The physics and perception of violin tone

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Abstract

We consider the temporal variations in the pitch, waveform and spectrum of bowed notes on the violin resulting from the use of vibrato in terms of physical models and by processing digitally recorded sounds of fine violins played by international soloists. Without such variations in waveform, we demonstrate that the sound cannot be distinguished as that from a violin and is indistinguishable from that of an electronic harmonic synthesiser. The physical factors affecting variations in waveforms resulting from the use of vibrato are considered, highlighting the importance of the Q-values of the structural modes excited.

INTRODUCTION

The problem of understanding the tonal quality of a violin in purely physical terms is at least 150 years old. Nevertheless, it remains largely unsolved, despite major advances in acoustical instrumentation, which can provide a remarkably detailed description all the physical properties of a violin that must ultimately determine its tone quality. Much of this recent research has been inspired by Carleen Hutchins and her fellow co-founders of the Catgut Acoustical Society and is described in the two volumes of Research Papers in Violin Acoustics (1) and modern textbooks such as Fletcher and Rossing (2).

The spectral content of waveforms produced by a bowed violin varies wildly from one note to the next, despite the instrument still sounding like a violin and, and for good instruments, having a fine tone regardless of the note being played. Art Benade (3) has persuasively argued the consequent importance of global features that must not only define the sound of a violin but also determine the quality of a particular instrument.

We revisit this problem both from the point of view of the physics involved and by the use of computer software (4) to assess the relative importance of the spectral and temporal changes of the sound of a violin in defining its quality. By artificially processing the sound of outstanding Italian violins played by international soloists, we demonstrate the importance of vibrato in defining the sound of a violin and ultimately of its quality. We underline the importance of the quality of the wood used in the construction of the violin in enhancing such variations, which must therefore be an important factor in determining the quality of individual instruments – a result that will come as no surprise to any violin maker.

PHYSICAL MODEL

Much research on violin acoustics has concentrated on the spectral response of the instrument, which from a physicist's viewpoint can be considered as a linear, multi-resonant mode, mechanical system. The acoustical response at an angular frequency $\omega = 2\pi f$ for the Fourier component $F(\omega)\, e^{i\omega t}$ of the force on the bridge at the point of string support is then given by

$$A(r,\theta,\Phi,\omega) = \sum_n \frac{C_n}{\omega_n - \omega + i\dfrac{\omega_n}{Q_n}} R_n(r,\omega,\theta,\Phi)\, F(\omega) \quad , \qquad (1)$$

where ω_n and Q_n are the frequencies and quality factors of the n-th vibrational modes of the violin excited with amplitude C_n, while R_n describes the dependence of radiated sound amplitude on distance r and polar angles θ and ϕ, which define the distance and orientation of the instrument relative to the listener.

The acoustic radiation term R_n for any given mode excited is a rather complicated, complex (i.e. involving variations in phase in addition to amplitude), function of all the variables. It involves the spatial dependence of the induced vibrations on all the radiating surfaces and the relative magnitude of acoustic wavelength to the distance of the listener from the violin. For example, the frequency dependence is different in the near-field region ($r\,\omega/c$ <1, where c is the speed of sound) experienced by the player from that in the radiating-field region ($r\,\omega/c$ >1) experienced by the listener. The player's and listener's perception of the tonal quality of an instrument may therefore be somewhat different.

It is important to recognise that the resonant modes (eigen modes of the system) are those of the instrument as a whole, involving the interacting vibrations of body of the instrument, the air inside, the bridge, the tailpiece and all string lengths. The energy of the bowed string is communicated to the body of the instrument through the bridge, which essentially acts as an acoustic transformer (5). The bridge has characteristic resonant modes involving rocking and bouncing motions, which will be strongly influenced by interactions with central regions of the front plate between the f-holes. Because of the importance of the vibrational characteristics of the bridge and coupling to the vibrational modes of the front face, it is sometimes helpful to approximate the overall response of the instrument as the product of the response of the bridge and that of the body of the instrument. We can then write

$$A(r,\theta,\Phi,\omega) = \sum_{j=1,2..} \frac{1}{\omega_j - \omega + i\dfrac{\omega_j}{Q_j}} \sum_n \frac{V_{n,j}}{\omega_n - \omega + i\dfrac{\omega_n}{Q_n}} R_n(r,\omega,\theta,\Phi)\,F(\omega) \quad , \qquad (2)$$

where $\omega_{n,j}$ and $Q_{n,j}$ represent the uncoupled modes of vibration of the bridge and violin structure and $V_{n,j}$ includes a factor that accounts for the coupling of the induced bridge motions to the vibrational modes ω_n of the main body of the instrument.

To a rather good approximation, bowing excites a simple, single-kink, Helmholtz wave on the string producing a saw-tooth waveform at the bridge (6). The force at the bridge can therefore be represented by a Fourier series, with components of force decreasing with harmonic number N as $1/N$. The amplitude of the sound wave produced by a bowed note can therefore be expressed as

$$A_B(r,\theta,\Phi,t) = \sum_N A(r,\theta,\Phi,N\omega_B)\frac{F_1}{N}e^{iN\omega_B t} \quad , \qquad (3)$$

where, F_1 is the amplitude of the first Fourier component of the exciting saw-tooth waveform.

For a particular note, the waveform generated can then be considered as a convolution of the comb-like spectrum of harmonically related frequencies generated by the bowed string, modified by the acoustic response of the bridge, coupling to the individual resonances of the instrument as a whole. This is represented graphically in Fig. 1, where we have uses a simple 2-dimensional model of weighted transverse plate-resonances to simulate the structural resonances, with radiation only from those modes with a net transverse displacement, plus an air resonance at 300 Hz. We have also assumed a frequency independent Q-value of 70, an important factor that we will return to later.

In Figure 2 we have plotted the waveforms generated by such a model for the open-A string and the note B a tone above. The waveforms and spectra generated by such a model vary wildly from one note to the next, as they do on any real instrument. This emphasises the point that there is no such thing as a typical waveform or spectrum that describes the sound produced by a violin. Any such model, *by definition,* will produce a sound that is indistinguishable from that of a crude harmonic synthesiser. It is also easy to see why even slight changes in frequency, such as that associated with the use of vibrato, will give rise to major changes in waveform and spectral content even within a bowed single note.

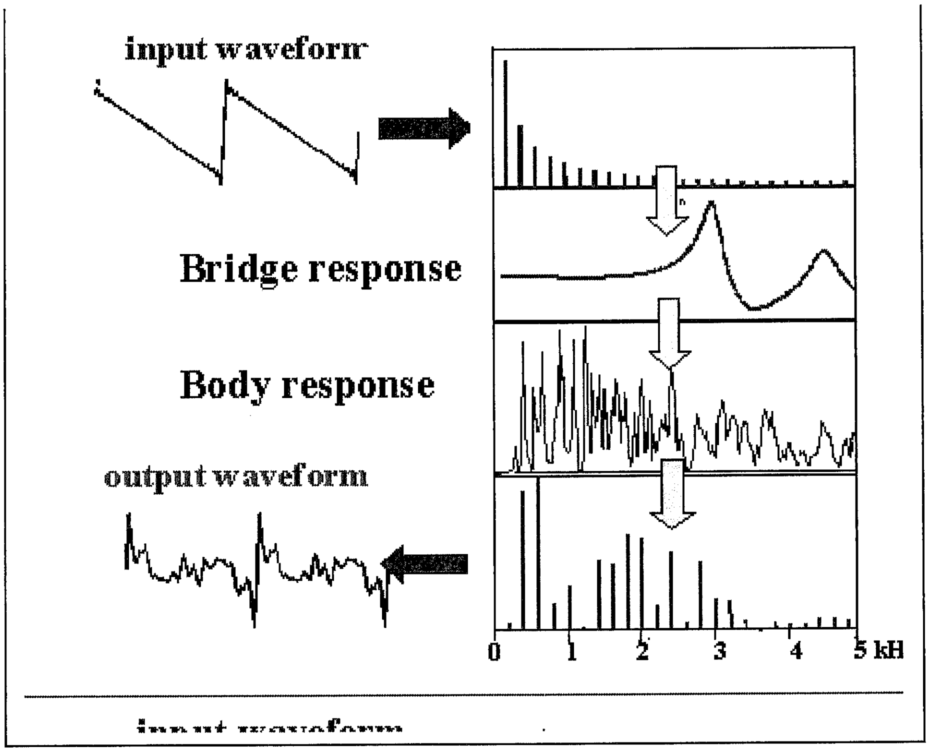
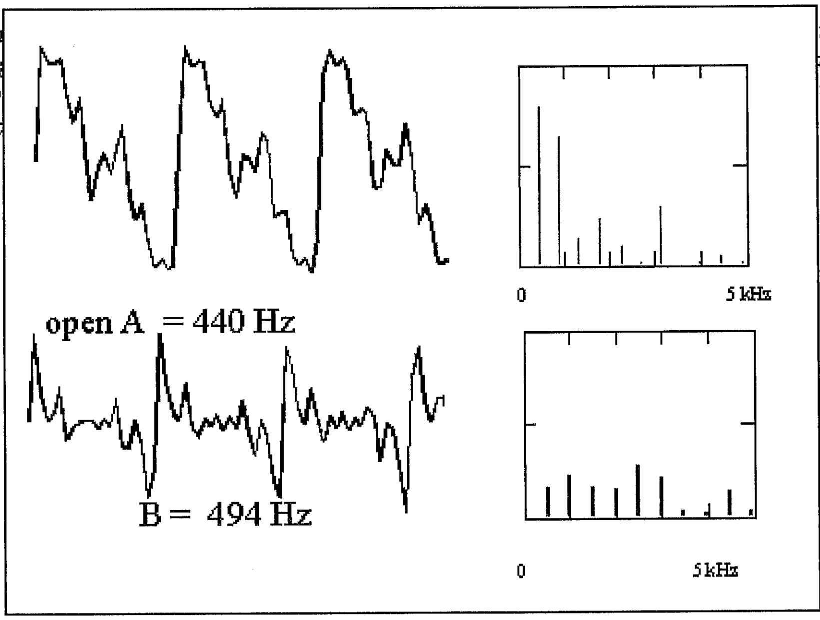


Fig 2. Synthesised waveforms at A= 440 Hz and B = 494 Hz, illustrating the major variations in waveforms and spectra from note to note, mimicking the large variations observed for real instruments.

Fig.1 The "physi … ring energy through the brid… dependence of the radiated wave-fo… mb of harmonic exciting frequenc…



REAL VIOLIN SOUNDS

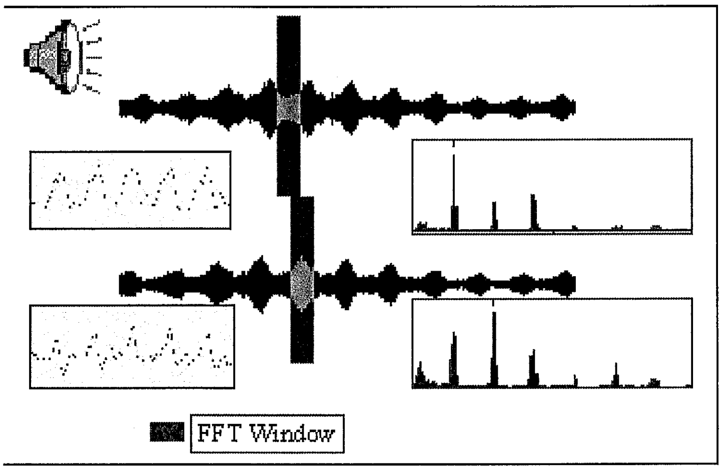


Fig. 3. Envelope and sections of the wave form and associated spectra of a Stradivarius of outstanding quality played by an international soloist on the note D (~300 Hz) on the g-string illustrating the marked influence of the use of vibrato on both waveforms and spectra within an individual bowed note.

We now compare the predictions of such a model with sounds produce by a real violin. For this comparison, we first consider a recording taken from a radio broadcast of the fine British violinist Tasmin Little playing an outstanding Stradivarius instrument once owned by Milstein. Figure 3 shows the amplitude and expanded sections of the waveform of a single bowed note (D ~300Hz played on the g-string). This particular note was highlighted by the player, to demonstrate the “fantastic, amazing, rich and vibrant” quality of the violin. We note the very large changes in amplitude of the waveform and the very different waveforms and spectra at the peaks and troughs of the envelope. The changes in amplitude with the use of vibrato has been known for many years. However, the magnitude of the induced changes in waveform and spectra is not widely appreciated and the relationship of such affects to the assessment of violin quality has received remarkably little attention.

Indeed, in assessing the sound produced by a fine violin played by any first-class soloist, it is difficult to judge the quality of the violin without first recognising the contribution to its quality from the player’s use of vibrato.

To further demonstrate this point, we have used a commercial recording of Perlman playing the first few unaccompanied bars of the Bruch Violin Concerto. By sampling the waveform and repeating a chosen single period of the waveform, we can differentiate between the sound produced by the real violin from that expected from to the simple “physicists model” applied to the actual instrument being played.

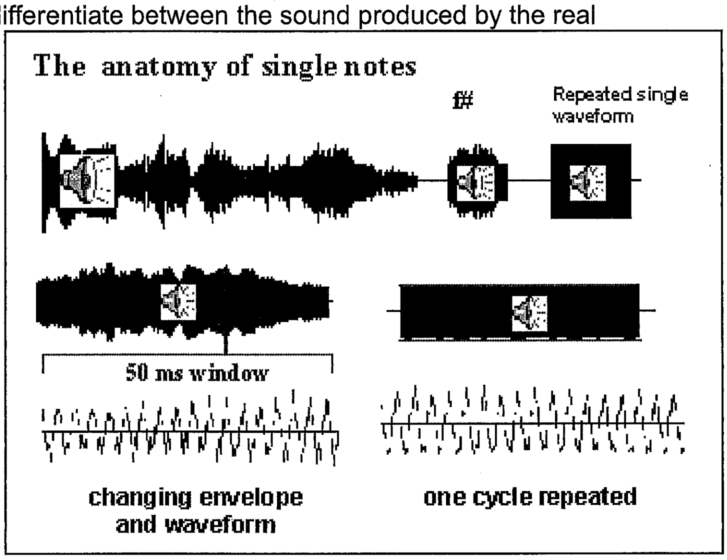


Fig. 4 The envelope of the first half of the opening statement of the Bruch violin concerto and the envelope, expanded waveform and synthesised repeated individual period. The loudspeaker symbols refer to recorded waveforms demonstrating the importance of variations in sound in identifying the instrument as a violin.

The comparison is dramatic. Whereas the sound produced by Perlman playing the chosen note is “amazing, warm, exciting, vibrant” - just the qualities one expects from a fine instrument – the repetitively sounded selected period is characterless and indistinguishable from that of a simple synthesiser. This is exactly what is expected from our earlier discussion.

It follows that it is the variations in waveforms and spectra and not simply the spectrum of individual notes that enable the listener to recognise an instrument as a violin. Such variations must therefore be equally important in any assessment of violin quality. It seems very likely that similar considerations apply to the identification and perception of quality of all continuously bowed and even blown instruments (i.e. it is not only the starting transients that are important in identifying an instrument).

The importance of the starting transients is well known and easily demonstrated by playing a recording of the sound of a piano or plucked violin backwards - or the same note on a flute and trumpet with their starting transients interchanged. Interestingly, reversing the sound produced by a violin (on medium-length bowed notes) makes almost no difference to the perceived sound quality.
Within the main body of a note, the affect of reversing time is essentially the same as reversing the bow direction, involving a reversal in shape of the exciting saw-tooth waveform at the bridge. Similarly, the affect of the periodic changes in spectra with the use of vibrato is unchanged with the direction of time.

Aperiodicities in the slip-stick motion of the bowing action (4) are also responsible for generating a wide "noise spectrum" superimposed on the more periodic bowed waveform. This appears to be particularly pronounced for high quality Italian instruments. The spectrum of noise produced will reflect the multi-resonant resonant response of the instrument itself and will be determined at least in part by the Q-values of the individual resonances

It is easy to understand why the periodic variations in the waveforms and spectral content are important to the listener, as they produce a continuously changing signal to maintain the listener's interest, quite unlike a synthesised uniformly repetitive waveform. The use of a wide vibrato by the modern violin virtuoso helps the solo violin to stand out from a large string section, where the use of vibrato by individual members of the section will tend to be averaged out. The use of a controlled vibrato is certainly one of the ways in which one can easily distinguish between the fine tone produced by an experienced performer from that of a learner playing on the same instrument. The importance of the performer in determining perceived quality is readily seen from the envelope of the bowed waveforms, which illustrates the importance of bow control (or lack of it) in determining the quality of sound. With regard to vibrato, it is interesting to note the recent increase in the use of a small amount of vibrato by players of the baroque violin, making the sound more pleasing to the ear to the average listener.

CONCLUSIONS

We have demonstrated that it is the variations in amplitude and spectra of the sound that identifies an instrument as a violin. Such variations must therefore also play an important role in determining violin quality. It follows that no physical model of the violin will explain the quality of an instrument unless the factors influencing such variations are properly understood.

The larger the Q-values of the wood used in the construction of an instrument, the larger will be the variations in amplitude associated with the use of vibrato. This underlines the importance of using high quality tone-woods for the front and back faces of the violin. Increasing the Q-value of the wood used also increases the overall amplitude of the response, particularly at higher frequencies when the resonances become more closely spaced and overlap. The importance of Q-values also explains: (i) why the use of too thick a coating of varnish, a visco-elastic medium, will degrade the sound of an instrument, (ii) why the tone of an instrument changes on ageing as the wood dries out, and (iii) also accounts for changes in the tone of an instrument with weather, due to additional losses from absorbed moisture. Of course a degree of damping is important, as otherwise the interaction of string and the main body resonances would result in mode splitting of the string resonances (7) leading to the troublesome wolf-note phenomena, often encountered for high quality instruments - particularly the cello. From the point of view of the proposed strong relationship between Q-values and the quality of an instrument, it is clearly important to investigate the frequency dependence of Q-values of tone woods used for the violin over a rather wide frequency range.

While emphasising the importance of the "responsiveness" of a violin to vibrato in the assessment of tonal quality, we would not pretend that this is the whole story. Indeed, the use of digital signal processing to filter out frequencies in selected frequency ranges, again using the first few bars of the Bruch Violin Concerto, demonstrates the contribution of such frequencies to the overall sound quality. Filtering out a 500 Hz frequency band above around 1 kHz makes only a slight difference to the perceived sound quality, apart for those notes with a fundamental or first harmonic coincident with the filtered band. In contrast, such filtering below 1 kHz leads to a very marked "thinness" in the sound of any notes with low harmonics lying within the filtered band. Conversely any artificial enhancement of the response below 1 kHz will increases the "richness of the sound" for notes with low harmonics in the specified range. Therefore, for a violin to have a uniform full-bodied tone in the lower registers, there has to be a fairly uniform strong response below 1 kHz . Although certain notes will be emphasised by particularly strong structural resonances, the overall low frequency response involves the low frequency response of all the vibrational modes of the instrument included in equations 1 and 2. This is directly related to the flexural and transverse responses of the plates of the instrument when a couple is applied via a force at the bridge. This in turn will be governed by the "feel" of the individual plates of an instrument as they are flexed and bent by the skilled craftsman during plate thinning.

This suggest a rationale for plate-tuning different from that of the exact placing of specific plate resonances. The scientifically directed adjustments of the frequencies and nodal line shapes of given low frequency modes will automatically determine the global flexural and bending properties of the plates, which we have proposed are important in determining the global "richness" of violin tone in the lower registers. Scientific tuning of the plates will therefore clearly result in a greater degree of uniformity in the tone of an instrument than if no attention is paid to plate tuning. However, those craftsmen who assess the flexural and bending of the plates by their "feel" during plate thinning may well be just as successful in controlling the global low frequency properties. This must have been true for all the great makers of the distant past.

ACKNOWLEDGEMENTS

I am particularly grateful to Patrick Gaydecki, who introduced me to the use of Cooledit for the analysis and digital processing of recorded waveforms and for several important discussions that alerted me to the importance of vibrato in defining the sound of a violin.

Transparencies for this talk with attached sound files illustrating all the major points made in this paper will be available on the Web as a PowerPoint presentation at http://www.cm.ph.bham.ac.uk/ceg/acoustics .

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