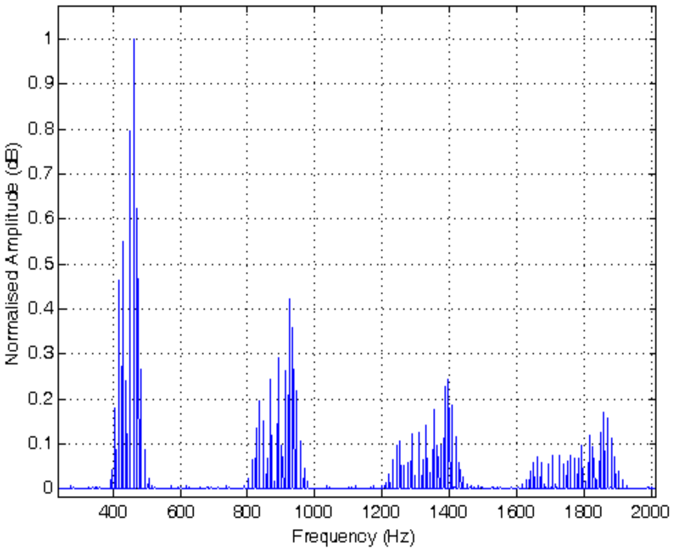


Figure 4.13. Spectrum of first four harmonics of a sawtooth wave with frequency and amplitude modulation. Modulation is in phase.

4.4 Spectrum of a real violin vibrato tone

In chapter 3 the frequency content of a steady-state real violin tone was described. In the current chapter up till this point, fundamentals of violin vibrato were described in the synthesis environment. This section aims to fuse the two thought processes by way of an experiment in order to comprehend the spectrum of a real violin vibrato tone. An investigation into this, a seemingly simple hand movement on a string, appears to have no boundaries and the descriptions of its finer scientific intricacies can become exceedingly complex. An effort will therefore be made to restrict the discussions to the already described fundamentals; the approach is somewhat speculative.

Figure 4.14 shows the waveform and spectra of two violin tones. For the purpose of this experiment[23], a professional violinist[24] was asked to play, firstly, a few G4 notes (on the D-string) as steady as possible and after that, adding vibrato to the same note. The graphs at the top of figure 4.14 are the waveform and spectrum of a one second sample, i.e. the most stable of the few played notes. At the bottom is the same note, but played with vibrato. Only the first two harmonics are indicated for the sake of clarity.

---

[23] The experiment is in accordance with the methodology of Fletcher and Sanders (1967).

[24] Refer to footnote no. 12.

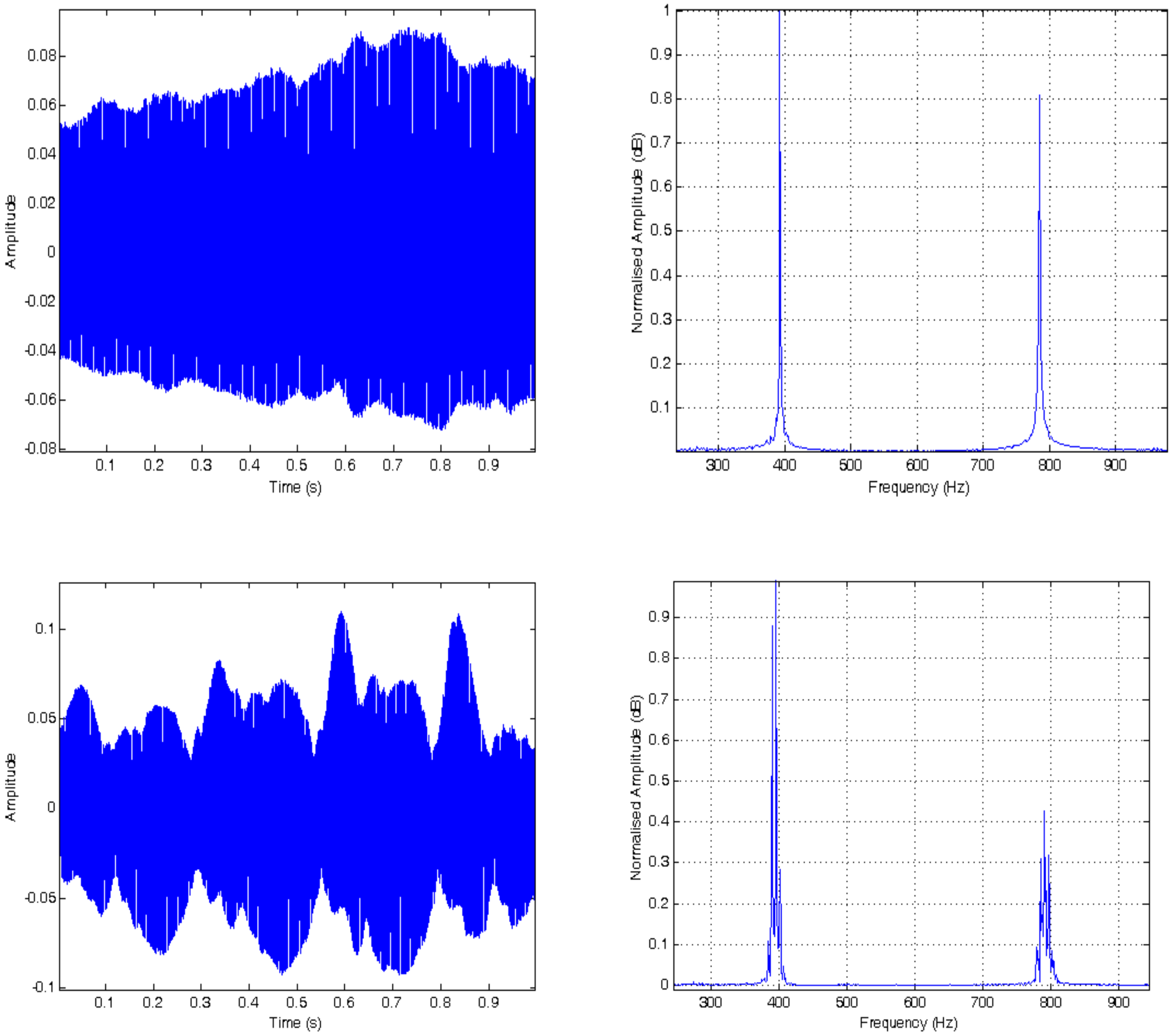


Figure 4.14. Waveform and spectrum of first two harmonics of note G4. Top: no vibrato. Bottom: with vibrato.

The first visible difference is that of the relative intensity levels of the harmonics. The above spectra show the average intensity for the duration of the notes (1 second) at the specific frequencies. Another two samples taken from the same two notes at different times could yield entirely different results. This is due to the phase difference in the frequency and amplitude changes of the various harmonics (Fletcher and Sanders 1967:1535). Notice the periodic amplitude changes in the waveform of the note played with vibrato. What is of importance to the current discussion is the frequency activity around the harmonics of the vibrato tone. This is of course the visible influence of the combined and simultaneous frequency and amplitude modulation, or sidebands. The upper harmonics exhibit the same behaviour as the harmonics of the modulated sawtooth experiment earlier. An integer harmonic of the played tone often ‘disappears’ and the newly created sidebands are accentuated or equally suppressed. This sort of behaviour was noticed first with the phase relationship between amplitude and frequency changes. The offset angle between the two varying parameters determined to which side the louder frequencies would ‘lean’. What was also found in the synthesis experiments was that the greater the modulation index of the AM, the more pronounced the leaning effect becomes. Therefore, the greater the difference between the softest and the loudest section during intensity vibrato, the greater the latter described effect would be.

Upon closer inspection of the various harmonics and each one’s surrounding sideband activity, it was found that the leaning of sidebands differ from one to the other. In one case the fundamental may have a strong carrier component and frequencies in its lower sidebands may be accentuated. A couple of harmonics up in the frequency ladder of the same note, the situation may be reversed. In other cases, the sideband activity may resemble the spectrum of that seen in the 90 degree offset case of figure 4.12. The spectrum in figure 4.15 shows the fundamental and the 1st harmonic of a violin note, C4, played by a professional violinist, indicating that random distributed resonances are present in the violin’s register.

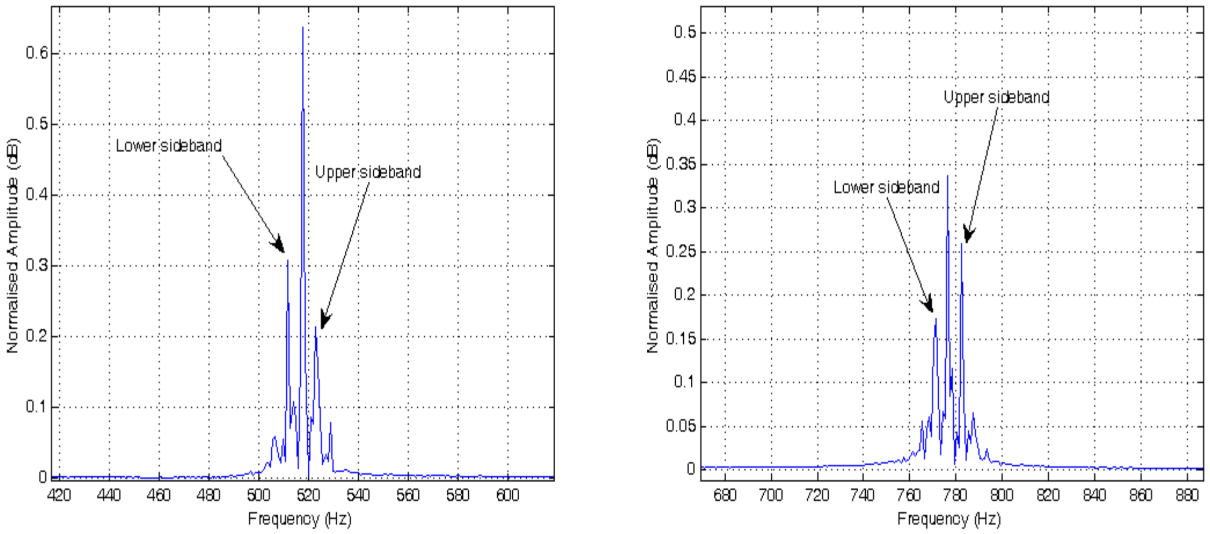


Figure 4.15. First and second harmonics of a note C4 played with vibrato. The arrows indicate the upper and lower sidebands of each.

It is argued that the above observations are a direct result of the resonance properties of the violin. The argument thus takes a full circle back to the evidence provided by Weinreich (1997) that each violin has randomly distributed resonance areas that enhance certain frequency bandwidths. Based on the latter author's findings and the observed behaviour of the harmonic sidebands, it is argued that each harmonic acts as an isolated FM-AM system with its own frequency and, importantly, its unique phase relationship with surrounding resonances.

4.5 An alternative possibility for the changes in amplitude

During the research process it was noticed that there may be another explanation for the periodic changes in amplitude in the waveform of a note played with vibrato. Up until this point, it was argued that the periodic changes in the waveform and the leaning-characteristic of the vibrato spectrum were due to the presence of true AM. The possibility of sidebands induced by AM was also researched. It was found through experimentation that periodic changes in the waveform and leaning sidebands also occur when the sidebands of a single sine wave with only FM applied to it, are filtered in some way.

During normal violin vibrato, each harmonic acquires extra sidebands on either side (See figure 4.5). The resonance (or alternatively 'dead') areas described by Weinreich (1997) are argued to act as filters when sidebands happen to lie in their area of activity. The leaning of sidebands thus occurs when, for example, the lower frequency sidebands of a harmonic happen to fall in a ‘dead’ area and the upper sidebands remain unchanged. No literature has been found that explores this angle of approach.

For the purpose of investigating this phenomenon, a 440Hz sine wave was frequency modulated at a rate of 6.3 Hz and with 15 Hz deviation. The signal was sent through a Csound Four-Pole[25] highpass filter (to simulate the scenario of the lower sidebands being attenuated by being positioned in a ‘dead’ area) with a cutoff frequency at 440Hz. Figure 4.15 shows the resulting waveform and spectrum. Notice the periodic changes in amplitude as well as the leaning sidebands in the spectrum.

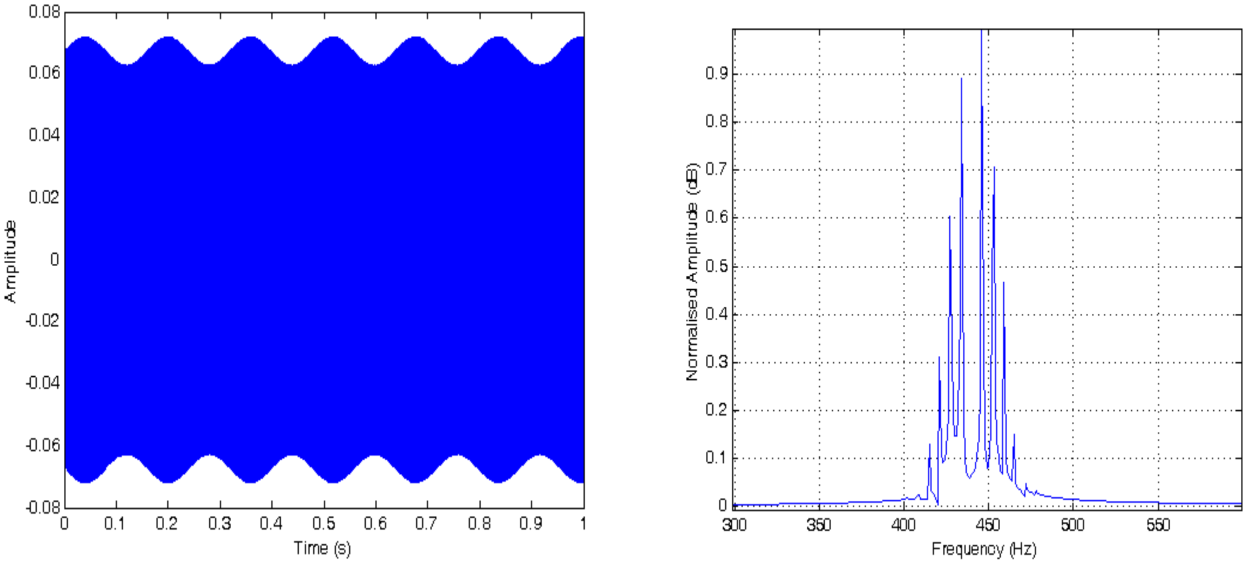


Figure 4.16. Waveform and spectrum of 440Hz sine wave frequency modulated at 6.3 Hz with a deviation of 15 Hz. Signal was filtered by a four-pole highpass filter.

4.6 Conclusion

It is in these unpredictable relationships between frequency, amplitude, and changing timbre that Seashore’s “beauty” of vibrato tone is found. Weinreich’s (1997) contribution to our understanding of the violin’s changing timbre and Reger’s (1931) contribution to the statistics regarding relationships between the varying quantities add to the understanding of the organic existence of this technique.

---

[25] A one-pole filter corresponds to 6dB per octave attenuation at the cut-off frequency. In this case a *cascade* filter design was used which combines four one-pole filters to construct the four-pole filter which attenuates at 24 dB per octave. For further reading consult Boulanger (2001:42-45).

Surprisingly, the violinist has very little to do *directly* with any of the above descriptions. The change in timbre, amplitude and frequency are all governed by the player's initial intention to periodically alter only the pitch of the played note. The extra phase relationships, sidebands etc. are all fortunate add-ons to only two parameters under the direct control of the instrumentalist: speed and width. Speed being the rate per second that violinist moves the finger and the width being the 'distance' in frequency or cents between the backward and forward excursions on the string.

Katz (2002) argues that the individuality factor may be one of the reasons why violinists adopted vibrato as a continuous device rather than as an embellishment used in earlier years. Modern violinists therefore make very efficient use of these parameters in order to distinguish themselves from others who have exactly the same resources to their disposal.

Chapter 5 departs from chapter 4 in extending the foundations laid for vibrato in a stable synthesis environment to 'real-life' situations where professional violinists impart emotion and musical sense through every note played. It further measures and compares the application and individuality 'trademarks' observable in their performance.

Chapter 5

Vibrato measurement and comparison

5.1 Introduction

In this chapter, the emphasis shifts from the “what” violin vibrato is, described in chapters 3 and 4, to “how” it is used by professionals; thus a shift from the laboratory to the concert hall. “Beauty in the vibrato”, says Seashore (1947:61) “is found in the artistic deviation from the precise and uniform in all the attributes of tone.” Up to now, the scientific research documented in this thesis has dealt primarily with this phenomenon in a steady-state environment. However, the reason why violin vibrato has been the centre of so much research is not because of its stability but most probably because of its relative instability in real life performance. No two notes can ever be replayed with exactly the same vibrato rate or width and no two violinists can ever have an identical vibrato. Bang (1923:2) confirms:

> Vibrato is the most individual of all tonal effects in violin playing. It may justly be claimed that not two violinists produce their vibrato in the identical manner. Every great violinist in a way, is the sovereign possessor of his own individual vibrato, which as a rule, defies imitation.

In the light of the fundamental question underlying this thesis as to why vibrato may be such an appreciated effect of violin playing, we proceed to study the differences in vibrato application, however minute, between four violinists. Two parameters of violin vibrato are measured for the purpose of investigation: rate (number of vibrato cycles per second in Hertz, from here on referred to as Modulation Frequency (MF)) and extent (distance between minimum and maximum excursions of vibrato in cents, from here on referred to as Modulation Depth (MD)). Measurements were performed on samples extracted from the audio recordings of four violinists performing Sonata No.1 in G minor, BWV 1001, for solo violin by J.S. Bach[26]. Ten notes in the score (see table 5.1) were identified in which all four violinists apply at least some vibrato. The MFs, MDs and other applicable information were extracted from the samples[27] and summarized in tables 5.2-5.5.

The aim of the experiment is to observe and document by simple analysis the differences, if they do exist, between the selected violinists. There are of course many measurable parameters by which one

---

[26] Full score of the Sonata No.1 in G minor appears in Appendix C.
[27] List of samples on enclosed audio CD is available in Appendix A.

violinist may be distinguished from another, but in essence the only human element involved in this action is the vibrating of the fingers on the string. The periodic changes in amplitude and timbre, etc. are secondary effects as a result of the speed and width of the violinist's digits. Eberhardt (1910:22) confirms:

> Individuality of tone can arise only when the fingers of the left hand are placed upon the strings. Theses fingers vibrate. They vibrate differently. Difference in vibrato begets difference in tone.

The next section gives an overview of different research approaches and their findings, after which the present research method and results are explained. The results are then discussed and the chapter ends with conclusions.

5.2 Different research approaches and results

The study of the 'unsteady-state' of vibrato can be approached in many ways. The pioneering studies of Carl E. Seashore and his associates on vibrato at the Iowa University in 1932 instigated a scientific interest in the artistic application of this technique by both singers and violinists. Their research resulted in many publications addressing a variety of aspects related to this technique in expressive performance. As a basis for further scientific inquiry, Seashore (1931) first of all found and stated that specifically violin vibrato varies periodically in its three constituent factors, namely pitch, intensity, and timbre, over a continuum of time. These factors collectively produce a "pleasing flexibility, mellowness and richness of tone" (Seashore 1931:1). The varying quantities were confirmed by Fletcher and Sanders (1967).

Each of these constituents varies in extent, rate, and form and is separately measurable (Fletcher and Sanders 1965). However, as it was stated earlier, pitch vibrato is the only factor of violin vibrato that is under the direct control of the performer. Periodic changes in amplitude and timbre are a result of the frequency-varying partials interacting with the wood and air resonances of the violin body (Mellody and Wakefield 2000; Weinreich 1997). The emotional intent of a string player via vibrato is introduced to the total sound wave emanating from the violin body by the fingers alone. Hollinshead (1931) and Reger (1931)[28], who studied the vibrato of famous violinists, subsequently concluded that measuring

---

[28] M. Hollinshead and S. Reger are both associates of Carl E. Seashore's investigative study of the phenomena of artistic voice and violin vibrato. Their papers, along with many other likewise scientific studies is published in Seashore, C. 1932. *The vibrato*, Iowa: University of Iowa.

the extent, rate, and form[29] of pitch vibrato in artistic violin playing will yield sufficient data to permit successful comparison.

Hollinshead measured the rate and extent of 11 violinists of professional standing, including Kreisler, Elman and Heifetz. He found the average rate between the 11 artists measured over 109 samples to be 7.1 Hz and the average extent to be 26 cents. Reger found that vibrato rates varied between 5.8 and 7.0 Hz. Extents varied between 16 and 29 cents. An interesting comparison to vocal vibrato indicates that on average the vocal vibrato is half a cycle slower than its strung counterpart. The average extent of artistic vocal vibrato is at times twice the amount of violin vibrato.

More recent research found vibrato rates of violin virtuosi to be between 6.4 and 6.9 Hz and extents varying between 43 and 78 cents (Wakayama et al. 2004). College graduate violin students have an average rate of 5.56 Hz and an extent of 31.25 cents (Geringer and Allen 2004). The latter authors noted a difference between the vibrato extents depending on which finger on the left hand executes the movement. Fingers 2-4[30] extend 30 cents on average, whereas the first finger manages 27 cents on average. Pappich and Rainbow's (1974) measurements of violin performance yielded a mean vibrato rate of 6.5 Hz across all the violinists. Their data regarding vibrato extents seem erroneous when compared to other studies, however, they did observe a trend in that vibrato played in the third position is much wider than when played in first. Prame (1994) noted a 15% increase in vibrato rate towards the end of any sustained note, regardless of tempo.

Other studies in turn focus more on the relationship between vibrato and other musical features such as phrase structure (Timmers and Desain 2000). It was found that vibrato rate, extent and mean loudness is affected by the position of the note in a musical phrase. In a parallel study by Desain et al. (1999) it was found that there is a direct relationship between tempo and vibrato rate: the faster the tempo, the more hastily the back and forth movement on the string. The latter results also confirm the amount of control that violinist have over pitch vibrato parameters. Schoonderwaldt and Fiberg (2001) studied the aspects of violin vibrato needed to yield a natural sounding artificial vibrato model and found that meaningful within-note variation is just as important as proper rates and extents. This aspect is known as the form or shape of vibrato.

---

[29] The published article of both Reger and Hollinshead are abridged and the comments regarding vibrato form is omitted and will subsequently not be dealt with fully in the current text. It is however a significant feature in violin vibrato and some reference will be made to it in the conclusion.

[30] In violin playing terms, the index finger is referred to as the first finger, the middle finger is the second, the ring finger the third and the pinkie is the fourth.

Maynard (1998) found that in terms of rate and extent preferences for vibrato, listeners preferred 6 Hz as the desired rate. Preferences for extents varied considerably, suggesting that width is less of a factor in the overall preference of vibrato.

The perceived pitch of string instrument vibrato tones has also raised some debate. Gockel et al. (2001:701) states that “if fluctuations are of moderate depth, the fluctuation rate is not too high, and the tones are reasonably long, then the tones are perceived as having a single overall pitch.” Some advocate that the perceived pitch is the mean of all frequencies present in the vibrato cycle (Brown and Vaughn 1996; Shonle and Horan 1980; Geringer and Allen 2004). Others believe the perceived pitch to be at the sharp end of the cycle (Fletcher et al. 1965; Pappich and Rainbow 1974) or at the flat end (Fletcher and Sanders 1967). Seashore (1938) proposes that it might be the average of the extreme frequency excursions.

In the light of prior research on the subject summarized above and the scientific foundations laid in chapters 3 and 4, this chapter proceeds to measure and compare vibrato use among the four virtuosi violinists by the method described in the introduction. It aims to provide data which could be used to measure and compare violinists’ vibrato use in a real musical setting as opposed to the more controlled studio-laboratory environment. This type of research has been performed before (Wakayama et al. 2004; Hollinshead 1932; Reger 1932), but sample tones were selected at random from different works. The present research concentrates on a few notes selected from the Bach G minor Sonata. The aim is not a quality judgment in terms of which vibrato may be better than another, but rather to observe the differences (if there are any) and highlight the individuality with which each performer approaches every note in a selected piece of music.

5.3 Research method and results

5.3.1 Selection and sampling

Below is a list of factors influential in the process of selecting and sampling the appropriate sounds for the purpose of analysis.

1. In order to compare different violinists’ rate and extent, it was first of all necessary to find suitable samples. Similar studies selected random samples from various recordings and compared different players’ use. Since the aim is to extract possible individuality traits and

compare them to others, it was decided that a single work was needed that have already been recorded and sold on the market by at least four professional players. The Sonata No.1 in G minor, BWV 1001, for solo violin by J.S. Bach was selected for three reasons. Firstly, it contains many long and isolated notes suitable for this type of analysis. Secondly, there are a number of recordings of this piece of music freely available on the market. Thirdly, since it is a work for solo violin, it is free from other instrumental sounds which could blemish the accuracy of the pitch tracking software used in this study.

2. The following violinists and recordings were used in the study: Itzhak Perlman, EMI (1988); Mark Lubotsky, Collins Classics (1989); Nicolas Chumachenco, Edelweiss (1988); Sigiswald Kuijken, BMG (1983).
3. Specific notes in the score were selected where all four violinists applied some vibrato. Interpretation differences and choices of tempi rendered this a time-consuming exercise. For example, Perlman's majestic and comparatively freer rhythmic considerations allow many more analyzable samples than Kuijken's stricter and 'narrower' vibrato application. Ten notes were found to have vibrato applied by all four violinists.
4. The audio was extracted from the CDs and sampling was performed in ProTools LE 7.1.1., hosted on a Mac Pro 1.1 with a 2Ghz Dual-Core Intel Xeon processor. The stereo files were first split into mono files and in all cases the samples were selected from the left channel. Sampling was performed at 44.1 kHz /16-bit.

5.3.2 Data Extraction

Below is a list of factors influential in the process of extracting the appropriate data from the selected sounds for the purpose of analysis.

1. All analysis were performed in Praat, version 5.0.05. Praat was developed for phonetic research and allows accurate analysis of frequency, using an autocorrelation method of periodicity detection. Sampling in the present study was standardized at a rate of 891 samples/second (sampling every 0.00112 seconds). Macleod (2006) and Geringer and Allen (2004) have applied it with success.

2. The raw Praat data (frequency and time values for every sample taken) was extracted and imported into a Microsoft Excel worksheet for analysis.
3. In order to extract the vibrato rates and extents of the various samples the following methods were used:

   Rate: The time values at the extreme frequency excursions of successive positive vibrato cycles were taken from the resulting graph and calculated to a mean:

$$MF = \frac{n}{(\sum_{k=1}^{n-1} t_{k+1} - t_k)} \tag{5.1}$$

   where *n* is the number of peaks in the sound sample and t_k is the time of the individual peak in the sound sample. In certain cases the actual peak of the vibrato cycle was not clear. In such circumstances, the highest point in that specific vibrato peak was then selected to be the time of maximum excursion.

   Extent: The extent is the vertical distance (f_2-f_1) between the two most extreme frequencies in a sample and is given in cents, which is calculated[31] by:

$$MD = \frac{1200}{\log 2} \times (\log f_2 - \log f_1) \tag{5.2}$$

4. In addition to the rate and extent values, the graphs below also indicate the maximum and minimum, the difference between them and the average frequency of all the frequencies in the sample.

---

[31] Information on the derivation of this formula can found at: http://arts.ucsc.edu/faculty/lieberman/Cents.html

5.4 Results

Tables 5.2-5.5 contain all the data extracted from the samples collected from the recordings. Problems were experienced with reverberation on the recordings in that the selected sample often contained the sound trail of the previous played note and problematized precise pitch tracking by Praat 5.0.05. Breathing sounds by the performers at the start and end of notes occasionally contaminated some samples. In the case of these extra sounds, the attacks and decays of the samples were lost and only the sustain (middle) portions were used.

Table 5.1 contains the list of all the notes used in the study plus a description of their position in the score (which appears in Appendix C).

Measure	**Note**	**Description**
1	G5	Top note of 1st g minor chord
2	D5	2nd beat, 2nd last note
2	Eb5	4th beat
3	D5	2nd beat 1st note
4	A5	2nd beat, 1st note
5	F5	2nd beat, 1st note
5	Eb5	3rd beat, 3rd note
6	F4	2nd beat, 1st note
12	G5	1st beat, 3rd note
12	Db5	2nd beat, 1st note

Table 5.1. List of samples extracted from the audio recordings of the four violinists performing the Bach Sonata No.1 in G minor.

Violinist	Tone sample	MD (cent)	MF (Hz)	Max	Min	Dif (Hz)	Avg (Hz)
Chumachenco	1-G	45.020	6.433	807.991	787.251	20.741	799.139
	2-D	61.034	6.124	609.015	587.919	21.097	599.060
	2-Eb	63.117	6.249	640.863	617.919	22.944	630.212
	3-D	43.323	6.942	603.062	588.158	14.904	594.832
	4-A	53.024	6.558	907.570	880.195	27.375	896.394
	5-F	45.589	6.191	710.103	691.648	18.455	702.058
	5-Eb	43.666	5.996	633.791	618.005	15.786	626.590
	6-F	37.354	6.788	356.562	348.951	7.611	353.085
	12-G	76.259	6.704	818.552	783.278	35.274	799.670
	12-Eb	57.375	6.346	566.919	548.438	18.480	558.447
	Average	**52.576**	**6.433**	n.a	n.a	n.a	n.a

Note: n.a. = not applicable.

Table 5.2. Nicolas Chumachenco.

Violinist	Tone sample	MD (cent)	MF (Hz)	Max	Min	Dif (Hz)	Avg (Hz)
Kuijken	1-G	41.436	5.818	752.913	735.107	17.806	743.970
	2-D	55.756	#	562.278	544.458	17.820	555.681
	2-Eb	32.889	5.328	594.836	583.642	11.194	590.886
	3-D	27.895	5.625	557.608	548.696	8.913	553.489
	4-A	35.574	6.211	840.945	823.841	17.104	834.125
	5-F	26.177	6.178	669.229	659.186	10.043	664.282
	5-Eb	43.602	5.672	598.433	583.550	14.883	590.388
	6-F	44.354	5.936	331.877	323.482	8.395	328.953
	12-G	33.957	5.861	752.768	738.147	14.621	744.431
	12-Eb	23.076	6.181	527.409	520.426	6.983	524.174
	Average	**36.471**	**5.868**	n.a	n.a	n.a	n.a

Notes: n.a. = not applicable; # = no value could be obtained for this signal.

Table 5.3. Sigiswald Kuijken.

Violinist	Tone sample	MD (cent)	MF (Hz)	Max	Min	Dif (Hz)	Avg (Hz)
Lubotsky	1-G	49.885	6.765	803.768	780.939	22.830	792.211
	2-D	68.085	7.584	604.479	581.168	23.311	592.856
	2-Eb	43.533	7.297	645.068	629.049	16.018	636.835
	3-D	63.865	6.857	604.884	582.977	21.907	594.696
	4-A	60.547	7.038	906.377	875.226	31.151	893.700
	5-F	37.548	6.460	718.319	702.908	15.412	711.527
	5-Eb	41.233	6.529	641.330	626.236	15.094	632.755
	6-F	48.537	6.722	357.525	347.640	9.884	354.354
	12-G	62.203	6.264	806.387	777.928	28.459	793.587
	12-Eb	55.525	6.914	563.333	545.552	17.781	556.323
	Average	**53.096**	**6.843**	n.a	n.a	n.a	n.a

Note: n.a. = not applicable.

Table 5.4. Mark Lubotsky

Violinist	Tone sample	MD (cent)	MF (Hz)	Max	Min	Dif (Hz)	Avg (Hz)
Perlman	1-G	68.745	6.203	815.936	784.172	31.765	800.054
	2-D	64.744	7.708	608.183	585.858	22.325	598.754
	2-Eb	57.017	6.261	638.170	617.495	20.675	628.676
	3-D	58.268	6.390	603.040	583.081	19.959	594.662
	4-A	70.161	6.238	910.746	874.574	36.172	892.825
	5-F	77.666	6.330	714.828	683.468	31.360	703.161
	5-Eb	41.978	5.972	639.479	624.160	15.319	630.548
	6-F	60.748	6.677	355.475	343.218	12.257	350.855
	12-G	37.261	5.714	803.574	786.463	17.110	794.614
	12-Eb	42.259	6.666	561.229	547.696	13.534	555.366
	Average	**57.885**	**6.416**	n.a	n.a	n.a	n.a
Note: n.a. = not applicable.							

Table 5.5. Itzhak Perlman.

Tone sample	Violinist	MD (cent)	MF (Hz)
1:G5	Chum	45.020	6.433
	Kuijk	41.436	5.818
	Lub	49.885	6.765
	Perl	68.745	6.203
	Average	**51.271**	**6.305**
2:D5	Chum	61.034	6.124
	Kuijk	55.756	#
	Lub	68.085	7.584
	Perl	64.744	7.708
	Average	**62.405**	**7.139**
2:Eb5	Chum	63.117	6.249
	Kuijk	32.889	5.328
	Lub	43.533	7.297
	Perl	57.017	6.261
	Average	**49.139**	**6.284**
3:D5	Chum	43.323	6.942
	Kuijk	27.895	5.625
	Lub	63.865	6.857
	Perl	58.268	6.390
	Average	**48.338**	**6.453**
4:A5	Chum	53.024	6.558
	Kuijk	35.574	6.211
	Lub	60.547	7.038
	Perl	70.161	6.238
	Average	**54.827**	**6.511**

Tone sample	Violinist	MD (cent)	MF (Hz)
5:F5	Chum	45.589	6.191
	Kuijk	26.177	6.178
	Lub	37.548	6.460
	Perl	77.666	6.330
	Average	**46.745**	**6.290**
5:Eb5	Chum	43.666	5.996
	Kuijk	43.602	5.672
	Lub	41.233	6.529
	Perl	41.978	5.972
	Average	**42.619**	**6.042**
6:F4	Chum	37.354	6.788
	Kuijk	44.354	5.936
	Lub	48.537	6.722
	Perl	60.748	6.677
	Average	**47.748**	**6.531**
12:G5	Chum	76.259	6.704
	Kuijk	33.957	5.861
	Lub	62.203	6.264
	Perl	37.261	5.714
	Average	**52.420**	**6.136**
12:Db5	Chum	57.375	6.346
	Kuijk	23.076	6.181
	Lub	55.525	6.914
	Perl	42.259	6.666
	Average	**44.559**	**6.527**

Table 5.6. MFs and MDs of violinists categorized by note.

5.4.1 Discussion of results

MF results:

From the tables and other data, the following conclusions can be made regarding the violinists' MFs

1. The averaged MFs of the violinists were found to be between 5.868 Hz and 6.843 Hz, with an average of 6.390 Hz. It is significant to compare Kuijken's MF (5.868) to the rest of the group. He is known for 'correct' interpretations of especially Baroque violin music (the era in which the Sonata No. 1 was composed) and even plays on an 18th Century Italian violin by Giovani Grancino, prepared with gut strings and original dimensions, including a shorter neck at a less acute angle, etc. It was deliberately decided to include Kuijken in the hope that his historically-informed performance may reveal adherence to the interpretation of the Baroque-style of vibrato as well. From the few available sources from the 17th and 18th centuries that deal with vibrato (discussed in chapter 1), it can be concluded that less 'anxious' vibrato and less use overall were the norm. It is thus useful to have his Baroque-vibrato in quantified data. The other three performers, Chumachenco (6.433), Lubotsky (6.843), and Perlman (6.416) reveal 'modern' interpretation in terms of notes and the findings are in agreement with the results of Wakayama et al. (2004).
2. Variance between the average MFs of specific notes (table 5.6) revealed a difference of 1.096 Hz, i.e. the MFs vary between 6.042 Hz and 7.139 Hz.
3. The inter-note MF variance (difference between minimum and maximum rates) is an indication of how much a violinist changes his average vibrato speed from one note to the next. The study revealed the following: Chumachenco, 0,946 Hz; Kuijken, 0.884 Hz; Lubotsky, 1.320 Hz, and Perlman (showing the biggest variance), 1.994 Hz.

MD results:

From the tables and other data, the following conclusions can be made regarding the violinists' MDs.

1. On average, the four violinists vibrated with a width of 50.007 cents, varying between Kuijken's 36.471 and Perlman's 57.885. Chumachenco's average MD is 52.576 cents and Lubotsky's data reveals an average of 53.096 cents. It can be seen that Kuijken's average MD is once again significantly lower than the other three. The same possible explanation as given

above applies here too. In a parallel study (Wakayama et al 2004) Perlman's average MD was measured to be 78 cents. The samples selected for the latter study were taken from violin concertos composed in the Romantic era and a wider vibrato would thus be appropriate.

2. Variance between the average MDs of specific notes (table 5.6) revealed a difference of 19.785 cents, varying between 42.619 and 62.405 cents.
3. The inter-note MD variance (difference between minimum and maximum deviations) is an indication of how much a violinist changes his average vibrato width from one note to the next. Perlman shows once again the most variance with an average difference of 40.405 cents between maximum and minimum excursions. Chumachenco varies by 38.905 cents, Kuijken by 36.680 and Lubotsky by 30.538.

5.4.2 General observations

The data and results of the various samples reveal that there are always minute, yet very important differences between the ways in which performers approach every note. It is not only the notes that differ but each performer has a statistical 'trademark' which he[32], perhaps unknowingly, recalls at every vibrato occasion. Kuijken in general has a slower and narrower width than the rest; Perlman has the greatest MF and MD variance between notes and Lubotsky generally has the fastest fingers. As will be seen below, Lubotsky also has a unique way of starting and ending most notes. These differences would not have existed if it did not make a significant difference to the sound.

But what about the so-called vibrato 'form' or inter-note variance that Reger (1932), Hollinshead (1932) and Schoonderwaldt and Fiberg (2001) mentioned in their studies? Wakayama et al. (2004) also noted the importance of this aspect and in terms of MF found that there are three noticeable patterns: constant, increasing and decreasing. They found that all violinists play with all three patterns. However, the samples selected for this study were too random for significant conclusions regarding for example a general trend amongst the violinists in this regard. Reverberation trails of previous notes and breathing noises by the performers often left only the sustain portion of notes available for analysis. The distinguishing factors exist mainly in the beginnings and endings of notes and without that any comparison in this regard would not be entirely accurate. There were a few notes which could be

---

[32] In this case all the performers were men, but the same will no doubt apply in the case of female performers.

sampled in its entirety and it is interesting to view these in graph format nonetheless. Figure 5.1 presents the inter-note variance in terms of frequency over time of two violinists, Perlman and Lubotsky, playing the same note, Eb5 in bar 5 of the Sonata in G minor.

These notes were sampled without loosing any of the beginning or the end parts and thus give a proper indication of the differences in vibrato application. It is clear from the graph that Lubotsky eases into the note before any vibrato is applied, becoming wider towards the middle portion and shows a slight decrease in width towards termination. Perlman starts off with a consistently wide vibrato and decreases towards the end. Their average frequencies are very much the same and without vibrato the notes would have revealed no immediately recognizable distinction. Comparing other notes of the two performers will present similar differences.

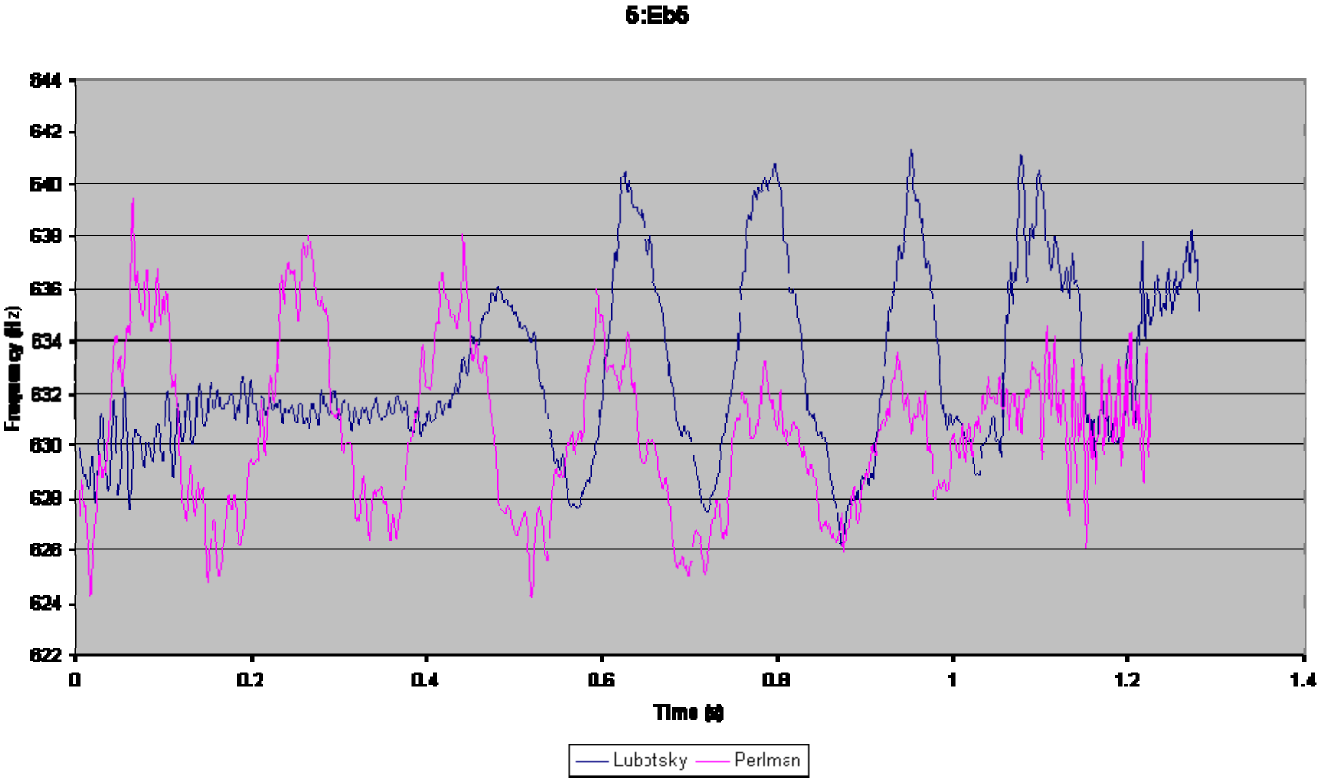


Figure 5.1. Graph showing Perlman and Lubotsky’s vibrato differences of the note Eb5 from bar 5 of Bach’s Sonata in G minor. Average frequencies: Lubotsky, 632.755 Hz; Perlman, 630.548.

Each performer may have a unique approach to a specific note but it was observed that in some cases a specific violinist had a specific trademark in their vibrato in almost all notes. Observe, for example, the graphs (figures 5.2-5.5) of Lubtosky playing different notes. Even though the average frequency, MDs, and MFs differ from one another in each case, there is still a very distinct shape or form to his vibrato application. Notice first a slow rise in frequency, followed by a smaller cycle or two, before the sustain portions containing the widest excursions and the easing off with a couple of smaller cycles towards the end.

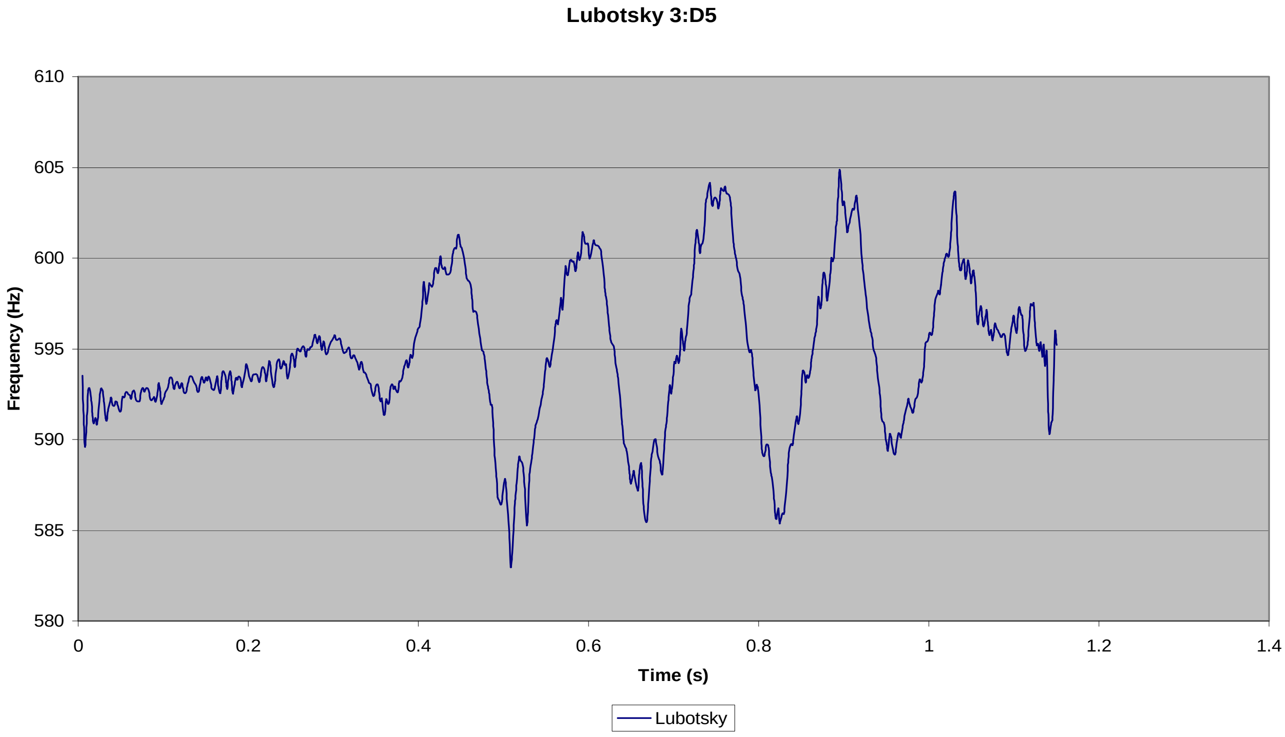


Figure 5.2. Lubotsky playing note 3:D5. MD: 63.865 cents. MF: 6.657 Hz. Average Frequency: 594.696 Hz.

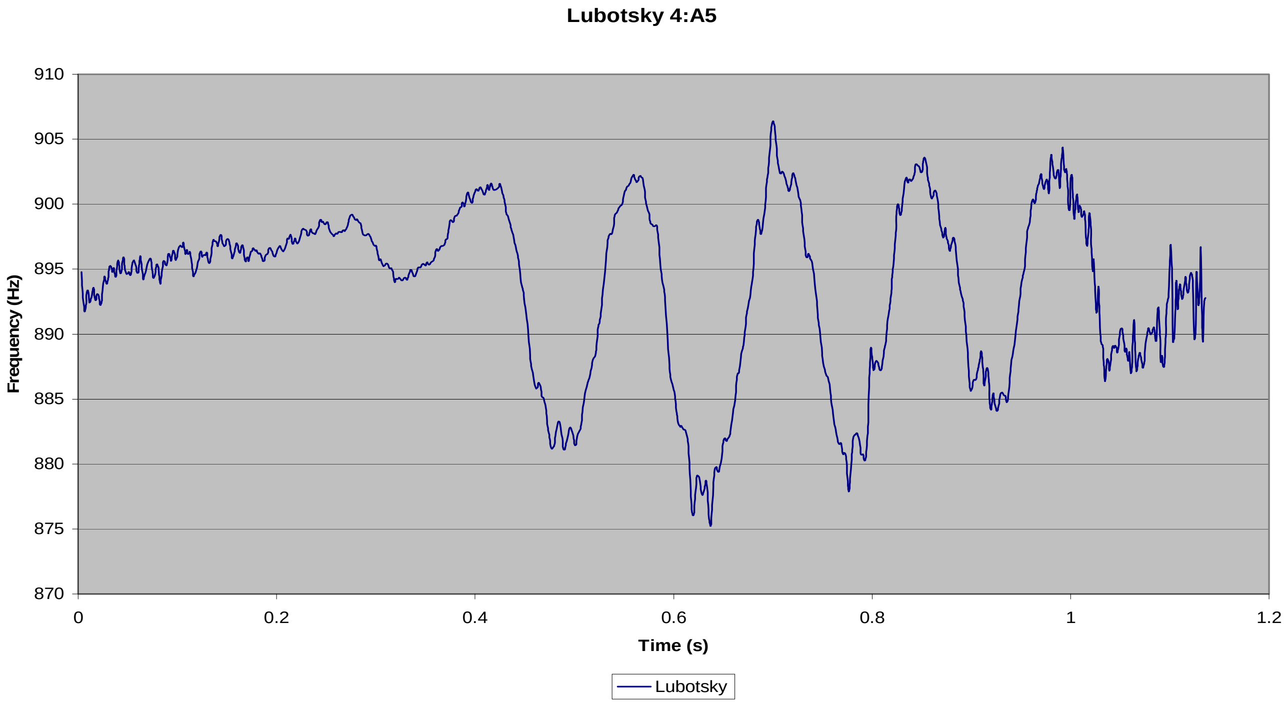


Figure 5.3. Lubotsky playing note 4:A5. MD: 60.547 cents. MF: 7.038 Hz. Average Frequency: 893.7 Hz.

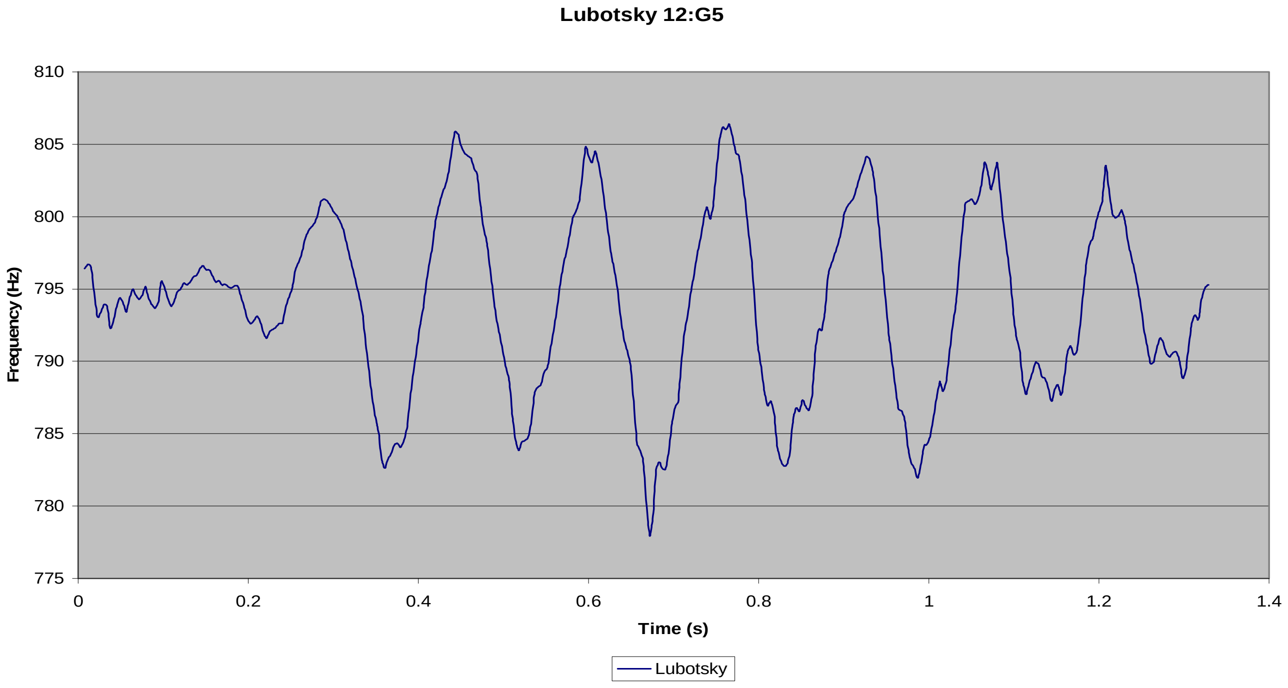


Figure 5.4. Lubotsky playing note 12:G5. MD: 62.203 cents. MF: 6.264 Hz . Average Frequency: 793.587 Hz

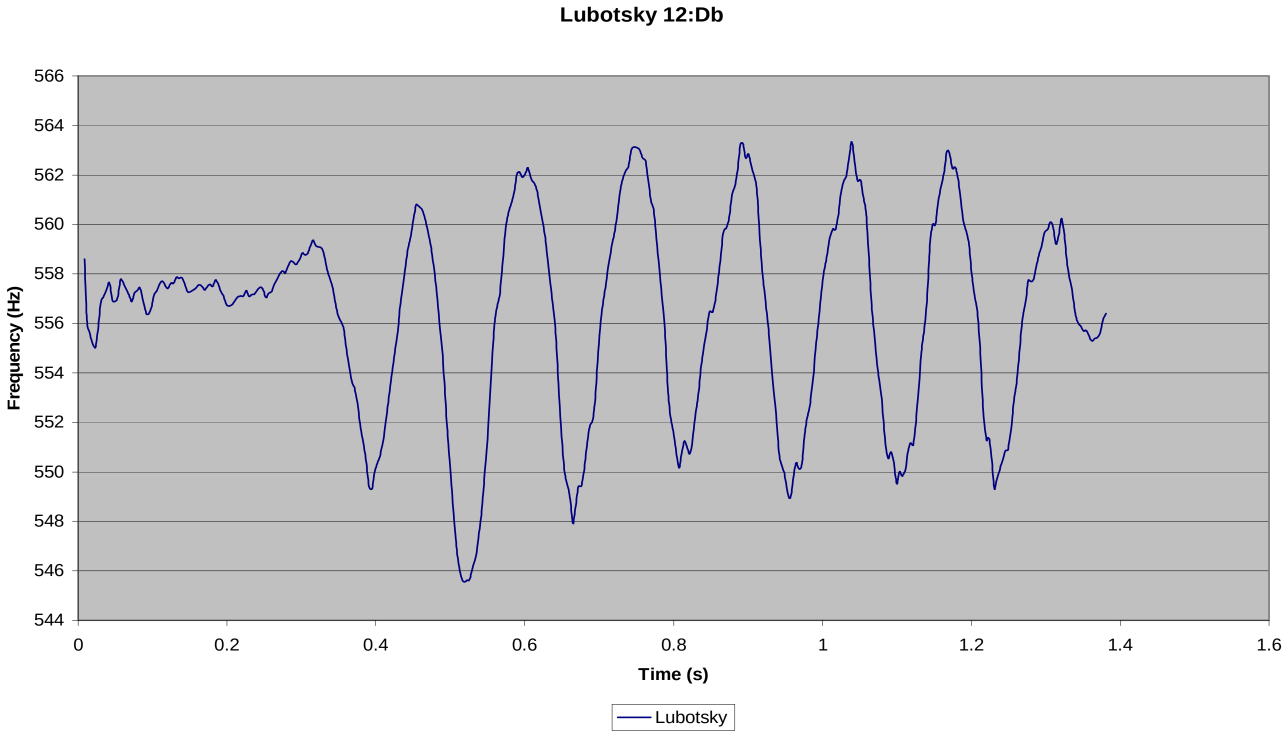


Figure 5.5. Lubotsky playing note 12:Db5. MD: 55.525 cents. MF: 6.914 Hz. Average Frequency: 556.323 Hz

5.5 Conclusion

The primary aim of this chapter was to search for possible differences and unique vibrato traits which, according to other research findings, differentiate one performer from the other. It was argued that these fine intricacies and minute variations play an important role in distinguishing violinists from one another and are thus important in the present investigation of the phenomenon of violin vibrato. Samples were selected from four recordings of four different violinists performing Sonata No.1 in G minor, BWV 1001, for solo violin by J.S. Bach. Ten notes were identified and processed into quantifiable data in which all four violinists apply at least some vibrato. Only vibrato rate (MF) and extent (MD) were measured.

In general it was found that there are noticeable differences between the averaged MFs and MDs of the performers. Kuijken’s figures indicate a much slower (5.868 Hz) and narrower (36.471 cents) vibrato compared to the combined averages of the rest (6.564 Hz; 54.519 cents). Lubotsky has the fastest average vibrato (6.843 Hz) and Perlman the widest average extent (57.885 cents). Performers also show deviation in width and rate application from one note to the next. Perlman is the most liberal in both rate (1.994 Hz) and width (40.405 cents) variation. Lubotsky is the most conservative in terms of extent (30.538 cents) and Kuijken in rate (0.884 cents).

Apart from these figures it was also found that the within-note variance plays an important role in vibrato distinction. Some start with a wider vibrato than others, slowing and narrowing down towards the end whilst others ease into a note; fluctuation in frequency is only observed some time after the start of the note. The samples of Lubotsky were used to demonstrate the trademark quality that some performers apply to most notes. A noticeable shape in terms of vibrato extent and variation across the duration of the note was identified in four of his ten selected samples.

The following and concluding chapter in this thesis describes some of the mechanisms involved in human physiology, psychology, and even neurology which contribute to our understanding and appreciation of violin vibrato. Current research on the topic of vibrato perception is only in its infancy and the perception of the finer detail of vibrato described in this chapter have according to the available sources not been adequately addressed. Chapter 6 will therefore focus only on the perception mechanisms involved in perceiving the most basic features of violin vibrato.

Chapter 6

Vibrato perception

6.1 Introduction

In this chapter the perception of vibrato will be investigated. An attempt will be made to answer the question as to how vibrato is perceived physiologically and psychologically and if the brain has specialist centres for detecting its various components such as frequency and amplitude modulation, which were discussed in chapter 5. It also aims to answer the fundamental question stated in the beginning of the thesis: Why is vibrato such an important aspect of violin performance and why do we like it? The information from the preceding chapters will serve as important inputs in understanding the biological mechanisms active in receiving and decoding the vibrato as an acoustic stimulus.

Is there something like vibrato perception? Researchers believe that our ability to detect and interpret continuously changing pitch and frequency in naturally occurring sounds, such as in speech, is a predetermined biological function assisting us in making sense of the acoustic world around us. Low modulation rate of frequencies in the voice have been found to be crucial for speech recognition (Houtgast and Steenenkamp 1985). When frequency modulation is removed from the voice signal it looses a great part of its comprehensibility since the “significant message” is carried by the changes in the waveform (Kay and Matthews 1972:676).

Changes in amplitude are equally important and the various centres in the auditory system active in interpreting such changes are said to be an “ecological necessity” by which man makes sense of the sound world around him (Jorris et al. 2003:543). Hart et al. (2003) found certain areas in the brain that are activated solely when either amplitude or frequency modulation is present. Timbre vibrato will not be discussed here since very little research has been performed on the subject in the context of this chapter.

The study of vibrato perception is then a study of how the various biological systems, respond to a musical tone with changes in frequency and amplitude. It may be argued that in the same way that the message in speech is carried by the temporal changes in the waveform, changes in the violin tone waveform contribute to imparting a meaningful musical message.

This chapter traces the perception of sound right from where it enters the ear canal, through the auditory system's various decoding stations and, finally, where it ends in the primary auditory cortex. Since the biological perception can not entirely answer the question as to why vibrato may be such an important aspect of violin performance, the last section of the chapter is dedicated to musically relevant principles of the Gestalt-theory. This perspective is more psychologically based and provides some answers and closure to the fundamental research question.

6.2 Auditory physiology

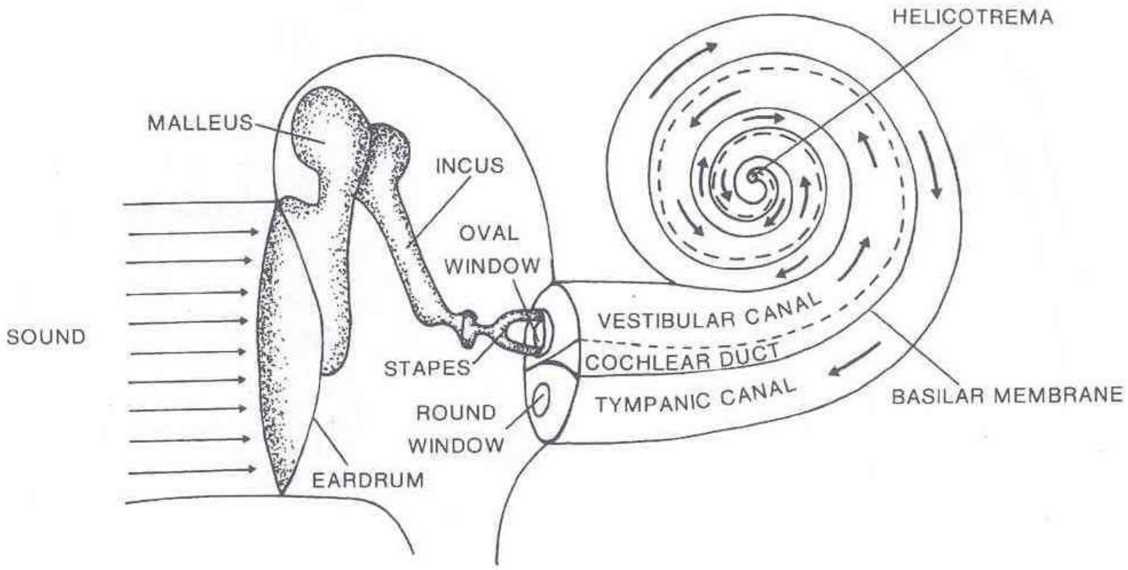


Figure 6.1. Conversion from air conduction to liquid conduction of sound by the ear (Source: Warren (1999)).

The descriptions that follow are based on figure 6.1. Sound enters the auditory system via the auditory canal of the outer ear and causes the tympanic membrane (eardrum) to vibrate at the frequency of the stimulating sound wave. The vibrations are transmitted from this membrane through the middle ear via three little bones, the malleus, incus and stapes. They are responsible for the efficient transfer of sound from the air to fluids in the cochlea (the actual hearing organ in the inner ear). Moore (1989:17) refers collectively to these bones as an "impedance-matching device", since air and fluid are different acoustical systems and much of the important sound information would be lost if the inner ear were to be stimulated by direct means. An estimated 60% of the energy is conserved through these interactions compared to the 3% if direct coupling were used (Sano and Jenkins 1991:42). The transmission of sound through the middle ear is most efficient at frequencies between 1 and 4 kHz (Mazzola 2002:1027).

The stapes-bone connects the middle ear to the inner ear via a membrane covering the oval window: the entrance to the fluid-filled cochlea. The shape of the cochlea in humans resembles that of a snail with two and a half turns (Mazzola 2002:1027). This spiral is filled with almost incompressible liquid and houses three parallel, longitudinally orientated channels: the scala vestibule (vestibular canal), scala tympani (tympanic canal), and scala media (cochlear duct). The entire complex is wrapped up in a bony rigid cast. The scala vestibuli starts at the oval window (the basil end), runs the entire length of the spiral and terminates at the apical end. A sound wave emitted to the oval window travels along the scala vestibuli and eventually reaches the helicotrema, a little opening that joins the scala vestibuli with the scala tympani. The latter channel now spirals outwards towards the basal end again and terminates at the round window situated just below the oval window, and releases the intra-cochlear pressure - built up by the travelling waves in the scalae (Sano and Jenkins 1991:42).

The above procedure is a broad description of the mechanical functioning of the ear. The more sophisticated perception of the sound occurs in the cochlea: from the moment of impact at the oval window to the time of energy dissipation at the round window. The focus now turns to this event.

Between the scala tympani and the scala vestibuli, lies the scala media or cochlear duct. It is also filled with a liquid, endolymph, through which sound follows the same path as in the other canals: from the basil end to the apex. It is separated from the scala vestibuli at the top by the Reisner’s membrane and from the scala tympani by the basilar membrane (see figure 6.2). Resting on the basilar membrane, inside the scala media, is the delicate and immensely complex organ of Corti, or often referred to as the “seat of hearing” (Rossing 1982:64). The organ of Corti runs the entire length of the scalae. If the cochlea were to be uncoiled it will be noticed that the basil end (where the sound enters via the oval window) is broader and tapers towards the apical end where the two outside scalae meet via the helicotrima. In contrast, the basilar membrane becomes progressively wider towards the apical end.

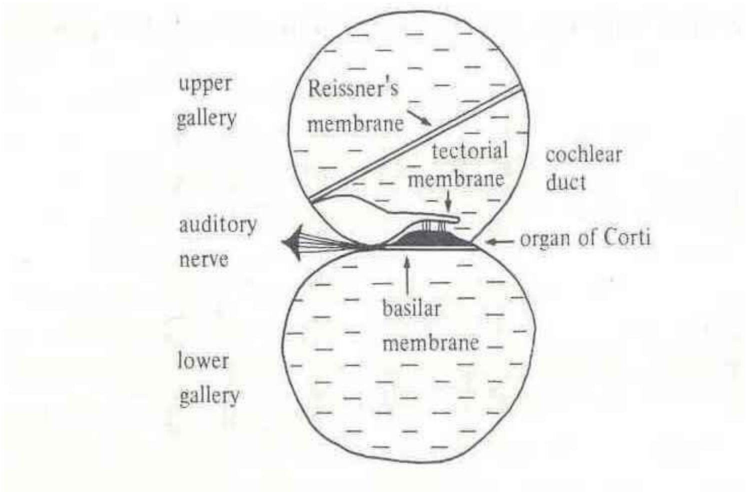


Figure 6.2. Cross-section of the cochlea (Source: Campbell and Greated (1987)).

At the base-end the membrane is about 16mm thick and widens to about 52 mm at the apex (Mazzola 2002:1027). The travelling wave in the fluid moves along the basilar membrane from the base to the apex. Waves with a high frequency cause the membrane to vibrate maximally closer to the basil end where it is thinner and more manoeuvrable. The lower the frequency, the closer the area of maximum excitation will be to the thicker apex. Thus, "the position of the peak in the pattern of vibration differs according to the frequency of stimulation" (Moore 1989:18). The frequency selectivity resembles a Fourier analysis of limited resolution (Warren 1999:11).

Now, the organ of Corti on the basilar membrane houses two types of sensory cells, one layer of inner hair cells and three sets of outer hair cells, each topped by a cuticular plate containing stereocilia (visible at the top of the hair cells in figure 6.3). In humans there are about 3 500 inner hair cells and 25 000 outer hair cells (Moore 1989:26). A tectorial membrane (attached to the basilar membrane) as such 'flops' over these hair cells. At a point of stimulation in the cochlea, the tectorial membrane chafes the stereocilia on top of the outer hair cells in regular motion, at the frequency of the waveform, if it is assumed that the sound is periodic. The to-and-fro motion of the tectorial membrane causes the steriocilia to bend open at their basil ends (Mazzola 2002:1040). Electrochemical changes take place as a result of in- and outflow of substances at this opening which in turn leads to stimulation of the auditory nerve fibres.

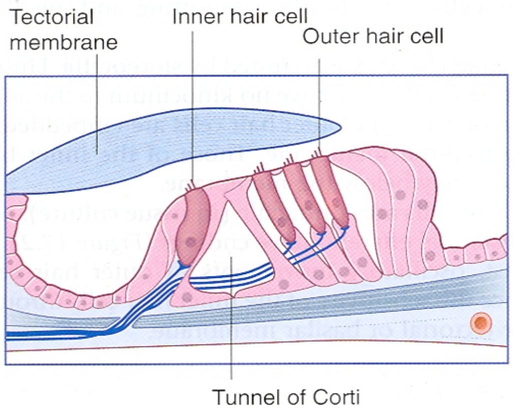


Figure 6.3. Enlarged view of organ of Corti (Source: FitzGerald and Folan-Curren (2002:171)).

Two types of nerve fibres need to be distinguished: afferent fibres transport information from the hair cells to the brain and efferent fibres send information from the higher areas of processing to appropriate places in the lower auditory system.

Over 90% (out of a total of 30 000) of the afferent nerve fibres terminate in the inner hair cells, with each hair cell innervated by about eight separate fibres (Warren 1999:12). The rest of the afferents are shared amongst the outer hair cells. Although it is only the outer cells that are mechanically stimulated, it is the inner hair cells that transduce mechanical movements into neural activity and transport most of the information of the sound to the auditory nervous system via the cochlear nerve (Moore 1989:27). This relationship is still poorly understood.

The perception of a pitch responds in general terms to the area of stimulation on the basilar membrane. The organization of the basilar membrane in this regard is thus *tonotopic* (place representation of frequency along the basilar membrane is preserved as a place representation in the auditory nerve) (Moore 1989:27). A pure tone of a given frequency induces maximum basilar membrane movement at a certain area. The hair cells located at that specific point proceed to fire nerve impulses which are transported to the brain via the cochlear nerve.

6.3 Pitch perception theories

There are two prevailing theories regarding pitch perception. The place theory simply states that the perceived frequency dictates which place of the membrane is excited. The periodicity theory is however more complex and requires more explanation. The periodicity theory states that the neural discharges are proportional to the frequency stimulus, i.e. neural firings tend to occur at a particular phase of the stimulating waveform. For example, when a pure tone of 440 Hz is admitted to the ear, nerve firings will tend to occur at the peaks of the waveform, i.e. a nerve pulse every 0.002 seconds. This is known as "phase-locking" and determines that frequency information is organized as a time code (Wallin 1991:156). A refractory period exists between successive nerve firings and determines that above 4 kHz, the timing mechanism becomes erratic due to the latency effect. It is assumed then that above this frequency all pitch is determined by the place mechanism, for which timing is irrelevant. There are many variations and exceptions to this basic explanation but the explanation should suffice for the purpose of the study.

The perception of loudness of an acoustic signal is also determined by the nerve impulses. Intensity changes are signalled in two ways: firstly by an increase in firing rate at the centre of the excitation pattern, and secondly by the spreading of the excitation pattern, so that more adjacent neurons are brought into operation (Moore 1989:615).

6.3.1 Pitch perception of complex tones

Thus far we have only considered perception of a pure tone. Sounds in their natural state are always complex in that they usually comprise of a multiple of sinusoids (see chapter 3). The perception of a complex tone (such as the violin) is different from that of the single sinusoid but still makes use of some of the principles described above. The understanding of vibrato perception requires an understanding of the latter concept and this will therefore be briefly explained below.

Licklider proved in 1954 that the pitch of a complex tone is not dependent on activity on the basilar membrane at the place where a pure tone would produce the same pitch. He demonstrated this by removing the fundamental from a complex tone, where after the pitch was unaltered. Only a slight change in timbre was noticed (Warren 1999:66). This realization sparked a renewed interest in the workings of the auditory system and the exact mechanisms in the perception of pitch. The physiology of the cochlea and other related issues have been explored since Helmholtz's (1885) *On the Sensation of Tone*, but the so-called "missing fundamental" phenomenon was not known then.

The literature regarding this concept is still speculative. Among the theories are Terhardt's learning model and Goldstein's template matching (Warren 1999). One of the prevailing theories (Schouten (1970) seems to be the most authoritative voice on this theory) however states that the fundamental of a complex periodic signal is produced by the interference of the various harmonics with one another on the basilar membrane. The key concept to the theory is that the collective disturbance of harmonic components at a certain place on the membrane creates the perception of a tone, the residue, which is equal in frequency to the fundamental. The intricacies regarding this theory are rather complex but Schouten (1970) concludes in his article the following three relevant points regarding the missing fundamental:

1. The ear follows Ohm's law, that is, it can hear out the different frequencies in a complex which are further apart than about a full tone.
2. Higher harmonics are heard collectively as one subjective component (one percept), called the residue.
3. The residue has a pitch equal to that of the fundamental tone. If both are present in one sound they can be distinguished by their timbre.

Ritsma (1970:258) confirms this by saying that "if pitch information is available along a large part of the basilar membrane the ear uses only the information from a narrow band. This band is positioned at 3-5 times the pitch value."

How is the residue pitch created? The vibration pattern of the sound that enters the cochlear fluids at the oval window activates many resonance regions along the basilar membrane, depending on the frequency content of the tone. Each frequency component in the complex wave is disentangled from the complex and vibrates at a single point along the membrane. This process is known as frequency discrimination. It is a mechanical process, controlled by the hydrodynamic and elastic properties of the inner cochlea (Roeder 1979:27).

However, not every frequency is equally well resolved by Ohm's predictions, especially those in the higher registers. This may be explained by the arrangement of the basilar membrane and the existence of so-called "critical bands". Regarding the arrangement, Kandel et al. (2000:594) reckons that "the relation between the characteristic frequency and its position of excitement along the basilar membrane varies smoothly and monotonically but is not linear. Instead the logarithm of the frequency is roughly proportional to the distance from the cochlea's apex." In lay terms, equal steps in frequency equal progressively decreasing steps on the membrane and the resonance regions will crowd closer and closer together as one moves up the harmonic series.

Békésy performed experiments in 1960 on preserved cochleae and found that the musically most important range of frequencies, about 20-4000 Hz, covers roughly two-thirds of the basilar membrane, 12-35mm from the base. The remaining portion of the frequency scale (4000-12000 Hz) is decoded by the remaining third (Roeder 1989:22). Doubling the octave always displaces the corresponding resonance region by more or less 3.5-4 mm.

Apart from the physical properties of the basilar membrane, a second reason for the interference of harmonics and the creation of a residue pitch can be explained by critical bands on the basilar membrane. It was stated earlier that the membrane acts as a sort of spectrum analyzer where a specific frequency causes a vibration at a specific place. Each of these places acts as a bandpass-filter with a more or less fixed bandwidth. The width of such a band is roughly 10% of the centre frequency (Sano and Jenkins 1991:44). A filter with a centre frequency at 440 Hz will have a bandwidth of 44 Hz and will be sensitive to or 'pass' frequencies that are up to 22 Hz below and up to 22 Hz above. Similarly, a tone at 2 000 Hz will have a bandwidth of 200 Hz. Such an area on the membrane, known as a critical band, covers a basilar membrane stretch of more or less 1.3 mm long and embraces 1 300 neurons. There are more or less 24 critical bands, arranged edge to edge, that span the audible frequency range (Rossing 1982:85). Section 6.5 will discuss this concept in more detail.

The residue is created when two resonance regions overlap somewhere in the frequency range. The physical nature of the membrane does not allow precise resolution of tones that are close in frequency. When two tones, such as the upper harmonics of a complex tone, are cramped up in the higher regions of frequency decoding, their vibration areas will overlap and have an influence on one another. When two components are presented that fall within a critical bandwidth they will not be heard as separate tones, but as a single percept. For example, a 440 Hz pure tone presented in isolation results in a corresponding vibration at a specific place along the basilar membrane. If a second tone at 500 Hz is added, the resulting sensation will be that of two separate tones. However, due to the finite vibration properties of the membrane, when the second tone is decreased in frequency to, say 410 Hz, the two tones will no longer be separately perceptible but will tend to fuse.

For the purpose here, the essential idea should suffice: if two tones are separated by much more than one critical band, they fire two largely separate areas of hair cells on the basilar membrane; if the two tones lie well within one critical band, they fire almost the same set of hair cells (Campbell and Grated 1987:59). The single percept has a pitch corresponding to the collective firing and integration of neural pulses for that specific region. A “pattern recognizer” in the higher orders of the brain then processes this information to find a common pitch corresponding to the timing pattern (Moore 1989:168). The resulting pitch of the above mechanism is the residue or fundamental observed by Schouten (1970).

We may conclude then that the pitch of a complex tone can be derived form neural signals corresponding to individual partials in the complex, at least for stimuli with low harmonics – and only a small number of harmonics at that. It is still not established whether the information about these partials is coded in terms of place or in terms of temporal patterns of neural firing (Moore 1989:180).

6.4 Vibrato Perception and the brain

The literature concerning the perception of vibrato is scarce in comparison to the perception of other acoustic stimuli. In addition to this, the research is still speculative as to how the auditory system and higher brain functions cooperate in registering the stimulus as one having vibrato. The physiology of the peripheral auditory system is in general well documented. The aim of this section is to firstly get an overview of supporting, related and fringing literature and secondly to possibly arrive at a physiologically supported answer as to why vibrato has become such an important aspect of expressive violin playing.

6.4.1 The physiological view

Any complex periodic tone is frequency analyzed in the cochlea so that each component excites a correlated region in the basilar membrane. The spacing of the components is a function of the fundamental frequency. A raise in pitch of a sound causes a change in the area of vibration of the fundamental and the related harmonic components. If the idea is applied to violin vibrato specifically, the following assumptions can be made:

- An upward roll of the finger induces a rise in perceive pitch of the radiated sound.
- The original pitch and its related harmonics are shifted nearer to the base end (oval window) of the cochlea and the spacing of the harmonics, as a function of the new fundamental, is automatically adapted on the membrane.
- When the finger rolls backwards to produce a lower pitch, the excitation pattern on the membrane as a whole moves towards the apical end.

6.4.2 Pitch and the neural pathway

Before the perception intricacies of the actual vibrato are discussed, consider the pathway that a periodic complex stimulus travels up the brainstem to the auditory cortex where the final processing takes place.

Afferent nerve fibres transport the acquired information from the stimulated hair cells via the cochlear nerve towards the final processing station, the primary auditory cortex, in the cerebral cortex. Along the way the information passes through various cell stations in the brainstem that are responsible for extracting various bits of information from the acoustic stimulus. Figure 6.4 gives a schematic presentation of the main pathway from the cochlea to the primary auditory cortex.

Each station along the path in the central nervous system (CNS) has the function of extracting information from the sound stimulus. Some of the decoding centres are responsible for a variety of tasks in emphasizing, segregating or suppressing various aspects and qualities of the acoustic stimulus (Wallin 1991:151).

The first station in the central nervous system (CNS) is the cochlear nucleus (CN) (see figure 6.4). It consists of various sub-nuclei, each responding to a variety of stimuli mainly responsible for detecting frequencies ranging from the threshold of audibility up to 3 kHz. Phase-related and intensity features are preserved and enhanced here as well.

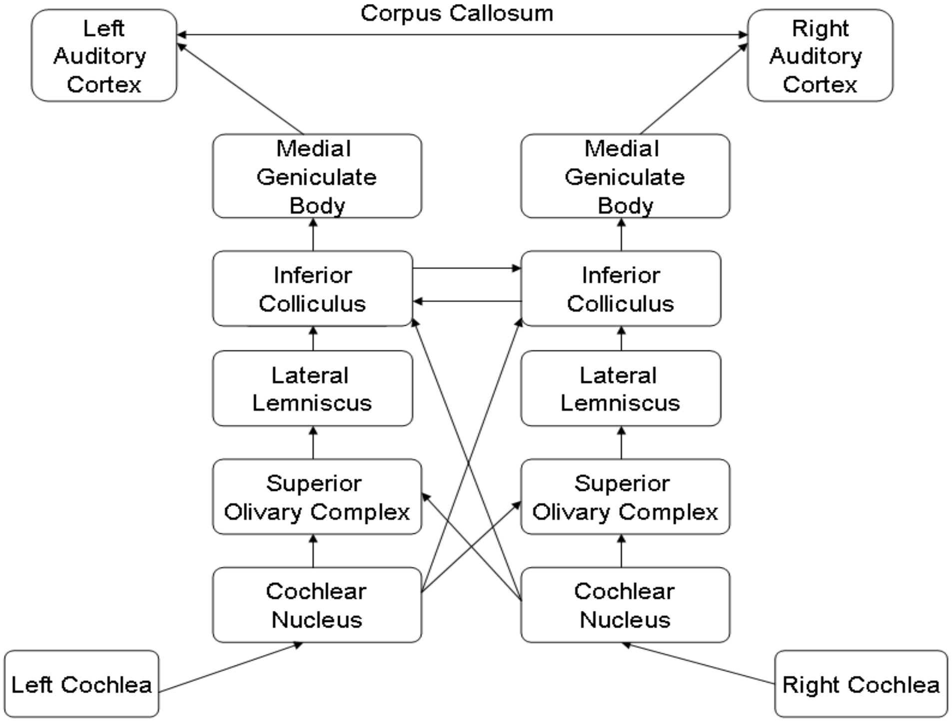


Figure 6.4. Basic plan of the central auditory pathway with main nerve connections (Adapted from Mannell (2002)).

Certain cells in the CN respond well to all frequency modulated (FM) stimuli but other groups of cells are only active when the modulation frequency increases above 20 Hz (Wallin 1991:164). This is an important observation in the journey towards the understanding of vibrato perception and the discussion will return to this in section 6.6. Cells found in the CN seem able to retain the periodic information of the fast-firing nerve impulses coming from the hair cells in the cochlea and are believed to be involved in the detection of periodicity pitch (Wallin 1991:164).

The flow of neural information now reaches the superior olivary complex (SOC) from both the right and left ears. The SOC is primarily responsible for the processing or “mixing” of information coming from the left and right cochleae. It contains binaural neurons affected by inputs from both ears and by being responsive to differences in intensity and timing, helps to indicate the spatial direction of incoming sounds (FitzGerald and Folan-Curren 2002:171).

The lateral lemniscus (LL) receives input from both sides and it is believed that it may be involved in further processing of pitch and spatial direction information. Nuclei within the LL participate in reflex arcs (FitzGerald and Folan-Curren 2002:171).

Next in line is the inferior colliculus (IC). Spatial information from the SOC and intensity and pitch information from the CN are all integrated in the IC. Mannell (2002) says: "The Central Nucleus combines the complex frequency analysis of the cochlear nucleus with the sound localizing ability of the superior olive." This cell is highly tonotopic; sheets of cells represent segments of the basilar membrane (Wallin 1991:151). Wallin refers to the IC as a "sorting house for all auditory information" in the lower brainstem. The organized acoustic information is now passed on to the medial geneculate body (MGB).

The MGB is the specific nucleus in the thalamus[33] for hearing. It accepts afferent fibers from the IC and projects to the central cortex. Groups of cells respond, amongst other things, to complex temporal information, binaural information, and interaural intensity and timing differences (Mannel 2002).

The final stage of acoustic information processing occurs in the primary auditory cortex (AI) situated in Herschel's gyrus[34] in the temporal lobe of the brain. John Eccles (1977:243) comments on this part of the brain by saying:

> We can only dimly imagine what is happening in the human cortex or indeed in the cortices of the higher mammals, but it is at a level of complexity, of dynamic complexity, immeasurably greater than anything else that has ever been discovered in the universe.

In the light of this statement care should be taken when aiming to describe a rather specialist function such as pitch and vibrato perception. However, with the use of microelectric mapping techniques, neuroscientists have been able to track down which area of the brain is activated during different frequencies (Wallin 1991:199). It was found that the cortical area consists of a number of subdivisions serving a common function, yet they are functionally distinct. These divisions can be subdivided into two broad categories: tonotopic areas and auditory response areas. The tonotopic areas are all interconnected and it is here that pitch is finally decoded. Specific frequencies activate specific areas in

---

[33] The Thalamus is the largest nuclear mass in the entire nervous system. The connections from cell bodies to the Thalamus are very diverse so that it can not be said to have a single function.

[34] Schreiner et al. (2002) found that the volume of grey matter in the Herschel's gyrus is highly correlated with musical aptitude. It was also found that certain parts of this brain area are 130% larger in professional musicians than in non-musicians.

the tonotopic areas. The auditory response areas form an outer layer around the latter group and are sensitive to other qualities of the acoustic stimulus.

Goldstein et al. (Wallin 1991:207) found that certain cell units within these pitch areas respond to only a limited frequency range. They conclude that the average response breadth is no larger than 650 cents or a narrow fifth. In general low pitches are registered in the anterior (front part) and high pitches in the posterior (back part) (FitzGerald and Folan-Curren 2002:171).

6.5 Mechanisms for vibrato perception

In order to define the perception of vibrato systematically it is necessary to expand a little more on the basilar membrane physiology and elaborate on the critical-band concept that was briefly described in section 6.3.1.

The physiological properties of the critical band have a great influence on how we perceive vibrato. The membrane can only vibrate that finely, and as a result any two tones that happen to be close in frequency will be coded as one. There are a few extra ‘effects’ added when tones are so closely spaced. One of them is the perception of so-called ‘beats’ which happens for example if two flutes play the same note whilst one plays the note slightly higher or lower. The beats that one experiences are the slow periodic change (amplitude modulation) in the total volume of the complex.

We note a few general facts about the beats experienced when two tones are presented in close proximity (Roeder 1979):

1. The perceived pitch between the two tones will be $f = \frac{f1 + f2}{2}$, so that a simultaneously presented 440 Hz tone and 444 Hz tone will yield a perceptual pitch of 442 Hz.
2. The experienced beating will occur at a rate equal to the difference between the two tones, $f1 - f2$. In this case, four variations in amplitude will be experienced every second, i.e. amplitude modulation with a frequency of 4 Hz.
3. As long as the difference in frequency is less than 10 Hz, the variations can still be clearly perceived. When it increases to about 15 Hz the beat sensation disappears, giving way to roughness added to the tone sensation. Above about 20 Hz, the resonance regions have separated sufficiently so that the pitches may now be separately distinguishable as $f1$ and $f2$.

> Increasing the beat frequency even more, the roughness still persists for a few Hertz above 15 Hz, but after that the two tones sound “smooth” and “pleasing”. The tones are now said to be in their own critical bands.

Figure 6.5 is a graphical presentation of the critical-band concept and places the above three points in perspective.

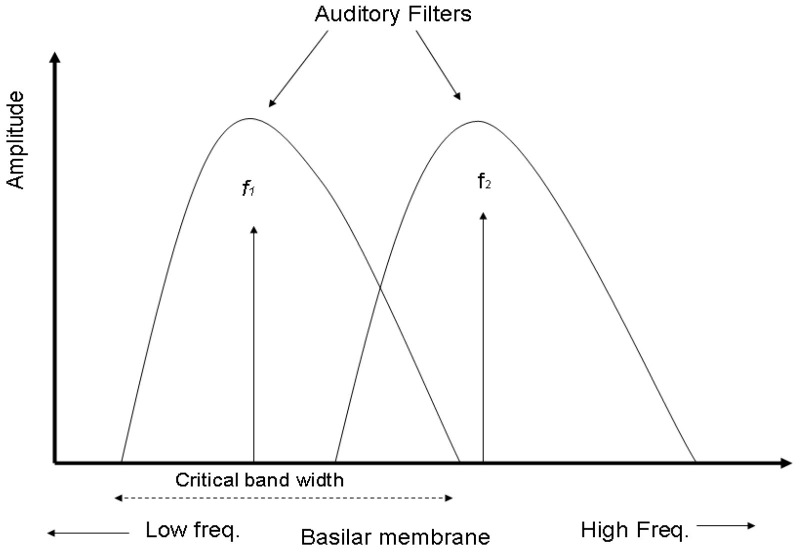


Figure 6.5. Two overlapping auditory filters on the basilar membrane (Adapted from Warren (1999)).

The area where the two critical bands overlap causes the beating or amplitude modulation. When the filters have separated sufficiently so that there is no overlap in resonance area, f_1 and $f2$ will be separately perceived with no modulation.

Now consider the situation from a reversed angle: If ‘beats’ are added to a tone, it is essentially the same as modulating a carrier frequency with amplitude (as described in chapter 4). A tone treated in this manner will acquire a set of extra frequencies, or sidebands, which are present in the signal. In the case of violin vibrato (only considering amplitude vibrato for the moment) the rolling finger, as it passes in and out of resonance regions, causes the sound to modulate at a certain frequency which induces the sidebands. The speed of the finger roll (modulating frequency) determines the distance in frequency between the carrier and adjacent sidebands.

The reason why vibrato is then generally perceived as a pleasing musical attribute is partly due to our basilar membrane's inability to resolve components which are spaced closely together on the basilar membrane. If our auditory system had an infinitely sharp resolution function, we would experience all sounds to be separate in existence as opposed to the fusing capability of such a non-linear system.

Consider a practical example: if a violinist performs vibrato at a rate of less than 10 Hz, according to the above points made by Roeder, the beating will be separately tracked and the sidebands which are also present will not be perceived because they are situated in the same critical-band as the carrier. If the performer could, and he/she increased the rate of the vibrato progressively, the sidebands will eventually be outside the critical band of the carrier and will be perceived separately. Kay and Matthews (1972:675) confirm this by saying that below 10 Hz, the ear hears the "instantaneous frequency change such as might be displayed on a rapidly acting frequency meter." They also found that above 30 Hz modulation, the sidebands start "petering" out and can then be separately heard. The fusion of a vibrato tone thus depends, in part at least, on the proximity of the resolution area of the partials on the basilar membrane.

The question that arises naturally is: How does the basilar membrane inform the brain of this periodic amplitude pulsation? The ear responds to the beats as a residue pitch as observed by Schouten (1970). Neural firings occur at envelope maxima so that a time-based message is relayed to the higher orders of the brain.

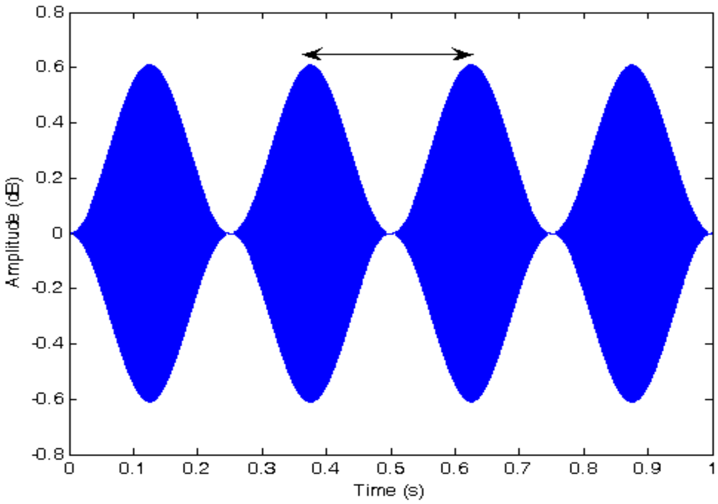


Figure 6.6. Displacement waveform of an amplitude modulated sinusoid.

The arrows in the above graph indicate where nerve firings would typically occur. In this case a 440 Hz sine tone is modulated 100% at a frequency of 4Hz. Therefore, an amplitude modulation firing occurs every 0.25 seconds (Ritsma 1970).

Thus far we have only described the mechanisms involved in amplitude modulation, the reason being that the basilar membrane ‘equipment’ used to produce and detect the fundamental pitch, or residue, of a complex tone are also involved in the detection of amplitude modulation. Frequency modulation is just as much a part of vibrato and some believe its coding mechanism to be essentially the same as that active in the detection of amplitude modulation.

Kay and Matthews (1972) argue that frequency modulation detection cannot be coded by the same temporal phase-locking mechanism used in amplitude modulation and suggest that separate mechanisms are at work to distinguish the two effects. Their argument is that if neural firings occurred at the maxima of the amplitude waveform (figure 6.6) and also on the maxima of the frequency contour, the ‘nerve message’ would essentially be the same and they would be indistinguishable. An array of listening tests confirmed that the detection of FM was not influenced by the presence of AM.

By the time of the publishing of their article, Whitfield and Evans (1965) had obtained some neurophysiological data from tests performed on cats that suggested that frequency modulation was an adequate stimulus to excite many cells in the auditory cortex and in the inferior colliculus (the ‘sorting’ centre of the auditory pathway). They were therefore sure that separate mechanisms were at work but not exactly sure how. Kay and Matthews (1972) conclude with two attributes relevant to the FM specific decoder:

1. It is little concerned with modulation periodicity *per se* but more with the instantaneous frequency changes carried in the modulation waveform of the frequency modulated wave.
2. It is independent of any carrier frequency.

Moore and Sek (1996) on the other hand believe that FM detection depends on a combination of a phase-locking and place mechanism, depending on the carrier frequency. They suggest that phase locking may play a role in the detection of FM for carrier frequencies below 4 kHz and only for modulation rates below 10 Hz. Their conclusions regarding separate coding channels for FM and AM are in agreement with Kay and Matthews (1972). The phase-locking mechanism for FM detection appears to operate by sampling the stimuli at different time points during its duration.

Below is a displacement time graph showing the phase-locking mechanism involved in FM, quite similar to AM detection. According to Moore and Sek (1996:1329), the FM temporal mechanism operates by “sampling the stimuli at different points during the modulation cycle.” Ritsma (1970) confirms the sampling at the peaks of the modulation waveform.

Figure 6.7 is a displacement time graph indicating the times of neural firing in the time domain in decoding FM. In this case a 440 Hz sine tone is frequency modulated at a rate of 11 Hz and with exaggerated extent of 300 Hz for the purpose of illustration.

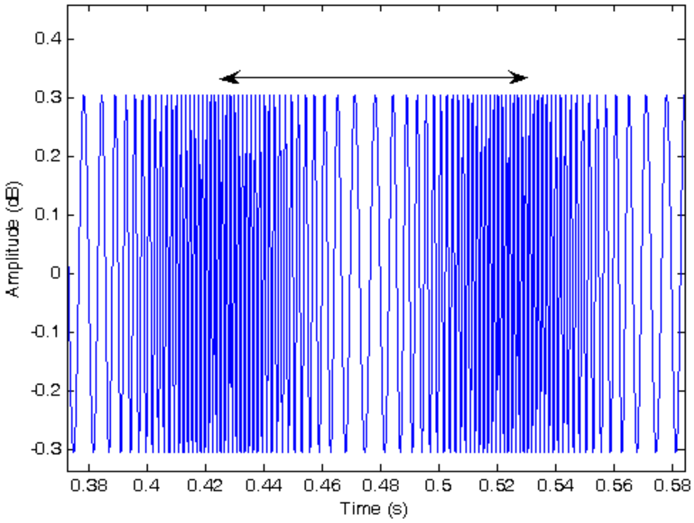


Figure 6.7. Displacement waveform of a frequency modulated signal.

6.6 The bigger picture

From the reviewed literature, the picture regarding tone perception and more specifically vibrato perception is for practical purposes still sketchy. Even the above overview of the auditory system defining the flow of neural information and some of the specialized mechanisms at work may be confirmed by one author and then expanded on or contradicted by another. As far as the physiology and anatomy of the lower auditory system is concerned most of its intricate detail have been researched and documented to a level where current research is at least generally united on that information. However, the higher up in the brain stem the research treads the more speculative the physiology of the different areas in the brain becomes. This compels the outsider-researcher to appreciate the complexity and the intricacies of the mechanisms at work.

Only recently have the development of *functional magnetic resonance imaging* (FMRI) made it possible for researchers to literally ‘see’ how man hears. Hart et al. (2003) conducted tests to try and see the cortical processes involved in modulation. For the purpose of the study, they prepared two carrier signals of 300 Hz, the one a pure sine tone and the other a complex tone. Each one was modulated at a rate of 5 Hz, either in frequency or amplitude, to create six stimulus conditions: unmodulated, FM and AM for both the pure and complex tones. FM signals were modulated with an extent of 50 Hz and the AM signals were 100% modulated. The individual tones were played to 12 participants and images revealing brain activity during the duration of the stimulus were taken for each. In general, they found that the unmodulated 300 Hz tones, both pure and complex, yielded very little or no sound-evoked activation. Results for the modulated tones reveal bilateral (both sides of the brain) activation in certain areas of the HG and of a considerable greater magnitude. Comparing complex to pure tone modulation, the mean magnitude of activation between the participants is always greater for the harmonic-complex tones. It was found that FM and AM activate similar regions in the HG. However, some areas may be more sensitive to one than the other. One such specialized unit showed an especially high response to a spectro-temporally modulated tone.[35] The latter mentioned overlapping areas of activation in the auditory cortex are due to the fact that the “principle frequency components for both FM and AM tones are centred on the same auditory channel and hence would stimulate common populations of frequency-sensitive auditory cortical neurons” (Hart et al. 2003:780).

Figure 6.8 shows an FMRI scan taken from a subject who was presented with a complex tone containing both frequency and amplitude modulation. The red dot in the scan indicates the area where both AM and FM are active stimulants.

---

[35] Zattore and Belin (2001:946) attribute this finding to humankind’s innate sensitivity to the subtle changes in spectral energy distribution found in the speaking voice.

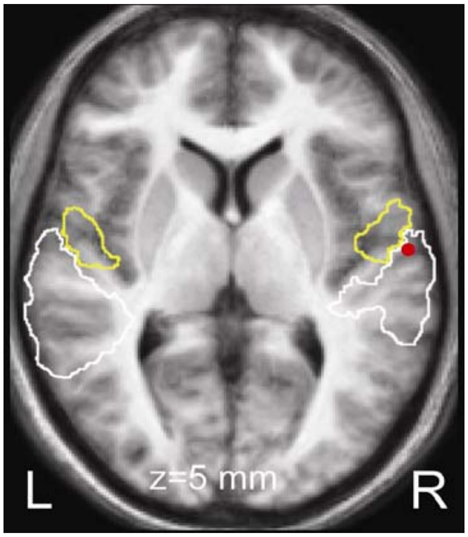


Figure 6.8. FMRI scan showing the regions of FM and AM activation. The yellow outline shows the border of the later HG and the white border shows the outline of the planum temporale. (Source: Dr Deb Hall, Senior Program Leader Scientist at the MRC Institute of Hearing Research, Nottingham).

Many years before the Hall et al. study, Creutzfeldt (1978) (in Wallin 1991) presented some interesting points already in support of the auditory cortex's predisposed function to be more acutely aware of sounds with change:

1. Tonic, i.e. maintained activity, during longer lasting sensory stimulus is largely if not completely suppressed, and cortical neurons respond preferentially if not exclusively to stimulus change (transients) in time, or space (movement of the stimulus along the sensory surface).
2. Repetitive stimulation, i.e., repetition of a signal, at a frequency of 5 to 20 Hz per second gives better responses than single stimulation.
3. Therefore, for many neurons in sensory projection areas, a combination of repetitive changes in space and time, i.e. repetitive movements along a sensory organ such as the organ of Corti, are optimal stimuli. These may be moving objects in the visual field, recurrent movement along the skin, or temporally structured frequency as well as amplitude modulation in the auditory system.

All evidence points towards a mechanism dedicated to periodic change in a signal and the results obtained from the Hall et al. study are of great importance for the purpose of the present study in proving exactly that. Firstly, the complex-tone stimuli used resembles to a certain degree the spectrum of an acoustic musical instrument (see chapters 3 and 4). Secondly, the modulation rates are similar to that of average violin vibrato (Seashore 1947). Reasonable assumptions can therefore be made with regard to the cortex's role in the processing of violin vibrato tones.

However, it is outside the scope of this study to indulge in deeper physiological functions than what has already been stated above and due to the complexity of the matter it seems unlikely that a clearer picture will surface anyhow. Unfortunately, the information is still inconclusive and even though Hart et al. were able to pin-point areas especially reserved for temporal detection, the question remains unanswered as to how exactly it is perceived. The problem could then be stated as follows: How does the auditory system manage to unite all the information extracted form the complex vibrato signal in the sub-cortical decoding stations and allow the listener to perceive it as a single percept?

One possible solution can be found in the so-called *Principle of Common fate.* The term has its origins in the Gestalt-theory that stresses the idea of totality instead of individual components of a perceptual entity. Reybrock (1991:58) sells the Gestalt concept as an "overall quality of content of consciousness that transcends its components parts". If science cannot yet provide the answers for a system's inner workings, this theory provides an alternative route for the explanation of a complex system and has been applied specifically to the phenomenon of AM and FM sounds. Furthermore, it compels the researcher to 'step back' as it were from the intricacies of the "component parts" and observe the situation from a wider perspective.

What this theory aims to answer is: under which circumstances do sounds tend to be segregated into its component parts or fuse into one percept? Bregman (1990) prepared a wide range of listening tests to answer similar questions than those of the present study. The following points provide a summary of his results:

Firstly, below are two reasons why sounds in a complex will not tend to fuse:

1. Simultaneous sounds fuse as a function of the basilar membrane. In general, the greater the frequency separation between harmonic and its nearest frequency neighbour, the easier it will be to hear the separate components.
2. Sounds that have a timing difference in their starting point will be heard as separate tones for the remainder of their duration.

Bregman continues with results from his experiments that suggest circumstances under which sounds will tend to fuse:

1. Again as a function of the basilar membrane, if sounds cannot be separated in this regard (overlapping resonance areas) it is unlikely that they will be coded separately in the nervous system.
2. The “harmonicity principle” determines that when all the harmonics of a complex are harmonically related to the fundamental (as in the case of a violin tone) the individual components will fuse.

And now to integrate Bregman’s findings with the comments of Creutzfeldt, below are results of fusion tendencies with regard to temporal change. Bregman continues:

3. If different parts of the spectrum change in the same way at the same time, they probably belong to the same environmental sound. This implies that during a vibrato cycle, upper harmonics change with the same ratio as that of the fundamental and this relationship is viewed as a ‘common fate’ characteristic of the sound source.
4. Sounds are also fused when they start and stop at the same time, glide up and down and swell and decline in intensity together.
5. Parallel changes causes fusion of partials.
6. Common amplitude changes in different spectral regions (and hence a common neural periodicity) could bind regions of the spectrum together into a single perceived sound.

All of the above points offer a very convenient and perhaps simpler alternative to the questions regarding violin vibrato perception. They do not change the uncertainty due to lacking evidence. Given the legitimacy of the theory, with substantial evidence, they offer closure to an otherwise open ended discussion.

6.7 Conclusion

This chapter traced the perception of an acoustic stimulus right from the time when it impinges on the basilar membrane, through the auditory system, to the final interpretation of sounds in the auditory cortex. The acoustic stimulus is disentangled into its component parts on the basilar membrane. The neural information acquired from these sounds contains information regarding its frequency, amplitude, time varying characteristics, timbre, etc. Specialized centres along the auditory pathway towards the brain interpret this information, rearranges it, enhancing certain aspects while diminishing others, and sends it off to higher centres for further processing. The auditory cortex, situated in Herchyl’s gyrus, miraculously moulds the extracted information into a unitary whole to be perceived as a single percept.

It was found that FM and AM components in the signal are coded separately from the carrier signal which provides evidence of a separate mechanism dedicated to the detection of temporal changes. The exact mechanisms for these intricate tasks are not known yet and an alternative approach in describing the system was offered in the form of a Gestalt concept. The principle of common fate continues to explain the auditory cortex’s ability of uniting a complex sound event such as the violin vibrato tone into a single percept. Reasons were given and it is assumed in general that humankind’s acceptability and perhaps need to hear vibrato stem form a deeper “ecological necessity” that enables humankind to make sense of the surrounding acoustic world.

Chapter 7

Conclusion

7.1 Introduction

The study set out to investigate the phenomenon of violin vibrato. During the initial stages of research on the topic, it became apparent that although the term is directly associated with left hand violin technique, it also manifests in many other disciplines not even directly associated with music. The broader field of violin vibrato literature was found to include components of history, performance practice, analytical science, digital signal processing, education, physics, psychology, physiology, sound synthesis, and many more. As it was stated in the introductory notes of the thesis, all research regarding the topic seem to fundamentally ask the same questions: *Why is vibrato such an important aspect of violin performance and why do we like it?* The study was consequently approached in a multidisciplinary manner in order to appropriately investigate the main research question and pursue the other objectives stated in chapter 1.

7.2 Summary of main research documented in chapters 2-6

One of the challenges that the researcher faced was the ordering of the vast and diverse amount of literature into a comprehensible and logical ‘vibrato story’. Below is a summary of each of the chapters in the thesis, highlighting the line of thought followed with reference to the research question:

- *Chapter 2: History and development of violin vibrato*. This chapter provided the historical backdrop to the thesis. The origins and development of the instrument and the technique, all the opinions, questions, and even mystical connotations to it were judged to be important information in establishing that vibrato is in fact an intriguing phenomenon worthy of further research. A handy link to the remainder of the thesis came in the form of the stabilizing of the technique to universal continuous use in the 1930s. The same decade saw the first large-scale investigation into the scientific realm of the technique. Chapter 2 thus set the stage for the subsequent scientific investigation.

- *Chapter 3: The sound of the violin.* Violin vibrato is essentially the periodic changing of a played note. However, before that could be described in detail it was necessary to thoroughly and accurately describe what constitutes a *steady* violin tone. In order to arrive at this point, the sound production process was traced from the moment of string excitation, through the various vibration properties of the instrument, to the factors contributing to the sound that humankind perceives as emanating from a violin. The spectrum and sound quality of the instrument was described as end results of the chapter.
- *Chapter 4: Fundamentals of violin vibrato.* This chapter described what happens to a steady violin sound when vibrato is administered to it. Various experiments were set up to investigate the changing sound of the instrument. It was indicated that vibrato does not only induce a change in pitch, but also in amplitude and timbre. It was concluded that the sound spectrum of violin vibrato tones is immensely complex – all governed by the only two parameters available to the violinist: the *rate* at which the finger is moved back and forth and the *width* of the finger movement.
- *Chapter 5: Vibrato measurement and comparison*. Vibrato use is said to be one of the most distinguishing features in violin performance. Whereas the previous chapter was concerned with the 'what' of vibrato, chapter 5 continued the story by investigating the 'how', i.e., how it is used by different violinists. The discussion was in the form of an experiment comparing the rates and widths of four virtuosi. The individuality element was graphically illustrated with the aid of specialized computer software.

Up until this point the history, physical sound production, science and application of violin vibrato had been thoroughly investigated. The reader had by now been introduced to the main disciplines of vibrato and this provided the information necessary to proceed to the conclusive chapter on how the human auditory system responds to vibrato tones.

- *Chapter 6: Vibrato perception.* In this final chapter the 'tools' for sound perception were firstly described. As a forerunner for the perception of a tone with periodic change, the perception of a steady-state tone was traced from the time that the sound wave enters the ear, up to the processing of acoustic information by specialize brain centres. The human auditory system seems to be specially equipped to interpret sounds with periodic change – such as violin vibrato tones. The pinnacle of the thesis is the evidence that certain centres in the brain are activated only by sounds with parameters closely associated with normal violin vibrato.

Although the research in the thesis is robust and daring at times, the above is evidence that the main objectives and an acceptable answer to the main research question have been achieved.

7.3 Summary of unique contributions to the study of violin vibrato

All the research documented in this thesis is somehow linked to prior research in one way or another. It was stipulated in chapter 1 that the study would be explorative in nature, which provided the platform to explore beyond the conventional boundaries set by existing literature. In some cases the available data were merely arranged in a certain manner which resulted in unique interpretations. In other instances, as in chapter 5, an existing experiment was adapted and improved upon to achieve better results and more accurate data for future research.

Below is a summary of the thesis's contributions to the study of violin vibrato. These constitute general comments and are not necessarily arranged according to the chapter in which it was described:

- From the literature addressing the historical aspect of vibrato, it was established that the origins and, more precisely, the geographical origins have never really been researched. It was established why northern Italy was responsible for the chain of events that led to its first formalized used in 1617.
- The sound production process of the violin has been fairly adequately researched before. However, the manner in which the information regarding this complex process was documented here provides a unique glimpse of the event as a comprehensive and interwoven process: from string vibration, to the conversion of energy into sound waves, collectively amounting to violin timbre.
- Chapter 4 indulged in experiments in an attempt to view the changes in the sound wave that is brought about by the action of vibrato. None of the literature studied has researched – especially – the 'sideband'-phenomenon (see section 4.3 and figure 4.12) to any length, let alone mention the existence thereof. It is believed that certain concepts such as the 'leaning' characteristics of harmonics and their related sidebands in the overtone series of vibrato tones are presented here for the first time in a musical context.
- The 'leaning' characteristic observed in section 4.3.3.2 when FM and AM are offset by specific angles was found to also manifest in higher harmonics. Figure 4.14 demonstrates that each harmonic is susceptible to the interaction of frequency and amplitude in different phases. A reason

for this may be due to different vibration modes found on the instrument, observed by Weinreich (1997).

- The type of experiment performed in chapter 5 has been used by other researchers to acquire similar results. However, it seems unlikely that analysis of this kind have been performed on the Sonata no.1 in G minor by J.S. Bach. The data acquired from the analysis thus constitutes unique research.

- The individuality of vibrato use amongst violinists has according to the available literature not been adequately researched. Although Hollinshead (1931) and Reger (1931) did mention the within-note variation that constitutes a great part of the individuality, there is no clear representation of what it exactly entails. The vibrato of Mark Lubotsky was used to graphically demonstrate the unique manner in which he approaches vibrato, which clearly distinguishes him from the other players. The other violinists’ sound samples were not always useable for such observations but it is believed that with more time and thorough research, the same vibrato ‘profile’ may be observed in other players.

- The discussion of vibrato perception in chapter 6 borders brittle academic grounds. Firstly, the physiology of hearing is immensely complex and even the more specialist researchers deliberately comment on the infancy of human understanding of this field. The same applies to the neurophysiology involved. As a result, a continuous line of thought of vibrato perception is constantly interrupted with ‘gaps’ in the available research. Therefore, a few well-argued assumptions were made in order to at least arrive at an answer that may stand up to a measure of academic scrutiny. One such assumption is in section 6.6 where the Hart et al. (2003) study proved that the brain is especially sensitive to complex musical tones, frequency and amplitude modulated by a certain amount. Given the timbre of violin tone, the fact that FM and AM are present in any vibrato tone, the average rates and widths of vibrato application etc. it is assumed that the brain would respond in a very similar manner to violin vibrato.

7.4 Future research

The complexity of violin vibrato tone in the acoustic sense, its irregularity in playing, the individuality of its application and the infancy of science's understanding of its perception renders it a phenomenon worthy of research in many academic disciplines.

In a musical and educational context, vibrato is still very much a developing technique. No style or specific piece of music can or should be approached with the same vibrato intentions. Teachers and performers could benefit from more in-depth research regarding what type of vibrato was applicable at the time of a specific work's composition. This would aid in more 'correct' interpretation and secure the integrity and respect for the work in generations to come.

Chapter 5's contribution to the individuality of violinists could be expanded to be of great use to violinists. Apart from the many years of practice and dedication needed to play on a professional level, the quantified vibrato data regarding a performer's exact way of playing could assist young instrumentalists in excelling towards greater understanding and better application of the technique.

All the analysis performed in this thesis could easily be adapted to any other instrument. Instruments which make efficient use of vibrato that have not been adequately researched, such as the bassoon or oboe, could only benefit from similar studies.

The various experiments performed in Csound and Matlab to investigate the sound spectrum of a violin tone only touched on aspects, beneath which a wealth of information and knowledge waits to be uncovered. Few sources are able to justify why violin timbre is so rich-sounding compared to other instruments. Our understanding of this concept would be greatly improved by research on the harmonic structure of vibrato tones. A possible angle of approach would be to clearly define the influences of AM and FM on the sidebands produced by the action of vibrato and then to define its effect on perception.

The human perception of sound is still not entirely understood, let alone sounds with change. We know that sounds that change periodically are more stimulating for the brain than ones that are steady, but how that happens is still a mystery. Violin vibrato oscillates not only in pitch but also in amplitude and timbre. Chapter six provided some insights into the mechanisms involved in coding sounds with frequency and amplitude modulation but the aspect of timbre vibrato has not even been mentioned in any literature reviewed.

7.5 Final thought

The thesis posed the question of why vibrato on the violin may be such an appreciated effect in violin performance. After a substantial amount of research and trial and error experimentation, a robust yet plausible answer was provided with the help of the Hart et al. (2003) study and the comments of Creutzfeldt (1978). Some may argue that the thesis could therefore have been shortened to no more than two pages of answers. However, it was stated in the first chapter that the documentation in the thesis will be a journey of scribbling down what may be of use in answering the research question. The comments of Hall et al. and Creutzfeldt would most probably have been missed in the whirl of data if it hadn't been for the cumbersome sifting and progressive documentation of research findings. And the contributions listed in section 7.3 would have been lost.

As a final word: it is sincerely hoped that others may benefit from the information documented in the thesis so that they may be inspired to part take in the understanding and improvement of a true musical phenomenon.

References

Internet and printed publications

Alesandrini, R. 1999. Performance practice in the *seconda prattica* madrigal. *Early Music*, 27(4): 632-640.

Askenfelt, A. 1989. Measurement of the bowing parameters in violin playing. II: Bow-bridge distance, dynamic range, and limits of bow force. *J. Accoust. Soc. Am.* 86(2): 503-516.

Auer, L. 1980. *Violin playing as I teach*. New York: Dover.

Baillot, P. 1991. *The art of the violin*. Translated and edited by Louise Goldberg. Original (1835). USA: Northwestern University Press.

Bang, M. 1923. *Violin method*. New York: Carl Fischer.

Beare, C., Chiesa, C., and Kass, P. ‘Amati’. *Grove Music Online* ed. L. Macy (Accessed 10 November 2007), http://www.grovemusic.com.

Benade, A. 1990. *Fundamentals of musical acoustics*. New York: Dover.

Bonta, S. 1990. The use of instruments in sacred music in Italy 1560-1700. *Early Music*, 18(4): 519-535.

Borchard, B. ‘Joachim, Joseph.’ *Grove Music Online* ed. L. Macy (Accessed 10 November 2007), http://www.grovemusic.com.

Boulanger, R. 2001. Introduction to sound design in csound. In R, Boulanger (Ed.), *The Csound Book.* Cambridge: The MIT Press.

Boyden, D. 1965. *The history of violin playing from its origins to 1761 and its relationship to the violin and violin music*. London: Oxford university press.

Boyden, D., and Walls, P. ‘Violin: history and repertoire.’ *Grove Music Online* ed. L. Macy (Accessed 10 November 2007), <http://www.grovemusic.com>

Bregman, A. 1990. *Auditory scene analysis*. Cambridge: MIT Press.

Brice, R. 2004. *Music engineering*. Second edition. Oxford: Elsevier.

Brown, C. 1988. Bowing styles, vibrato and portamento in nineteenth-century violin playing. *Journal of the Royal Musical Association*, 113(1): 97-128.

Brown, J., and Vaughn, K. 1996. Frequency ratios of spectral components of musical sounds. *J. Accoust. Soc. Am.* 100(3): 1728-1735.

Burney, C. 1957. *A general history of music: from the earliest ages to the present period*. New York: Dover.

Butler, D. 1992. *The musician's guide to perception and cognition*. New York: Schirmer.

Campbell, M., and Greated, G. 1987. *The musician's guide to acoustics*. London: Dent&Sons.

Capwell, C. 1986. Palastrina style. *The New Harvard Dictionary of Music*. London: Harvard University Press.

Carter, S. 1991. The string tremolo in the 17th century. *Early Music*, 19(1): 42-59.

Chew, G. 'Stile concitato.' *Grove Music Online* ed. L. Macy (Accessed 17 November 2007), http://www.grovemusic.com

Chowning, J., and Bristow, D. 1986. *FM Theory & Applications*. Tokyo: Yamaha Music Foundation.

Cutnell, J., and Johnson, A. 1995. *Physics*. New York: John Wily&Sons.

Davis, H. 1908. How does a violinist control his tone? *Meeting of the American physical society,* 4: 331-332.

Desain, P., Honing, H., Aarts, R., and Timmers, R. 1999. Rhythmic aspects of vibrato. In P. Desain and W, Windsor (Eds.), *Rhythm perception and production* (pp. 203-216). Lisse: Swets & Zeitlinger.

Dilworth, J. 1992. The violin: Introduction and terminology. In R, Stowell (Ed.), *The Cambridge companion to the violin*. Cambridge: Cambridge University Press.

Dodge, C., and Jerse, T. 1985. *Computer music: synthesis composition and performance*. New York: Schirmer.

Eberhardt, S. 1910. *Violin vibrato, its mastery and artistic uses*. New York: Carl Fischer.

FitzGerald, M., and Folan-Curren, J. 2002. *Clinical neuroanatomy and related neuroscience*. London: Saunders.

Flesch, C. 1957. *Mémoires.* London: Rockliff.

Flesch, C. 1924. *The Art of Violin Playing*. New York: Fischer.

Fletcher, H et al. 1965. Quality of violin, viola, cello, and bass-viol tones. *J. Acoust. Soc. Am.* 34(5): 851-863.

Fletcher, N., and Rossing, T. 1998. *The physics of musical instruments*. New York: Springer.

Fletcher, H., and Sanders, L. 1967. Quality of violin vibrato tones. *J. Acoust. Soc. Am.* 41(6): 1534-1544.

Gammie, I. 1978-9. Ganassi: regola rubertina (1542): A synopsis of the text relating to the viol. *Chelys*, 8: 51-58.

Geminiani, F. 1969. *A treatise of good taste in the art of music*. Original (1749). New York: Da Capo Press.

George, W. 1954. A sound reversal technique applied to the study of tone quality. *Acustica*, 4:224-225.

Geringer, J., and Allen, M. 2004. Analysis of vibrato among high school and university violin and cello students. *Journal of Research in Music Education*, 52(2): 167-178.

Gockel, H., Moore, B., and Carlyon, R. 2001. Influence of rate of change of frequency on the overall pitch of frequency-modulated tones. *J. Acoust. Soc. Am.* 109(2): 701-712.

Göllner, T. 'Mass.' *Grove Music Online* ed. L. Macy (Accessed 12 October 2007), http://www.grovemusic.com

Grey, J. 1977. Multidimensional perceptual scaling of musical timbres. *J. Acoust. Soc. Am.* 61(5): 851-863.

Haar, J. 'Madrigal.' *Grove Music Online* ed. L. Macy (Accessed 18 November 2007), http://www.grovemusic.com

Hart, H., Palmer, A., and Hall, D. 2003. Amplitude and frequency modulated stimuli activate common regions of human auditory cortex. *Cerebral Cortex*, 13: 773-781.

Helmholtz, H. 1885. *On the Sensations of Tone*. Translated by A. Ellis. London: Langman's Green and co.

Hollinshead, M. 1931. A study of the vibrato in artistic violin playing. In C. Seashore (Ed.), *The Vibrato*. Iowa: University of Iowa.

Holman, P. 'Violin.' *Grove Music Online* ed. L. Macy (Accessed 16 November 2007), http://www.grovemusic.com

Houtgast, T., and Steenenkamp, H. 1985. A review of the MTF concept in room acoustic and its use for estimating speech intelligibility in auditoria. *J. Acoust. Soc. Am.* 77:1069-1077.

Hutchins, C. 1990. A study of the cavity resonances of a violin and their effects on its tone and playing qualities. *J. Acoust. Soc. Am*. 87(1):392-397.

Illingworth, V. 1998. *The penguin dictionary of electronics*. London: Penguin Books.

Jannson, E. 2002. *Acoustics for violin and guitar makers*. Retrieved 6 June, 2007 from http://ww.speech.kth.se/music/music/acviguit4/index.html.

Joachim, J., and Moser, A. 1905 *Violinschule in 3 Bañden / Violin school in 3 volumes*. Translated by A. Moffat. Leipzig: Simrock.

Joris, P., Shreiner, C., and Rees, A. 2004. Neural processing of amplitude-modulated sounds. *Physiol Review*. 84: 541-577.

Kandel, E., Schwartz, J., and Jessel, T. 2000. *Principles of neural science*. Retrieved 17 June, 2007 from http://books.google.com/books. USA: McGraw-Hill.

Katz, M. 2002. Aesthetics out of exigency: violin vibrato and the phonograph. In H. Braun (Ed.), *Music and technology in the 20th century* (pp. 174-185). London: Johns Hopkins University Press.

Kay, R., and Matthews, D. 1972. On the existence in human auditory pathways of channels selectively tuned to the modulation present in frequency modulated tones. *J. Physiol.* 225: 656-677.

Lochner, L. 1951. *Fritz Kreisler*. London: Macmillan.

Lockwood, L., and Kirkman, J. 'Mass.' *Grove Music Online* ed. L. Macy (Accessed 1 November 2007), http://www.grovemusic.com.

Macleod, R. 2006. *Influences of dynamic levels and pitch height on the vibrato rates and widths of violin and viola players*. Unpublished doctoral thesis. Florida: Florida Sate University.

Mannell, R. The brainstem auditory nuclei and centrifugal pathways. *Lectures on auditory physiology and psychoacoustics.* Retrieved March 18, 2007 from http://www.zainea.com/The%20Brainstem%20Auditory%20Nuclei.html.

Marshall, K. 1984. Modal analysis of a violin. *J. Acoust. Soc. Am.* 77(2): 695-709.

Maynard, L. 1998. *The effect of vibrato rate on string instrument vibrato preferences*. Retrieved June 17, 2007 from http://www.tmea.org/080_College/Research/may1998.pdf.

Mazzola, G. 2002. *The topos of music*. Basel: Birkhäuser-verlag.

Mellody, M., and Wakefield, G. 2000. The time-frequency characteristics of violin vibrato: modal distribution analysis and synthesis. *J. Acoust. Soc. Am.* 107(1): 598-611.

Moore, B. 1989. *An introduction to the psychology of hearing.* London: Academic Press.

Moore, B., and Sek, A. 1996. Detection of frequency modulation at low modulation rates: evidence for a mechanism based on phase locking. *J. Acoust. Soc. Am.* 100(4): 2320-2331.

Mozart, L. 1975. *A treatise on the fundamental principles of violin playing*. 2nd Ed. Translated by Editha Knocker. Original (1756). London: Oxford University Press.

Newcomb, A. 'Madrigal.' *Grove Music Online* ed. L. Macy (Accessed 10 November 2007), http://www.grovemusic.com

Papich, G., and Rainbow, E. 1974. A pilot study of performance practices of twentieth-century musicians. *Journal of Research in Music Education*, 22(1): 24-34.

Phillips, P. 1978. Performance practice in 16th century english choral music. *Early Music*, 6(2): 195-199.

Prame, E. 1994. Measurements of the vibrato rate of ten singers. *J. Acoust. Soc. Am.* 96(4): 1979-1984.

Razzi, F. 1980. Polyphony of the seconda prattica: performance practice in Italian vocal music of the mannerist era. *Early Music*, 8(3): 298-311.

Reger, S. 1931. The string instrument vibrato. In C. Seashore (Ed.), *The Vibrato*. Iowa: University of Iowa.

Reybrouck, M. 1994. Gestalt concepts and music: limitations and possibilites. In M. Leman (Ed.), *Music, gestalt, and computing*. Berlin: Springer-Verlag.

Risset, J. and Wessel, D. 1999. Exploration of timbre by analysis and synthesis. In D. Deutsch (Ed.), *The psychology of music*. 2nd Ed. London: Academic press.

Ritsma, R. 1970. Periodicity detection. In R. Plomp and G. Smoorenburg (Eds.), *Frequency analysis and periodicity detection in hearing.* Leiden: Sijthoff.

Roeder, J. 1979. *Introduction to the physics and psychophysics of music*. New York: Springer-Verlag.

Rossing, T. 1982. *The science of sound*. Massechusetts: Addison-Wesley.

Russ, M. 1996. *Sound synthesis and sampling*. Oxford: Foal Press.

Sachs, C. 1949. *A short history of world music*. London: Dobson.

Sano, H., and Jenkins, B. 1991. A neural network model for pitch perception. In P, Todd and G. Loy (Eds.), *Music and connectionism*. Cambridge: MIT Press.

Saunders, F. 1953. Recent work on violin. *J. Acoust. Soc. Am.* 21(3): 491-498.

Schoonderwaldt, E., and Friberg, A. 2001. Towards a rule-based model for violin vibrato. In C. Buyoli, and R. Loureiro (Eds.), *Workshop on Current Research Directions in ComputerMusic, November 15–17, 2001*: 61–64. Retrieved 17 June, 2007 from: http://www.iua.upf.es/mtg/mosart/papers/p32.pdf

Schouten, J. 1970. The residue revisited. In R. Plomp and G. Smoorenburg (Eds.), *Frequency analysis and periodicity detection in hearing.* Leiden: Sijthoff.

Schnoebelen, A. 1990. The role of the violin in the resurgence of the mass in the 17th century. *Early Music*, 18 (4): 537-542.

Schreiner, P. *et al*. 2002. Morphology of Herchl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nature Neuroscience*, 5(7): 688-694.

Seashore, C. 1927. A base for the approach to quantative studies in the aesthetics of music. *The American Journal of Psychology*, 39(1/4): 141-144.

Seashore C. 1931. The Natural History of the Vibrato. *Proceedings of the National Academy of Sciences*, 17(12): 623-628.

Seashore, C. 1932. *The vibrato*. Iowa: University of Iowa.

Seashore, C. 1937. The psychology of music: IX. A performance score with phrasing score for the violin. *Music Educators Journal*, 24(1): 28-29.

Seashore, C. 1938. *Psychology of music*. New York: McGraw-Hill.

Seashore, C. 1947. *In search of the beauty in music: a scientific approach to musical aesthetics*. New York: Ronald.

Sethares, W. 2005. *Tuning, timbre, spectrum, scale*. USA: Springer.

Sherr, R. 1986. Mass. *The New Harvard Dictionary of Music*. London: Harvard University Press.

Shonle, J., and Horan, K. 1980. The pitch of vibrato tones. *J. Accoust. Soc. Am.* 67(1): 246-252.

Spohr, L. 1900. *Violin school*. Translated by F. Marshall, and edited H. Holmes. Original (1832). London: Boosey.

Stowell, R. 1994. *The Cambridge Companion to the Violin.* Cambridge: Cambridge University Press.

Timmers, R., and Desain, P. 2000. Vibrato: questions and answers from musicians and science. *Proceedings of the sixth ICMPC*: Keele.

Wakayama, T., Nagashima, M., Yamazaki, O., and Suzuki, H. 2004. Comparison of violin vibratos among four virtuosi. *Proceedings of the International Symposium on Musical Acoustics, 2004.* Japan: Nara.

Wallin, N. 1991. *Biomusicology*. New York: Pen Dragon Press.

Wang, L. and Burroughs, B. 2001. Acoustic radiation from bowed violins. *J. Accoust. Soc. Am.* 110(1): 543-555.

Warren, R. 1999. *Auditory perception: A new analysis and synthesis*. USA: Cambridge University Press.

Weinreich, G. 1997. Directional tone color. *J. Accoust. Soc. Am.* 101(4): 2338-2346.

White, G. 2002. *The audio dictionary*. USA: University of Washington Press.

Whitfield, I., and Evans, E. 1965. Responses of auditory cortical neurons to stimuli of changing frequency. *J. Neurophysiol*. 28:655–672.

Wood, A. 1962. *The physics of music*. London: University paperbacks.

Zattore, R., and Belin, P. 2001. Spectral and temporal processing in human auditory cortex. *Cerebral Cortex*, 11: 946-943.

Ziemer, R., and Tranter, W. 2002. *Principles of communications: systems, modulation, and noise*.
USA: John Wiley & Sons.

Discography

Bach, J. 1983. *Sonatas and Partitas*. BWV 1001-1006. Sigiswald Kuijken. GD 77043. Freiberg: Deutsche Harmonia Mundi. Sleeve notes by Christoff Wolff.

Bach, J. 1988. *The sonatas for solo violin*. Nicolas Chumachenco. Venizia: Edelweiss. Sleeve notes by Roberto Calabretto.

Bach, J. 1988. *Sonaten und partiten*. Itzhak Perlman. 0772 749455 24 DP. Holland: EMI Classics. Sleeve notes by Robin Stowell.

Bach, J. 1989. *Sonatas and partitas for solo violin*. Mark Lubotsky. 10782. England: Collins Classics. Sleeve notes by Ates Orga.

Sheet music (Appendix C)

Bach, J. 1959. *Sonatas and partitas for solo violin*. BWV 1001-1006. Kassel: Bärenreiter-Verlag.

Appendix A

List of audio samples

Track	**Description**
Disc 1	**Experimentation samples from chapters 3 and 4.**
1	Figure 3.6: 440 Hz sine tone.
2	Figure 3.7: 440 Hz sawtooth tone.
3	Figure 3.8: 440 Hz violin tone.
4	Figure 4.1: Perlman playing an F#4 (bar 60) of Brahms violin Sonata Op. 78.
5	Figure 4.5: 440 Hz sine tone. Frequency modulated. Rate = 4 Hz; extent = 20 Hz.
6	Figure 4.5: 440 Hz sine tone. Frequency modulated. Rate = 4 Hz; extent = 60 Hz.
7	Figure 4.5: 440 Hz sine tone. Frequency modulated. Rate = 4 Hz; extent = 80 Hz.
8	Figure 4.8: 440 Hz sine tone. Amplitude modulated. Rate = 4 Hz; mi = 20%.
9	Figure 4.8: 440 Hz sine tone. Amplitude modulated. Rate = 4 Hz; mi = 60%.
10	Figure 4.9: 440 Hz sine tone. Frequency modulated . Rate = 11 Hz; Extent = 30 Hz.
11	Figure 4.10: 440 Hz sine tone. Frequency modulated by: Rate = 11 Hz; Extent = 30 Hz. Amplitude modulated by: Rate = 4 Hz; mi = 100%.
12	Figure 4.11: 440 Hz sine tone. Freq. and amp. Modulated. Offset: In phase.
13	Figure 4.11: 440 Hz sine tone. Freq. and amp. modulated. Offset: 90 degrees.
14	Figure 4.11: 440 Hz sine tone. Freq. and amp. modulated. Offset: 180 degrees.
15	Figure 4.11: 440 Hz sine tone. Freq. and amp. modulated. Offset: 270 degrees.
16	Figure 4.12: 440 Hz sawtooth. Freq. and amp. Modulated. In phase.
17	Figure 4.13: G4 violin tone. No vibrato.
18	Figure 4.13: G4 violin tone. With vibrato.
19	Figure 4.14: C4 violin note. With vibrato.
Disc 2	**Samples extracted from the Bach recordings. Summary of samples in table 5.6.**
1	1:G5. Chumachenco.
2	1:G5. Kuijken
3	1:G5. Lubotsky
4	1:G5. Perlman
5	2:D5. Chumachenco.
6	2:D5. Kuijken
7	2:D5. Lubotsky
8	2:D5. Perlman
9	2:Eb5. Chumachenco.
10	2:Eb5. Kuijken
11	2:Eb5. Lubotsky
12	2:Eb5. Perlman

13	3:D5. Chumachenco.
14	3:D5. Kuijken
15	3:D5. Lubotsky
16	3:D5. Perlman
17	4:A5. Chumachenco.
18	4:A5. Kuijken
19	4:A5. Lubotsky
20	4:A5. Perlman
21	5:F5. Chumachenco.
22	5:F5. Kuijken
23	5:F5. Lubotsky
24	5:F5. Perlman
25	5:Eb5. Chumachenco.
26	5:Eb5. Kuijken
27	5:Eb5. Lubotsky
28	5:Eb5. Perlman
29	6:F4. Chumachenco.
30	6:F4. Kuijken
31	6:F4. Lubotsky
32	6:F4. Perlman
33	12:G5. Chumachenco.
34	12:G5. Kuijken
35	12:G5. Lubotsky
36	12:G5. Perlman
37	12:Db5. Chumachenco.
38	12:Db5. Kuijken
39	12:Db5. Lubotsky
40	12:Db5. Perlman

Appendix B1

Csound source code

Figure 3.6: 440 Hz sine wave

Orchestra file

```
sr = 44100
kr = 4410
ksmps = 10
nchnls = 1

instr 1
a1    oscil p4, p5, 1
out   a1
endin
```

`Score file`

```
f1 0 4096 10 1; sine wave

i1    0     1     10000 440
e
```

Figure 3.7: 440 Hz sawtooth wave

Orchestra file

```
sr = 44100
kr = 4410
ksmps = 10
nchnls = 1

instr 1
a1    oscil p4, p5, 3
out   a1
endin
```

Score file

```
f3 0 4096 7 0 2048 1 0 -1 2048 0 ; sawtooth

i1    0     1     10000 440
e
```

Figure 4.5: 440 Hz sine wave. Frequency modulated: rate = 4 Hz; Extent = 20/60/80 Hz.

Orchestra file

```
sr = 44100
kr = 4410
ksmps = 10
nchnls = 1

instr 1
kvibfreq    oscil       (20/60/ 80), p5/110, 1
a1          oscil       p4, p5+kvibfreq, 1
out   a1
endin
```

Score file

```
f1 0 4096 10 1; sine wave

i1    0     1     10000 440
```

Figure 4.8: 440 Hz sine wave. Amplitude modulated: rate = 4 Hz; mi = 20% / 60%.

Orchestra file

```
sr = 44100
kr = 4410
ksmps = 10
nchnls = 1

instr 1
kvibamp     oscil 3000, p5/110, 1
a1          oscil       p4+kvibamp, p5, 1
out   a1
endin
```

Score file

```
f1 0 4096 10 1; sine wave

i1    0     1     10000  440
e
```

Figure 4.9: 440 Hz sine wave. Frequency modulated: rate = 11 Hz; Extent = 30 Hz.

Orchestra file

```
sr = 44100
kr = 4410
ksmps = 10
nchnls = 1

instr 1
kvibfreq    oscil       30, p5/40, 1
a1          oscil       p4, p5+kvibfreq, 1
out   a1
endin
```

Score file

```
f1 0 4096 10 1; sine wave

i1    0     1     10000 440
```

Figure 4.10: 440 Hz sine wave. Frequency modulated: rate = 11 Hz; Extent = 30 Hz. Amplitude modulated by: rate = 4 Hz; mi = 100%.

Orchestra file

```
sr = 44100
kr = 4410
ksmps = 10
nchnls = 1

instr 1
kvibamp           oscil 10000, p5/110, 1
kvibfreq    oscil       30, p5/40, 1
a1          oscil       p4+kvibamp, p5+kvibfreq, 1
out   a1
endin
```

Score file

```
f1 0 4096 10 1; sine wave

i1    0     1     10000 440
```

Figure 4.11: 440 Hz sine wave. Simultaneous frequency and amplitude modulation with different offset angles: In phase / 90 degrees / 180 degrees / 270 degrees.

Orchestra file

```
sr = 44100
kr = 4410
ksmps = 10
nchnls = 1

instr 1
kvibamp     oscil 10000, p5/80, 1, (0 / 0.25 / 0.5 / 0.75)
kvibfreq    oscil       40, p5/80, 1
a1          oscil       p4+kvibamp, p5+kvibfreq, 1
out   a1
endin
```

Score file

```
f1 0 4096 10 1; sine wave

i1    0     1     10000 440
```

Figure 4.12. 440 Hz sawtooth wave with frequency and amplitude modulation.

Orchestra file

```
sr = 44100
kr = 4410
ksmps = 10
nchnls = 1

instr 1
kvibamp     oscil 10000, p5/80, 1
kvibfreq    oscil       40, p5/80, 1
a1          oscil       p4+kvibamp, p5+kvibfreq, 3
out   a1
endin
```

Score file

```
f3 0 4096 7 0 2048 1 0 -1 2048 0 ; sawtooth

i1    0     1     10000 440
```

Figure 4.15. 440 Hz sine wave with frequency and amplitude modulation. Resulting signal filtered by a four-pole highpass filter.

Orchestra file

```
sr = 44100
kr = 4410
ksmps = 10
nchnls = 1

instr 1
kvibfreq    oscil       15, p5/70, 1
a1          oscil       p4, p5+kvibfreq, 1
afilt4            atone   a1, 440
afilt3            atone afilt4, 440
afilt2            atone afilt3, 440
afilt1            atone   afilt2, 440
out               afilt1
endin
```

Score file

```
f3 0 4096 7 0 2048 1 0 -1 2048 0 ; sawtooth

i1    0     1     10000 440
```

Appendix B2

Matlab source code

Code to generate figure 3.5: Demonstration of how the addition of sine waves according to a certain formula, results in a saw tooth wave.

```
% Plots sawtooth wave as sum of harmonics

clear all;
close all;
clc;

k = 200;

f=1;
T=1/f;

t=linspace(0,4*T,1000);

x = sin(2*pi*t*f);
subplot(6,1,1);
plot(t,x,'linewidth',1.5)
title('1 Harmonic');
grid on;
axis([0 T*4 -2 2])
set(gca,'fontsize',10);

for i=2:k
   x = x + sin(i*2*pi*t*f)/i;
   if (i==2)
      subplot(6,1,2);
      plot(t,x,'linewidth',1.5)
      title('2 Harmonics');
      grid on;
      axis([0 T*4 -2 2])
      set(gca,'fontsize',10);
   end
   if (i==5)
      subplot(6,1,3)
      plot(t,x,'linewidth',1.5)
      ylabel('Amplitude','fontsize',10);
      title('5 Harmonics');
      grid on;
      axis([0 T*4 -2 2])
      set(gca,'fontsize',10);
   end
   if (i==10)
      subplot(6,1,4)
      plot(t,x,'linewidth',1.5);
      title('10 Harmonics');
      grid on;
      axis([0 T*4 -2 2])
```

```
      set(gca,'fontsize',10);
   end
   if (i==25)
      subplot(6,1,5)
      plot(t,x,'linewidth',1.5)
      title('25 Harmonics');
      grid on;
      axis([0 T*4 -2 2])
      set(gca,'fontsize',10);
   end
   if (i==200)
      subplot(6,1,6)
      plot(t,x,'linewidth',1.5)
      xlabel('Time [s]','fontsize',10);
      title('200 Harmonics');
      grid on;
      axis([0 T*4 -2 2])
      set(gca,'fontsize',10);
   end
end
```

Code to generate figures 3.6; 3.7; 3.8; 4.5; 4.8; 4.9; 4.10; 4.11; 4.12; 4.13; 4.14; 4.15; 4.16; 6.6; 6.7.

```
filename = '’
[sig,FS,Res] = wavread(filename);
sig = sig(:,1);
time = (0:(length(sig)-1))./FS;
figure(1)
plot(time,sig); xlabel('time (s)')

N = length(sig);

freq = (0:N/2).*FS/N;
f= fft(sig);
f = f(1:N/2+1);
af = abs(f);
af = af./max(af);
laf = 20*log10(af);

figure(2)
plot(freq,af,'linewidth',1.5);
%plot(freq,af);
%plot(freq,laf);
xlabel('F (Hz)'); ylabel('A (db)');
grid on;
axis([0 1000 0 1]);
```

Appendix C

Sonata No.1 in G minor, BWV 1001, for solo violin by J.S. Bach.

Sonata I

BWV 1001

Bärenreiter-Ausgabe 5116

Appendix D

Mathematical representations of FM and AM

Amplitude modulation: (Ziemer and Tranter (2002:106)

$$x_c(t) = [A + m(t)]A_c^{'} \cos(\omega_c t)\,,$$

Where A is a DC bias that is added to the message signal $m(t)$ prior to the modulation process and $A_c^{'} \cos(\omega_c t)$ is the carrier signal.

Frequency modulation: (Ziemer and Tranter (2002:124-125)

$$x_c(t) = A_c \cos[\omega_c t + \phi(t)]\,,$$

Where $\phi(t)$ is the phase deviation of the frequency-modulated carrier and is given by

$$\phi(t) = k_f \int_{t_0}^{t} m(\alpha)d\alpha + \phi_0\,,$$

where ϕ_0 is the phase deviation at time t_0. k_f is the frequency-deviation constant expressed in radians per second per unit of the message signal $m(\alpha)$.