A model for vibrato on stringed instruments is presented, based on the measured acoustic response for an impulsive force at the bridge. The model highlights the importance of both the violin's dynamic response and that of the performance acoustic in determining the fluctuations in amplitude of any note played with vibrato. Comparison of the influence of vibrato on the recorded and synthesised tones of violins of different quality and of electric violins will be presented, in addition to considering the additional influence of holding the violin and the sympathetic vibrations of unstopped strings.

1 Introduction

It is well known that a bowed violin note played with vibrato leads to both frequency and amplitude modulation of the radiated sound, resulting from the multi-resonant response of the violin body [1-3]. In this paper, we consider how the dynamic response of the violin and the acoustic environment significantly affect the radiated sound. In a recent paper [4], such effects were shown to give sound waveforms with very large and complex modulations in amplitude, in which the time-delayed reflections from the surrounding walls play a very significant role, as first noted by Meyer [3].

In addition, we develop a model to simulate the effect of vibrato on the sound of a violin at any position in the performance space, derived from measurements of the sound produced by an impulsive at the bridge recorded at the listener’s position.

Musical illustrations, downloadable from the internet [5], demonstrate the importance of vibrato and other fluctuations in defining the characteristic sound of different musical instruments. By inference, such fluctuations are therefore also likely to be important in any subjective assessment of violin tone quality.

The focus of this paper is to highlight the dynamic effects that determine the characteristic sound of a violin when played with vibrato, rather than attempting to synthesise violin vibrato sounds with 100% authenticity.

2 Vibrato and violin tone quality

If a violin or any other continuously sounding instrument could be played without any fluctuations in amplitude or frequency, the sound would be indistinguishable from that of a characterless signal generator. This is illustrated in Figure 1 and SOUND 1 [5], by the envelope and section of waveform of a long note A (440Hz) played with vibrato recorded at 2 m distance from the violin, which is followed by a note produced by continuously repeating a single period waveform extracted at random from the recorded sound. The repeated note has the same overall spectrum of partials and a similar but unchanging waveform as the parent waveform, but lacks the fluctuations in frequency and amplitude and additional noise, which characterise the sound as that of a violin.

Note the very large fluctuations in amplitude of the recorded sound largely arising from the use of vibrato with a typical frequency width $\Delta f / f \sim 3\%$ and vibrato rate of $\sim 5$ Hz.
The continuously repeated waveform is exactly the kind of sound predicted by a simple “physicists model”, in which the violin is excited by a constant frequency sawtooth bowing force on the bridge producing a comb of harmonic partials differentially exciting the many acoustically radiating vibrational modes of the instrument. Since the resulting sound has none of the characteristics of the sound of a real violin, such a model alone is unlikely to provide much useful information on what might distinguish the sound of a really fine instrument from that of a mass-produced factory instrument.

We therefore argue that it is the characteristic fluctuations in the sound of a violin that enable the listener to identify the instrument as a violin and, by inference, its quality also.

In this paper we focus our attention on fluctuations in frequency and amplitude from the use of vibrato, but other fluctuations from inherent bow noise [6] and both controlled and inadvertent fluctuations of bow pressure and velocity may also contribute to any subjective assessment of tone quality.

It has often been remarked that it is the initial transient that enables the listener to identify the sound of an instrument. Although this is undoubtedly true for the immediate recognition of certain instruments, the sound of individual instruments can generally be distinguished equally well when the initial transient is removed. This is illustrated for typical violin, flute, trumpet, oboe and sawtooth notes with the first 50 ms transient removed, followed by the sound of the full waveform ([5], SOUND 2)

3 model for vibrato

We now describe a model for vibrato in the time-domain, involving the dynamic response of the violin and the equally important room acoustics.

For simplicity, we assume the violin is excited by a sawtooth driving force at the bridge generated by a simple Helmholtz wave on the bowed string. As a first approximation, we ignore any additional ripples or noise on the driving force produced by reflections between the bow and bridge, the finite width of the collection of bow hairs and interaction with the excited body modes [6].

The sawtooth waveform can be considered as a succession of Helmholtz step-functions superimposed on a linearly increasing force of no acoustic significance. Each successive Helmholtz step will excite a transient response of the violin involving all the coupled modes of the instrument. In the steady state, the resultant vibrations will be determined by the superposition of a sequence of such responses.

For a sequence of step-functions $F_n$ at times $t_n$, the response is given by

$$ R(t) = \sum F_n h(t - t_n) \quad \text{for} \quad t_n < t $$

where $h(t)$ is the unit step-function response. If $h(t)$ is known, the response can be computed for a sequence of steps with a periodically modulated spacing, to simulate the effect of vibrato.

To synthesise a realistic waveform requires a knowledge of the step-function response $h(t)$ for the violin. This can be derived by integrating the measured impulse response $I(t)$ excited by a delta-function input,

$$ h(t) = \int_0^t I(t') dt' $$

The impulse response can be measured by striking the top of the bridge in the bowing direction with a force hammer or small mass.

The derived step-function response differs from the impulse response in giving greater emphasis to the lower frequency components, with relative weightings $1/\omega$. This is illustrated in SOUND 3 [5] by the initial acoustic “tap response” measured 2m away from the violin, followed by the derived step-function response, the transient responses sounding rather like the “tick” and “tock” of a grandfather clock. The step-function response is then repeated at 1, 10 and 200 Hz, the final sound simulating the sound of a violin, but
without vibrato, noise or any other fluctuations.

This simple demonstration highlights the importance of the transient response in defining the sound of an instrument. The response can be measured at any point on the body of the instrument or in the surrounding sound field. The latter is important, if one is interested in the quality of a violin sound. The radiated sound is determined not only by the structural resonances excited but also by their radiation efficiency and directivity.

In any realistic performing situation, as opposed to playing the instrument in the open air or inside an anechoic chamber, the transient acoustic response involves both directly radiated sound and time-delayed reflections from the surrounding walls. Because of the inverse square law decrease in intensity with distance, the relative importance of the direct and reflected sound will vary strongly with position from the violin.

\[ \frac{1}{r^2} \]

where \( r \) is the distance from the violin.

This is illustrated in Fig.2 and in SOUND 4 [5] for the sound of a violin with damped strings excited by a short impulse at the bridge. The impulse is first measured close to the front plate, where the sound is dominated by the violin rather than the room acoustic, close to the player’s ear, where the room acoustic already contributes significantly to the transient response, and at a distance of 2m, where the transient sound is dominated by reflections from the surrounding surfaces. The feedback of sound from the performance acoustic provides very important feedback and encouragement to the player in optimising the quality of sound produced.

At a distance from the violin, the sound of a violin is just as strongly influenced by the dynamic response of the room acoustics as it is by the violin. This has important implications for any subjective inter-comparisons of violin tone quality, particularly in an over-resonant acoustic. As our simulations show, the influence of the room acoustics is particularly important when the instrument is played with vibrato (see also ref [4]).

4 Synthesis of vibrato tones

4.1 Violin vibrato tones

The impulsive acoustic response of a number of violins of different quality has been measured at different positions from the violin in both an anechoic space and a relatively small (~ 5x6x3 m^3) furnished room. Impulse responses were excited by swinging a small pith ball (1.3g) against the top of the bridge in the bowing direction. Measurements were made with the violin both freely-suspended and held by a player in the normal way, with the strings damped and allowed to vibrate freely.

The step-function responses were computed by numerical integration of the impulse responses. Simulated vibrato tones were then computed from equ.1 for varying amplitudes and rates of vibrato. To give a further sense of realism, the sawtooth waveform was modulated with a 25 ms time exponential rise and decay time.

Fig.3 shows the simulated sounds of the freely suspended Vuillaume violin with damped strings derived from tap tones recorded very close to the instrument and then at a distance of 2m, first with no vibrato and then for a vibrato with \( \Delta f/f = 1.5\% \) at 3 and 6Hz. The ear can follow the cyclic changes in frequency at and below 3 Hz but at typical vibrato rates of 4-6Hz the sound simply
appears to pulsate, as illustrated by SOUND 5 [5] for the six waveforms shown. At typical vibrato rates, fluctuations in amplitude are more important in the identification of the sound of the violin than those in frequency, as previously noted by Melody and Wakefield [7].

![Figure 3: Simulated Vuillaume vibrato sounds from recorded tap tones at 2cm and 2m for a sinusoidal $\Delta f/f$ modulation of 1.5% and vibrato rates of 3 and 6 Hz.](image)

The initial transient and final decay of the simulated and all real waveforms retain many of the spectral features of the generating step-function response. However, once established, the waveform and sound, in the absence of vibrato, remain featureless. However, when simulated with even small amounts of vibrato (see [4]), the envelopes acquire a complexity very similar to that observed in real vibrato tones.

It is important to note, that the amplitude fluctuations are strongly asymmetric with respect to time. This is a characteristic signature of the importance of dynamic effects, which is not predicted by earlier models for vibrato [1-3], in which dynamic processes were ignored.

The difference in waveforms and sounds of the simulated tones played with and without vibrato is dramatic. We argue, as others have done before [1-3], that the complexity in envelope not only creates a much more interesting sound for the listener, but also enables a solo instruments to be heard above the collective sounds of a large orchestra. Essentially, the fluctuations in amplitude provide a continuous sequence of “transients” or time-varying fluctuations, which continue to retain the interest of the listener – quite unlike the predictable sound of a note played without vibrato or that of a crude electronic synthesiser.

### 4.2 Electric violin tones

It is a striking fact that the sound of an electronic violin is remarkably similar to that of a real violin (SOUND 6 [5]). This is despite having an almost flat frequency response without the prominent spectrum of resonances that characterise the acoustic spectrum of the violin, which many researchers have attempted to correlate with the defining quality of an instrument.

It is therefore interesting to see what our model tells us about the sound of an electric violin. We have therefore recorded impulse functions from the piezo-electric transducer mounted in the purposely massive bridge of a 4-string Violectra violin by David Bruce-Johnson.

![Figure 4: The note A (440 Hz) of an electric violin played without and with vibrato and the sound of a continuously repeated single waveform with a similar envelope.](image)

Figure 4 and SOUND 7 [5] compares the reproduced sounds of the note A (440Hz) on the electric violin, first without and then with vibrato, followed by a continuously repeated single period wave extracted from the vibrato waveform. As demonstrated earlier for the violin, the continuously repeated single period wave has none of the fluctuations that might characterise the instrument as a violin, though without prior knowledge the sound of the electric violin could easily be mistaken for a real violin.
Because of the absence of easily excited structural modes, the recorded impulse function decays very much more rapidly than that of a real violin. The waveforms generated by the sawtooth waveform will therefore lack the complexity generated by the much longer transients of the violin.

This is illustrated in Figure 5 and SOUND 8 [ ], which compares the waveforms and reproduced sound of an electric violin played with vibrato with synthesised vibrato tones generated from the short impulse response of the piezoelectric transducer. The width $\Delta f/f$ of the vibrato for the real instrument was $\sim 1\%$, while the synthesised tones are for 0.5% and 1% modulation.

As anticipated, the simulated waveforms exhibit none of the complexity observed for violin simulations, because of the very much faster decay of the transient response. The complexity of the recorded sound waveforms arises almost entirely from the transient response of the small room in which the recorded sounds were replayed.

5. Further Comments

In practice, violins are played under the chin rather than being freely suspended and any unstopped strings remain undamped, both of which significantly affect the transient response and hence complexity of the simulated waveforms. Modal analysis measurements by Marshall[8] and more recently by Bissinger[9] have demonstrated that holding the violin introduces a significant amount of additional damping of the vibrational modes. Figure 6 and SOUND 9 [5] illustrates the additional damping of the transient response when the violin is held under the chin rather than being freely suspended followed by the additional ringing of the open strings when they are left free to vibrate. The transients were recorded close to the top plate in an anechoic environment.

The short time FFTs, delayed by successive intervals of 12.5 ms, show that the increased damping from holding the violin is particularly pronounced for frequencies below $\sim 1.5\text{kHz}$. This is unsurprising, because at these frequencies the normal modes of vibration will generally involve significant bending and flexing motions of the violin body, which will be damped when the edges and neck of the violin are supported by the player.

An impulse at the bridge will excite all the partials of any strings left free to vibrate, which will contribute strongly to the transient response and radiated sound, as illustrated in Fig.6 and the recorded sound. The sound of the unstopped strings can easily heard in the decaying sound of any short note played on...
the violin and must contribute significantly to the sound and complexity of any bowed note. Figure 7 and SOUND 10[5] illustrate the influence of the above effects on the simulated sound. The simulated sounds are shown for first the freely held violin with all the strings damped and then with the strings left free to vibrate. Simulations are then illustrated for impulse functions measured when the violin is held by the player in the normal way, first with damped then with undamped strings. The simulations are for a vibrato width of 1.5% vibrato at 5Hz. The difference in the simulated sound is particularly marked when the strings are left free to vibrate.

6. Summary

Although our model for synthesizing the sound of a violin is relatively simple, it produces quite realistic violin vibrato sounds and serves to highlight and explain many of the observed features of real violin waveforms. In particular, it emphasizes the importance of dynamic effects in the time-domain associated with the vibrational modes of the violin, the acoustic in which the violin is played and the freely vibrating strings on the instrument.

The importance of vibrato in enhancing the quality of the sound of the violin, to produce a warmth and singing quality to the tone like that of the singing voice, was emphasized by many early writers, notably Leopold Mozart[10]. Whereas some modern players may use an excessive amount of vibrato when playing baroque and early classical music, the complete absence of vibrato advocated by some players and conductors appears perverse, on both aesthetic and scientific grounds. Our simulations demonstrate that fluctuations, and especially the use of vibrato, are important features in defining the sound of the violin, without which the sounds produced are characterless and lacking in interest to the ear.

References

[5] Downloadable as a packaged PowerPoint presentation with linked *.WAV files at www.cm.ph.bham.ac.uk/Gough/Forum-05