REAL-TIME SIMULATION OF VIOLIN TONES

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1 INTRODUCTION

We report progress on a project to simulate the sounds of the violin of any chosen quality in real-time on a normally bowed electric violin. There are a number of specific objectives:

(i) to produce an inexpensive instrument that recreates the sound of a first-class Cremonese or baroque-style violin, a Chinese two-stringed Erhu or an instrument with any pre-programmed response, at the flick of a switch,
(ii) to use such a system under the player's immediate control, to help understand which acoustic characteristics of the violin determine the player's and listener's perception of the quality of an instrument,
(iii) to manipulate the synthesized sounds of real instruments by additional filtering in either the frequency- or time-domain, and to investigate how such changes affect the perceived quality of the instrument by player and listener alike.

The project uses a commercial, solid-frame, Antoni violin, with a custom-built bridge and transducer designed to provide an accurate measurement of the force of the bowed strings on the bridge. The signal from the bridge pickup is filtered in real-time using the Signal Wizard 2 digital signal processor (DSP) developed by Patrick Gaydecki[(1)]. The DSP enables the real-time filtering or convolution of any input audio signal with the frequency or impulse response of any pre-recorded or artificially synthesized instrument.

This paper describes some of the problems encountered and progress made in realizing the above objectives. Similar investigations are also being conducted by Fritz and Woodhouse and their colleagues in Cambridge[2] and by Curtin and Weinreich[3] at Ann Arbor in the USA. Each group has slightly different objectives, but all make use of the Signal Wizard processor.

Matthews and Kohut[4] at Bell Laboratories in America were the first use the electric violin as an important tool to investigate the influence of the multi-resonant acoustics of the violin on the perception of the quality of its sound. Subsequently, the electric violin has been used in a number of investigations addressing specific problems in violin acoustics by Meyer[5], Melody and Wakefield[6], the above Cambridge group[2] and the present author[7].

2 SOUND OUTPUT FROM THE VIOLIN

The violin can be considered as a black-box with a characteristic linear frequency or impulse response that can, in principle, be determined to a high accuracy. The input at the bridge from the bowed strings has, to a good approximation, a sawtooth waveform However, if the string excites strong resonance of the bridge or violin, additional ripples and other perturbations occur, which can significantly affect the bowed input – leading to the well known wolf-note problem in extreme cases. We have therefore chosen to use a thick solid bridge on a solid skeletal-frame violin to minimize such problems.

The harmonic partials of the bowed string input signal excite the irregularly-spaced resonances of the real violin resulting a very different waveforms and spectra of the output. Each excited mode then radiates sound into the performance space with a frequency and angular dependence that depends on the distribution of modal velocities around the shell of the instrument. The radiated sound is then reflected from any surrounding walls, so that the sound heard by the listener is a convolution of the sound radiated from the violin and the impulse response of the performance space itself, which will superimpose its own filtering action on the instrument.

The quality of the sound heard by the listener is therefore dependent on the skill of the performer bowing the strings modified by the filtering action of both the violin and the performance space. The sound therefore depends on the listener’s position relative to the instrument. The player hears a combination of both the near- and far-field sound of the violin, which is generally usefully enhanced by a small amount of feedback from the room acoustic, whereas the listener hears the far-field radiated sound, which is strongly modified by the room acoustic. The player is therefore likely to be much more sensitive to changes in the acoustics of the violin than the listener – especially when the violin is played in a resonant acoustic. Hence any attempt to correlate the quality of an instrument with its acoustic properties should ideally be undertaken in a very dead acoustic – even though the absence of any additional reverberation from the performance space makes playing any instrument under such conditions a rather unsatisfactory experience. This is just as important when assessing the quality of electric violins as it is for the real instrument. For electric instruments, quality assessments can best be made by playing the output through headphones.

3 EXPERIMENTAL SET-UP

We currently use a simple rectangular bridge with a horizontal bar supporting the four stretched strings. This in turn is supported by two short and thick vertical columns mounted on a solid base. A piezo-electric bimorph strip is encapsulated in one of the supporting columns. Because the bridge is mounted on a solid frame, the force on the bridge from any of the four bowed strings results in a bending of the vertical supports inducing a pickup of typically many tens of mV in the piezo bimorph strip. This signal is buffered by a high impedance amplifier and used as the input of the Signal Wizard DSP.

In the course of the investigation we measured the response of a number of commercial bridge pickups in addition to our own. When the pickups are attached to conventional violin bridges mounted on a solid-framed instrument, the output tends to have a marked peak at the in-plane rotational resonance of the bridge, with a strong cut off at higher frequencies, as illustrated by specific examples in Fig.1. Such characteristics significantly affect the sound of an electric violin. To capture a true representation of the input bowing force, one should ideally use a pickup with a flat frequency response up to the highest audio frequencies of interest. Such a bridge, using a pair of orthogonal force-sensitive transducers under each string, to measure both the transverse and vertical bowing forces, was patented by Scherer[8]. A similar bridge detector was used by McIntyre, Schumacher and Woodhouse[9] to investigate the dynamics of the bowed string.

Connected to a PC, any pre-recorded impulse response from a chosen instrument can be loaded into the DSP filter. This can then be convoluted with the input signal in real-time to provide a filtered output. In principle, this output should be identical to that of the original instrument provided the input signals are the same.

Whereas the Cambridge group uses the measured admittance at the bridge to provide the filtering action, we chose instead to use the radiated sound from an impulsive tap at the bridge – ideally by a force hammer, but in our case from a light pith ball on the end of a short length of string. Both methods have their problems. Using the input admittance at the bridge as the filter assumes that the sound output has identical frequency dependence, whereas in practice different modes radiate more efficiently than others. The problem with our measurements is that above ~700 Hz the radiation becomes highly directional. Any measurement of the impulsively radiated sound therefore depends on the direction of the microphone relative to the violin. The synthesized sound using such an input for the DSP filter would reproduce the sound heard at the precise recording position, which could be assessed using a headphone on one ear. However, we would argue that the perceived quality of an instrument does not vary significantly as one moves around an instrument in a typical performing space, so the directional issue may not be as serious a problem as might otherwise be claimed. A possible explanation for this could be that, at the higher frequencies, the auditory system provides an averaging over many resonances each with very different radiation patterns. This implies that the multi-resonant response of the instrument itself provides an averaging over different directions within the bands of frequencies important in any subjective assessment of the quality of an instrument.

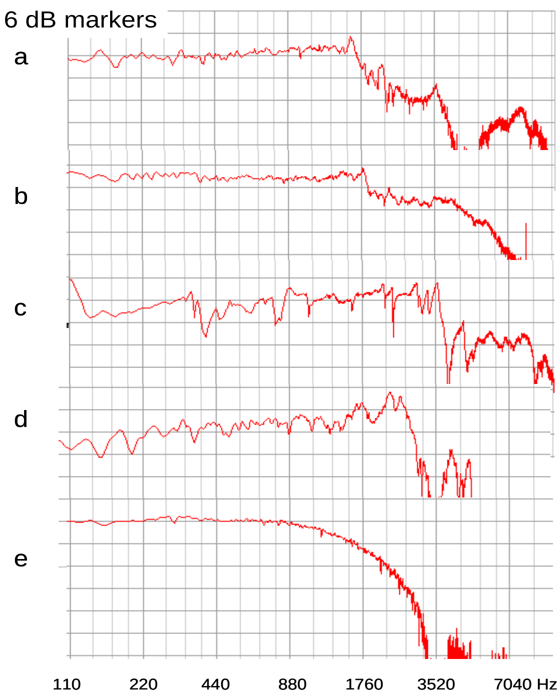

Figure 1 The frequency response of outputs from bridge-mounted, piezo pickups - from impact measurements. (a) A Barcus-Berry clip-on-side pickup on Vuillaume bridge, (b) a Violectra bridge on solid-frame electric violin, (c) our encapsulated piezo pick up on electric violin, (d) a Twin-T pickup under the feet of a conventional bridge on an electric violin, (e) a Shadow –Twin pickup attached mounted on the top of the Vuillaume bridge.

In addition to the acoustic impulse measurements on a number of our own violins, Joe Curtin has kindly provided several of his own measurements on Cremonese and fine modern instruments, which we have used as filter functions.

In comparative listening tests, it is often more convenient to have a prerecorded signal from the bowed string to avoid the inevitable variation in input when a player attempts to play a passage in exactly the same way. In addition, one can use an artificial sawtooth bowed input signal, which gives one even greater control of amplitudes, envelopes and frequency modulation (e.g. vibrato amplitudes and rates).

4 MEASUREMENTS

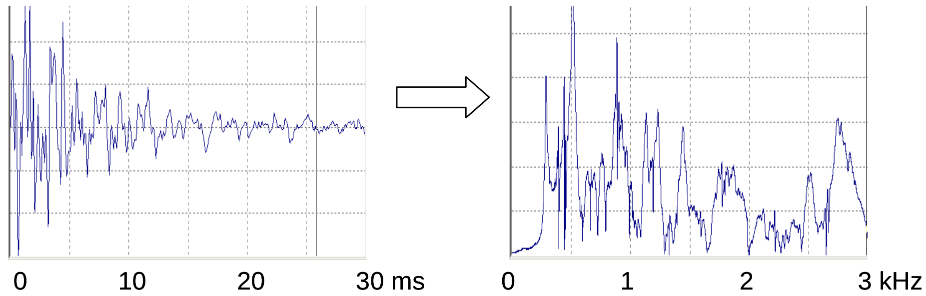

Figure 2 A typical acoustic impulse measurements with its Fourier spectrum measured close to a violin front plate, where the sound is dominated by the instrument rather than performance space.

The acoustic impulse in Fig. 2 shows a complex waveform with a spectrum having strong peaks at the A0 air resonance and one of the strong breathing modes of the body. Some of the higher frequency modes are relatively quickly damped in ~ 5-10 ms, while a number of modes ring for much longer. .

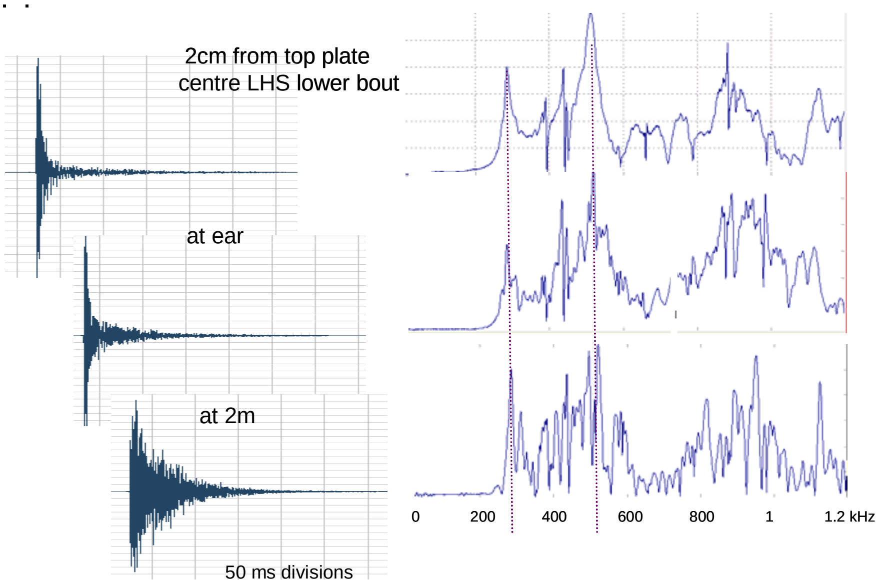

Figure 3 Acoustic impulse responses and associated spectra recorded close to the body of the Vuillaume violin, at the player's right ear and at a distance of 2m.

The acoustic impulse measurements in Fig.3 illustrate the increasing importance of the performing acoustic as one moves away from the instrument, with a much longer decay and additional room resonances contributing to the spectrum. However the main global features are reproduced with a strong decrease in output between 600 and 800Hz followed by a broad peak around 900 Hz, but with additional room resonances superimposed. These closely spaced resonances have a major impact on the spectrum, timbre and complexity of the sound waveforms, especially for notes played with vibrato, as argued elsewhere[7]. We can use the different impulse functions as the filter function in the Signal Wizard and listen to the filtered output through headphones to demonstrate the differences in the quality sound heard by the player and listener - using a real-time bowed input, a pre-recorded bowing input or synthesized sawtooth waveform.

In addition, we have used acoustic impulse measurements for a number of outstanding Cremonese instruments and many other old and modern instruments. The acoustic impulse responses for the four Stradivari violins were recorded at a central position 34 cm from the top position using Joe Curtin's impulse measuring rig, while the Vuillaume measurement is our own, recorded somewhat closer to the body of the instrument. In all cases, there are prominent peaks from the A0 and B1- and B1+ signature modes, though the positions and relative heights of the peaks vary from instrument to instrument.

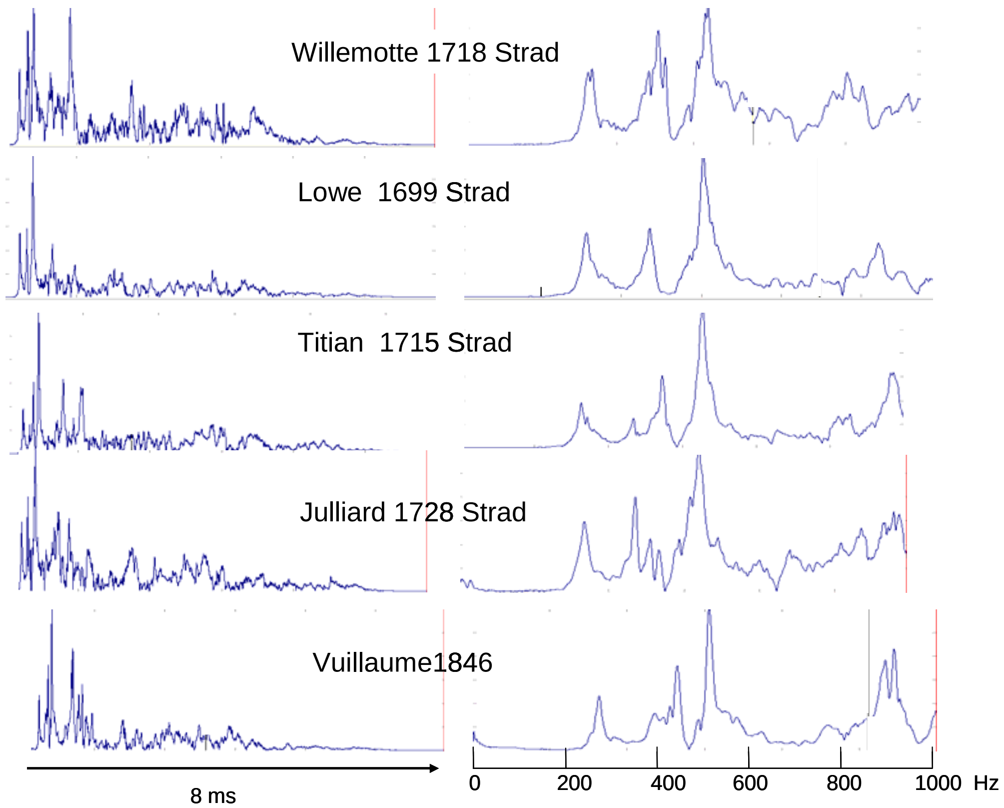

Figure 4 Acoustic impulse functions from four Stradivari instruments (Curtin data) and a Vuillaume violin used to synthesise real-time sounds on an electric violin

The synthesized sounds of our electric violin using these impulse functions can be demonstrated in real-time using the Signal Wizard DSP. It is also interesting to observe and listen to the difference in sounds of these and other fine Stradivari instruments using a synthesized, constant amplitude, sawtooth wave form to simulate the bowed input, using a controlled amount of vibrato, as illustrated in Fig.5.

The variation in intensity of the artificially bowed instrument changes from note to note and depends on the positions of the instrument's resonances across the whole playing range relative to the harmonic partials of the input waveform. As a consequence, the intensity of the sound produced varies from note to note, with significant differences between the instruments.

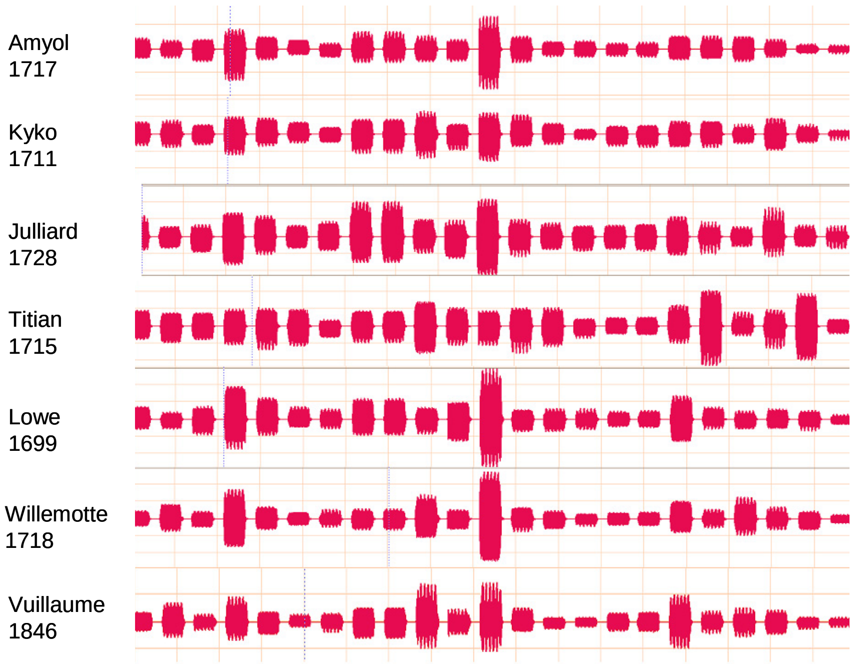

Figure 5 Output from the convolution of a six Stradivari instruments and a Vuillaume violin with synthesized 3-octave vibrato modulated sawtooth g-major scale (with repeated notes at the octave)

In each case there is a strong increase in intensity around the frequency of the A0 air resonance and close to the two main body resonances B1- and B1+. These measurements would suggest that the Titian Strad would have a more uniform response over the first octave and a half than any of the other instruments.

In listening tests, it is interesting to compare the sounds of the unfiltered input from the bowed strings in addition to the filtered sound. Perhaps unsurprisingly, the sound of the bowed string is remarkably like that of a violin – or rather viola - as previously noted by Mathews and Kohut[4]. This is because the electric violin with a flat response at low frequencies faithfully reproduces the amplitudes of all the low partials of the string force, whereas the very rapid fall-off in response of a real violin below the air resonance at ~280Hz leads to a strong attenuation of the fundamental of all the lower notes on the g-string. The sound of the unfiltered electric violin therefore has a much stronger fundamental component and sounds much richer and viola-like than the violin. However, the increased sound output of the electric violin at low frequencies comes at a price, because it is then more sensitive to the large change in dc transverse force acting on the bridge every time the bow changes direction. This produces a strong, wide-band, frequency spectrum extending to ~ 300 Hz, which produces a disconcerting "clunck" to the sound every time the bow changes direction. If an analogue filter is used to get rid of this signal, it also attenuates the fundamental of the lowest notes and hence sound more violin-like again. In principle, the Signal Wizard could be programmed to attenuate the wide band signal but leave pass-bands for the partials of the bowed notes.

5 CONTROL OF DAMPING

Violin makers are interested in whether or not the intrinsic damping of the wood used in the violin's construction affects the perceived sound of a violin. This was investigated in the important early experiments of Mathews and Kohut[4] using an electric violin with a large bank of electronic resonators (20-40) with resonant frequencies, amplitudes and damping under the researcher's control. The sound was judged best when the damping was adjusted to give a typical peak-to valley ratio between the higher frequency resonances of around 10-12 dB. A flat response gave an even, but slightly harsh, sound and was unresponsive to the player's use of vibrato or variations in bow pressure. When the damping was reduced to give a large peak-to-valley ratio ~20 dB, the sound was judged “hollow”, with obvious changes in intensity from note to note. This implies that optimized damping involves a compromise between being too large, resulting in an unresponsive instrument, or too small, resulting in a hollow-sounding instrument with an uneven response.

We have investigated the effect of damping by applying a time-varying “windowing” function to the acoustic impulse of the form

$$1 + 10\tanh(10mt) \sim \exp(1 + t/\tau) \qquad \text{at small } t,$$

where $\tau = 10/m$ ms. The damping across the whole spectrum is decreased by the same factor, with every mode acquiring a new damping time τ_k^*, where

$$1/\tau_k^* = 1/\tau_k - 1/(100m).$$

The form of the windowing function ensures that there is no problem at long times from any mode increasing in amplitude uncontrollably. The above method could be used selectively on different sections of the frequency spectrum, to describe frequency dependent changes in damping, but in this proof of principle experiment this has not yet been attempted. The damping of each mode can be increased in the same way by applying a simple exponential damping windowing function.

Figure 6 illustrates the effect of applying this windowing function to the impulse function and to the resulting complexity of the waveforms, which appears to be correlated with the brain’s ability to focus on the sound and hence affect the perceived quality. Note that increasing the decay time of the resonances increases both the intensity and complexity of the waveform envelopes. For the player, any increase in the resonant response or ringing quality of the violin is rather like the enhancement in perception gained from a small amount of additional room acoustic reverberation.

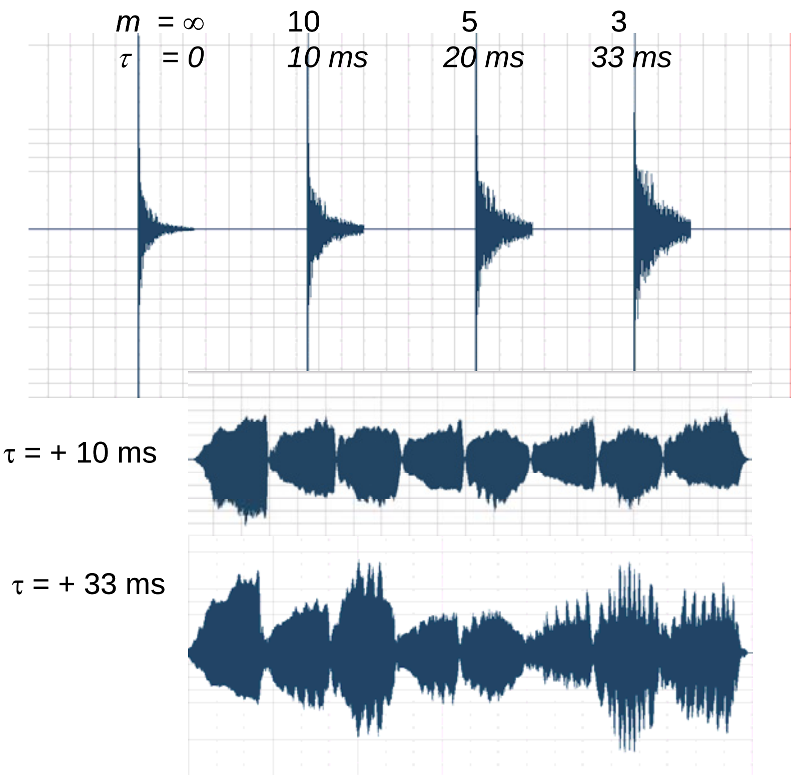

Figure 6. The effect of applying a windowing function to the acoustic impulse response, to artificially enhance the decay times of modes, and the resulting affect of such changes on the amplitudes and complexity of a bowed string scale of g-major using vibrato, starting on the open-string.

6 SUMMARY

These preliminary studies show that one can achieve quite a realistic violin sound from even the vibrating strings alone. Filtering the bowed string input with the multi-resonant response of the violin is rather like listening to the sound of any recording using what might be considered a very poor loudspeaker, with a very uneven response with many individual resonances that "colour" the sound. A completely flat response appears to lead to a rather dull sounding instrument. The peaks and valleys in the multi-resonant response add complexity to the bowed waveform and apparent ringing quality to the violin, especially when played with vibrato – conclusions that are in line with the earlier investigation by Mathews and Kohut[4].

What is new is the ability to use a real-time signal processor to modify and thereby "improve" the sound of the electric violin in almost any conceivable way. In the future, one can envisage commercially produced electric violins incorporating a simple onboard microprocessor controlling the DSP with any number of filter functions. This would enable the player to select a Stradivari, baroque, Chinese Erhu, or a completely different sounding instrument at will. If one could also integrate a battery driven amplifier and integrated loudspeakers, one would then have a truly portable instrument. This would be easy and fun to play – possibly a good instrument to start learning on, as the instrument is easier to bow because of the more rigid string terminations on the bridge of a solid-bodied electric instrument. The electric violin can certainly make a much more pleasing sound than the usual starter violin.

In addition, we have shown that the electric violin can be used as a serious research tool to address fundamental problems relating to the correlation of violin acoustics with the perception of sound quality.

7 ACKNOWLEDGEMENTS

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