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Novel Impulse Response Measurement Method for Stringed Instruments

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ABSTRACT

This paper introduces a measurement technique which delivers highly reproducible impulse responses of stringed instruments. The method bases on exciting the dampened strings at the bowing or plucking position by means of a thin copper wire which is pulled until it breaks. Taking into account the longitudinal and torsional movements of a bridge caused by string deflection, such stimulus of an instrument is close to the musical application. On the basis of the string-wire geometry, measurement setups can be exactly specified and individually adjusted, allowing for highly accurate repetition in comparative studies. The setup, including a fully automated exciting apparatus as well as a 'silent' quadrochord, is described in detail. Furthermore, the method is compared with the commonly used impact hammer method. Finally, an application in the context of a research project on violin sound quality is briefly described, where the technique is used to measure binaural impulse responses of violins.

1. INTRODUCTION

Measuring transfer functions of stringed instruments has always been a basic issue in musical acoustics and has been repeatedly approached with different methods [1], [2], [3]. The experimental determination of transfer functions of stringed instruments is still necessary as long as there are no complete and reliable physical models. Presuming that the resonator is a linear system (Fig. 1), its frequency response and impulse response offer a lot of information on timbre, reverberation and directional radiation properties. Impulse responses are used as starting point for modeling approaches for example, or to investigate the relationship between particular transfer functions and the instruments' quality. The so called resonance profile which is the magnitude spectrum of the impulse response shows the individual resonance constellation or energy distribution of an instrument (Fig. 2). The resonance profile can be treated as the instrument's acoustic fingerprint and is therefore closely related to the quality of the instrument.

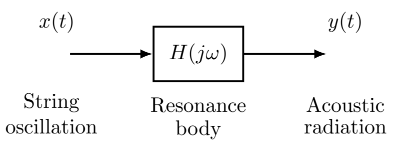

Figure 1: The resonance body treated as an LTI system.

For scientific purposes measurement techniques for string instrument body responses have to meet certain requirements: (i) a high degree of reliability is required in order to allow the comparison of measurements as well as the exact repetition of measurements at different times or places. (ii) Particularly for investigations on musical instruments a high validity is necessary. The choice of an appropriate point of excitation, for instance, determines whether an obtained impulse response is meaningful or not, in other words, to what extend it corresponds to an instrument's natural transfer behavior. (iii) The excitation signal has to have an adequate linear and broadband frequency behavior. (iv) In case of acoustic recordings, the excitation mechanism should be as quiet as possible. (v) The excitation mechanism must not add additional mass or affect the instrument's vibration characteristics in any other way. This demand is especially important for stringed instruments because of their complex and sensitive resonance behavior [4].

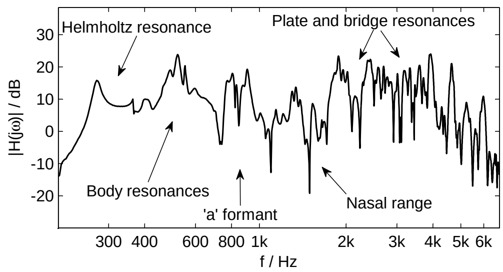

Figure 2: The resonance profile of a mid-priced violin (E. Roth, 1977).

There are several methods for achieving transfer functions of stringed instruments; however, they only partially meet the above mentioned requirements. Moreover, the results are often not reasonably comparable due to the wide variety of different techniques. The majority of investigators target the bridge when exciting string instruments because this is the location where the bulk of energy is decoupled from the strings. Methods with excitation signals of long duration usually do not meet the fifth requirement mentioned above, e.g. Dünnwald exciter [1], MLS signals [2], and sinusoidal forces [5], [6] [7]. In contrast, driving methods where bowing machines are used excite the instruments in a natural manner [8], [9]; but, due to the complex bowing process and the long measurement times, these methods are neither very reliable nor practicable. Hence, the most reliable and therefore most established measuring method for impulse responses is to excite an instrument at the side of the bridge by means of an impact hammer, used e.g. in [4], [10], or in [11]. During this excitation, all strings are damped. Typically, the impact hammer has a force transducer to record the input signal $f(t)$. The frequency response of the device under test (DUT) can then be calculated with

$$H(j\omega) = \frac{Y(j\omega)}{X(j\omega)}, \quad \omega = 2\pi f, \qquad (1)$$

where $Y(j\omega)$, for instance, is the radiated sound pressure or the structure mobility. The single impulse facilitates free vibration of the instrument and a sufficiently high bandwidth (up to about 8 kHz), depending on what type of impact hammer is used. However, this method also has three serious disadvantages:

(1) The impact excitation does not entirely represent the natural motion of the bridge as it occurs when it is driven by a plucked or bowed string. But especially the bridge motion and the bridge eigenmodes are known to have an important influence on overall sound characteristics [5], [12]. The eigenmodes can be of longitudinal, flexural and torsional nature. Using an impact hammer, the bridge is approximately driven only in one direction, namely the one according to the transversal string oscillation (x-motion, Fig. 3). However, the string oscillation causes several types of bridge motion and there is a need to differentiate: due to the impulse of the Helmholtz motion which runs along the string twice an oscillation, the string tension varies. This fact results in a changed downward force (y-direction, Fig. 3) to the bridge and therefore is immediately applied to the top plate [13]. In [14] this excitation is called indirect excitation. Another result of the string vibration is a tilting movement of the bridge due to the string deflection. This movement in z-direction (Fig. 3) actually does not significantly affect body resonances but causes a radiation of the bridge itself which then effectively represents an acoustic dipole. Additionally, the bridge wings vibrate due to the string deflection of the e- and g-string. This is even visible when pulling a string aside with a finger.

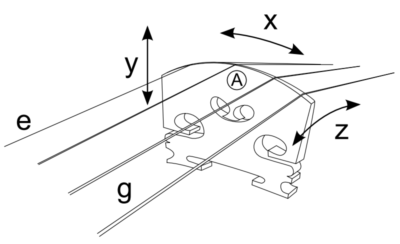

Figure 3: The violin bridge and its directions of motion.

(2) Even though the impact hammer approach is probably believed to be the most reliable among the commonly used methods, there remain difficulties to reproduce or communicate the exact point of excitation, the impact angle and the impact speed.

(3) Depending on the weight of the hammer and the type of the hammer suspension, there remains a risk of double hits which occasionally occur due to bridge backward motion. Furthermore, too heavy hammers may cause a bridge displacement.

Taking into consideration the above-mentioned factors, it becomes obvious to involve a string in the excitation process and hence to drive the instruments in a more natural way. So, this paper aims at introducing an alternative approach using a wire which pulls a string aside until the wire breaks. Apart from the more authentic excitation the proposed procedure is also very inexpensive and easy to reiterate. In Section 2 the basic principles of the wire technique are explained. In addition, an apparatus is described which allows automated string plucking. In Section 3 the reliability of the method is shown and compared with the impact hammer method. Furthermore, the wire method and the hammer method are compared in terms of resulting bridge motion (z-direction, Fig. 3) using a laser intensity measurement setup. Finally, an application of the authors is briefly described where the proposed method is used to obtain binaural impulse responses of violins.

2. METHOD

The method presented here is based on a simple principle: a string is pulled aside at the bowing or plucking position by means of a thin copper wire of specified diameter. When the wire breaks, an impulse runs along the string and hits the bridge. This method allows for easy repetitions at different times or places due to well definable geometric relations, i.e. the plucking point, a clear pulling direction, and an easily measurable angle between wire and strings. During the measurement, all strings are damped by means of a small rubber mat located near the beginning of the fingerboard (Fig. 4). This type of damping has a minimum weight and does not affect the fingerboard modes. The distance between damping material and bridge is chosen such that the remaining fundamental oscillation of the string takes place above the frequency range of interest. Plucking an e-string of a violin will result in a fundamental oscillation of about 11–14 kHz if the rubber mat is placed 15–20 mm from the bridge. For the sake of completeness it should be mentioned that damping the strings in such a manner results in a new, free oscillating spring-mass system of the coupled strings whose fundamental frequency is at about 120 Hz. This low-frequency oscillation can be tolerated since it occurs below the frequency range of interest in most cases and can be compensated for (see below). An alternative damping with fixed strings at the fingerboard would result in a disturbance of the fingerboard modes.

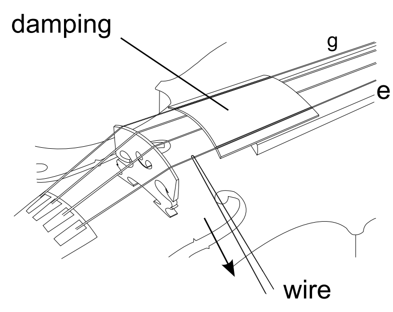

Figure 4: String deflection by using a copper wire.

Here, conventional enameled copper wire is used for excitation. It turned out that wires with diameters between 0.09 mm and 0.19 mm are best suitable for excitation, see also Section 3. If the diameter is too large, the string can be pulled down from the bridge. This is also the reason why the authors mostly use the e-string as excitation string in case of violins. The pulling direction is usually set to the respective bowing direction, in up-bow or in down-bow direction. The authors decided to use a driving point at a distance of 10 mm to the top edge of the bridge. Measurements have shown that a slight variation of the plucking point of about 5 mm in each direction does not affect the resulting frequency response in the frequency range up to 10 kHz.

Just like in other transfer function measurements the wire impulse method also requires knowledge of the input signal. The quotient of the output frequency response, i.e. the Fourier transform of the radiated sound pressure for example, and the frequency response of the input signal is the frequency response of the DUT. Determining the input signal at the bridge requires an additional measurement. Here, the input signal is obtained by means of a vibration-free instrument made of solid steel named quadrochord (Fig. 5). It has four strings, a variable mensur length, and a bridge which is equipped with piezoelectric elements. These pickups, connected to an impedance converter, allow for direct recordings of string oscillations. For measuring the input excitation signal of the wire impulse, the strings are damped in the same way as described above. The wire excitation is also the same as described above. Once the input signal is determined for a specific setup (string type, wire diameter, excitation position) it can be used for all individual measurements due to the homogeneity of the copper wires used. The tensile strength needed to break the wire will always be the same for each measurement. Fig. 6 shows exemplary measurements of the input signal in the frequency domain (violin e-string, wire diameter of 0.14 mm). Here, the outstanding peak at about 12.5 kHz represents the fundamental frequency of the string part between damping mat and bridge.

Figure 5: Steel quadrochord used for input signal measurements.

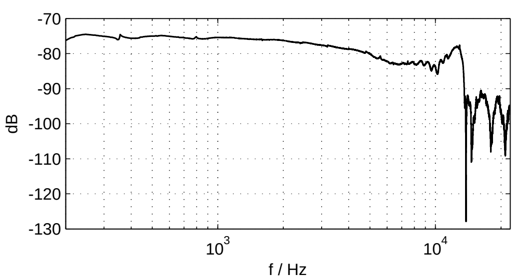

Figure 6: Frequency behavior of the input wire excitation signal measured on the quadrochord.

The proposed method is characterized by a very high degree of measurement reproducibility due to the good manufacturing accuracy of the wire and hence the corresponding, unchanged string displacement. Such high precision allows for good repetition accuracy even when wires are pulled manually (see also Section 3). Nevertheless, the authors of the paper have developed a fully automated exciting mechanism with which string instruments can be plucked [15]. The plucking apparatus consists of a solenoid with a movable iron/aluminium core which is accelerated and slowed down by the Lorentz force. The apparatus is nearly noiseless and due to a microprocessor control it can be triggered from another room. The advantage of a fully automated excitation is obvious: excluding human inaccuracies as well as perturbing noise of action enhance precision of measurements. This is also represented in increased correlation coefficients between measurements. Here, the Fourier spectra of 15 recorded measurements have been compared pairwisely. Fig. 7 shows the correlation coefficients of manually pulled wire excitation in comparison to the automated excitation.

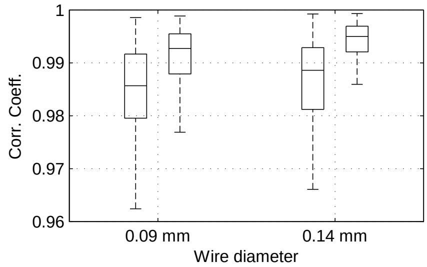

Figure 7: Box whisker diagram of the correlation coefficients of pairwisely compared spectra: manually pulling (left) and automated pulling (right) for two exemplary wire diameters.

3. RESULTS

In an anechoic chamber impulse responses of a high-quality violin (M. Schleske, 'Op.96', 2008) have been measured. The acoustic radiation of the instrument has been recorded using a condenser microphone placed directly above the bridge at a distance of 500 mm. At the same time—as part of a parallel project—microphone signals of an artificial head have been recorded, too. The artificial head has been placed at the playing position, as shown in Fig. 8. The violin has been clamped only at two points related to the normal playing situation: at the neck and at the chin rest. Fig. 9 shows the acoustic radiation recorded with the condenser microphone in the frequency domain for different wire diameters. In order to compare the wire excitation with the impact hammer method, the bridge has also been driven on the soundpost side by means of a miniature impact hammer (type: Dytran 5800SL, head weight: 2 g, ball bearing suspension). Fig. 10 shows the average resonance profile in comparison to wire excitation (0.18 mm diameter). The resonance profiles are normalized to their respective input signals. The increased first air mode ('Helmholtz resonance'), visible in case of wire excitation, is a result of the above mentioned indirect excitation which occurs due to the string deflection. The impulse responses have been normalized such that they show the same energy in the time domain. Fig. 11a and Fig. 11b show the resonance profiles at the left and right ear of the artificial head microphone, respectively. For comparison, the frequency curves have been equalized with the inverse transfer function of the artificial head.

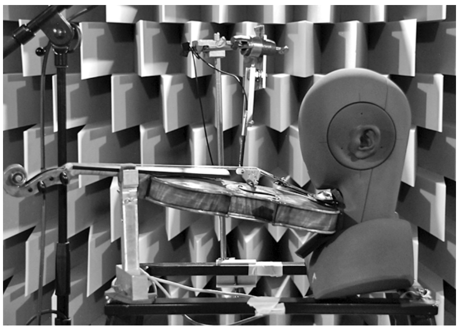

Figure 8: Violin impulse response measurement in anechoic room using a dummy head microphone.

3.1 Bridge Deflection Measurement

In order to examine the bridge mobility in z-direction (Fig. 3) for both types of excitation further measurement series have been done by means of a specific laser intensity technique. The

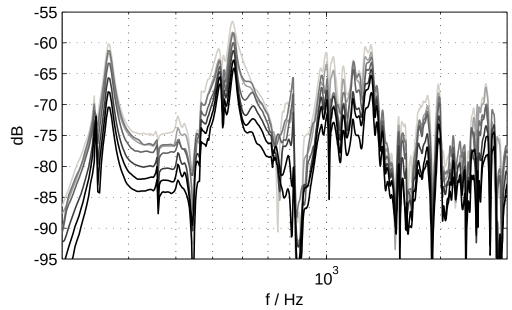

Figure 9: Acoustic radiation of a high-priced violin. Results for wire excitations with different diameters. From top down, diameters in mm: 0.18 (light gray), 0.17, 0.16, 0.15, 0.13, 0.12, 0.11 (black).

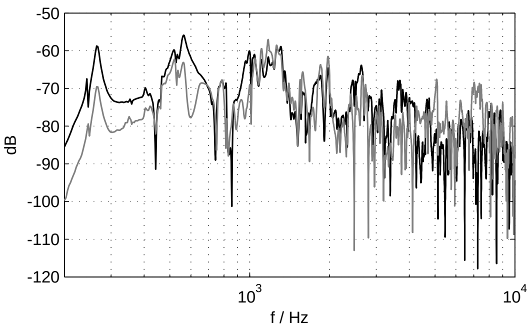

Figure 10: Violin resonance profiles recorded with a microphone at a distance of 500 mm directly above the bridge in an anechoic chamber; black: wire excitation, gray: impact hammer excitation.

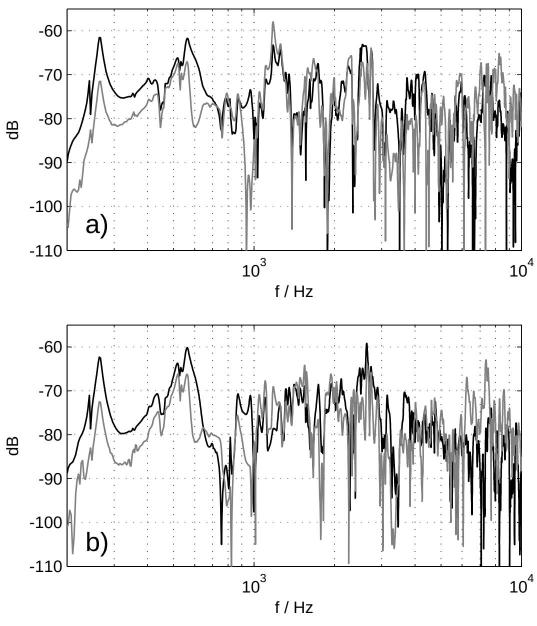

Figure 11: Violin resonance profiles recorded with a) left ear microphone and b) right ear microphone of an artificial head; black: wire excitation, gray: impact hammer excitation.

direct displacement of the bridge is obtained by measuring the intensity of a laser beam after it has passed a tiny aluminum plate (weight: 0.05 g) bonded to the bridge (Fig. 12). In [16] the technique is described in detail. The deflection of the bridge set into relation to the respective excitation input signals yields the frequency-dependent receptance (i.e. the dynamic compliance). The bridge deflection has been measured at the top edge of the bridge between the two middle strings (Point A in Fig. 3). Again, the time signals of the measured deflection have been normalized to a microphone signal which has been recorded directly above the instrument (500 mm distance). Fig. 13 shows the measured receptance of the bridge in z-direction for both the wire and the impact hammer excitation. The so called bridge hill, i.e. the frequency range at about 2 to 3 kHz, is clearly visible. The wire excitation yields a slight increase of the displacement amplitude of the mechanical bridge resonance which occurs at 2.5 kHz [17], [18].

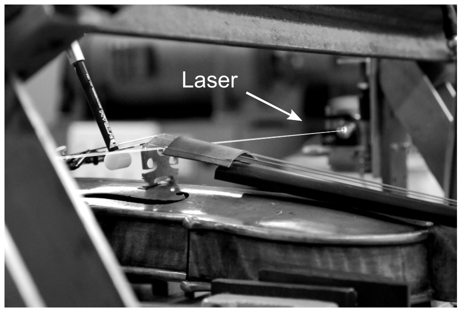

Figure 12: Bridge deflection measurements with laser intensity (description in the text).

3.2 Application Example

As mentioned above, impulse responses of string instruments are used for several scientific tasks. In a concurrent research project the authors of the paper focus on the perceived quality of violins. As part of the project, a real-time violin tool has been developed which can be used to investigate the relationship between spectral properties of the violin body and the perceived quality of the instrument [19]. The tool is based on binaural impulse responses of real violins which can be modified software-based in high resolution. The above described measurement method represents the start position for further signal processing. Using a near-field artificial head microphone located at the playing position, the measured impulse responses are as authentic as possible. Due to the complex directional characteristics of a violin, the measured transfer functions differ from one ear to the other ear. Fig. 14a and Fig. 14b show the binaural resonance profiles of a high-priced and a mid-priced violin, respectively. Again, the impulse responses have been equalized with the inverse transfer function of the artificial head microphone.

4. SUMMARY

In this paper a method for measuring impulse responses of stringed instruments has been presented. Since the string is involved in the measuring process, the proposed method is more closely related to the natural excitation of a string instrument than conventional methods. The method also meets the requirements for high-degree reliability and validity. Using copper wire for exciting the strings allows for high repetition accuracy both because of the good wire homogeneity and because of the well definable string-wire geometry. The measurement setup has been introduced in detail and first measurement results have been described, particularly in comparison to the established impact hammer method. By using a laser intensity

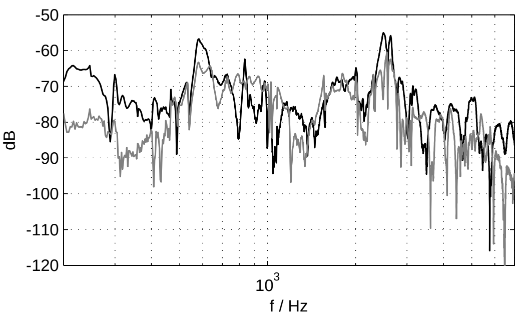

Figure 13: Bridge receptance in z-direction (see also Fig. 3) in case of wire excitation (black) and impact hammer excitation (gray).

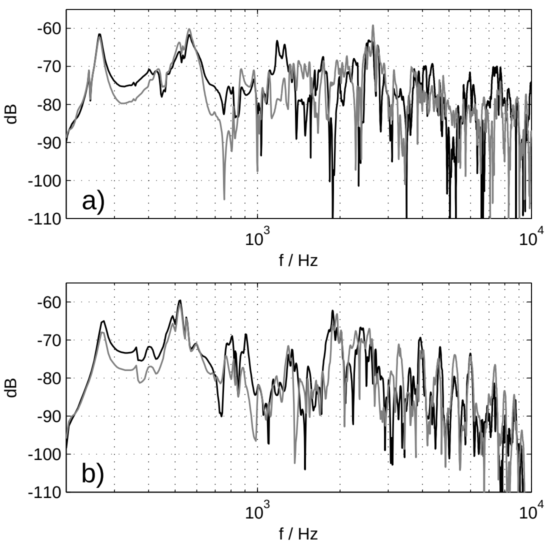

Figure 14: Binaural resonance profiles of a) a high-priced violin and b) a mid-priced violin. Black: left ear signal, gray: right ear signal.

measurement method it could be shown that the proposed wire excitation results in different bridge motion due to the string deflection. In addition, a fully automated plucking mechanism and a specific usage for impulse responses have been described. In upcoming measurement sessions, the method has to be verified and compared against the hammer method in more detail. This will include, for example, a registration of complete directional radiation patterns of different violins and transfer function measurements of other stringed instruments, e.g. guitars.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] H. Dünnwald, *Akustische Messungen an zahlreichen Violinen und Ableitung objektiver Kriterien für deren klanglichen Eigenschaften.*, Ph.D. thesis, RWTH Aachen, Aachen, Germany, 1984.

[2] A. Farina, A. Langhoff, and L. Tronchin, “Realisation of ’virtual’ musical instruments: measurements of the impulse response of violins using MLS technique,” in *Proc. 2nd Int. Conf. on Acoustics and Musical Research (CIARM-95)*, Ferrera 1995.

[3] A. Farina, A. Langhoff, and L. Tronchin, “Comparison of violin impulse responses by listening to convoluted signals,” in *Proc. Intern. Symp. on Musical Acoustics (ISMA-95)*, Paris, July 1995, vol. 53, pp. 1620–1626.

[4] E. V. Jansson, B. K. Niewczyk, and L. Fryden, “On the body resonance C3 and its relation to the violin construction,” *J. Catgut Acoust. Soc.*, vol. 3, pp. 9–14, 1997.

[5] M. E. McIntyre and J. Woodhouse, “The acoustics of stringed musical instruments,” *Interdisciplinary Science Reviews*, vol. 3, no. 2, pp. 157–173, 1978.

[6] J. C. Luke, “Measurements and analysis of body vibrations of a violin,” *J. Acoust. Soc. Am.*, vol. 49, pp. 1264–1274, 1971.

[7] E. Jansson, I. Bork, and J. Meyer, “Investigation into the acoustical properties of the violin,” *Acustica*, vol. 62, pp. 1–15, 1986.

[8] J. S. Bradley and T. W. W. Stewart, “Comparison of violin response curves produced by hand bowing, machine bowing and an electromagnetic driver,” *J. Acoust. Soc. Am.*, vol. 48, pp. 575–578, 1970.

[9] R. M. Lee, “An investigation of two violins using a computer graphic display,” *Acustica*, vol. 32, pp. 78–88, 1975.

[10] M. Karjalainen and J. Smith, “Body modeling techniques for string instrument synthesis,” in *Proc. Int. Computer Music Conf. (ICMC-96)*, Hong Kong, China, 1996.

[11] C. Fritz, I. Cross, B. C. J. Moore, and J. Woodhouse, “Perceptual thresholds for detecting modifications applied to the acoustical properties of a violin,” *J. Acoust. Soc. Amer.*, vol. 122, no. 6, pp. 3640–3650, 2007.

[12] W. Reinicke, *Die Übertragungseigenschaften des Streichinstrumentenstegs*, Ph.D. thesis, Technical University of Berlin, 1973.

[13] N.-E. Molin, A. O. Wåhlin, and E. V. Janssons, “Transient wave response of the violin body revisited,” *J. Acoust. Soc. Am.*, vol. 90, pp. 2192–2195, 1991.

[14] A. H. Benade, *Fundamentals of Musical Acoustics: Second, Revised Edition*, Dover Publications, 1990, ISBN: 978-0486264844.

[15] T. Smit, F. Türckheim, and R. Mores, “A highly accurate plucking mechanism for acoustical measurements of stringed instruments,” *J. Acoust. Soc. Am.*, vol. 127, no. 5, pp. EL222–EL226, 2010.

[16] R. Mores, M. t. Straten, and A. Selk, “Measuring transient structure-borne sound in musical instruments–proposal and first results from a laser intensity measurement setup,” in *Proc. 126th Audio Eng. Soc. Conv.*, Munich, Germany, 2009.

[17] N. H. Fletcher and T. D. Rossing, *The Physics of Musical Instruments*, Springer, New York, 2 edition, 1998, ISBN: 978-0387-98374-5.

[18] J. Woodhouse, “On the "bridge hill" of the violin,” *Acta Acustica united with Acustica*, vol. 91, pp. 155–165, 2005.

[19] F. Türckheim, T. Smit, and R. Mores, “A semi-virtual violin for investigations into sound quality and musician-instrument interaction,” in *Proc. Int. Computer Music Conf. (ICMC-10)*, New York, USA, 2010.