Evaluation of a Miniature Accelerometer with a Laser Doppler Vibrometer to Study Vibrations at the Neck of a Violin in Realistic Playing Scenarios

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ABSTRACT

This paper evaluates a miniature accelerometer to measure vibrations at the points where the violinist is in contact with the violin. The violinist perceives these vibrations as vibrotactile feedback, which plays an important role for the quality perception and the precise control of the instrument. The performance of the accelerometer is compared to a laser Doppler vibrometer in measurements with a loudspeaker and a violin. It is shown that the displacement calculated from the accelerometer signal has a resolution of 0.1 μm in the frequency range from 50 Hz to 1 kHz and that the added mass of the accelerometer does not influence the vibrations of the instrument. Finally, the capability of the approach is demonstrated in a violin neck vibration measurement, where horizontal and vertical vibrations were recorded with two accelerometers in a realistic playing scenario.

1. INTRODUCTION

Playing a musical instrument is a multi-modal task, where the musician controls the instrument based on sensory feedback. Vibrations of the instrument's body are perceived by the musician as vibrotactile feedback through the contact points with the instrument. The relevant frequency range of human vibration sensation extends from 40 Hz to 1 kHz; one of the most sensitive sites is the fingertip that can detect displacements as small as 0.1 μm [1].

In violin playing vibrotactile feedback is important for the quality perception, for the "feel" and for the precise articulation of the instrument [2, 3, 4, 5, 6]. The contact points between the violinist and the instrument are the thumb of the left hand holding the neck, the fingers of the left hand pressing the strings, the fingers of the right hand holding the bow, the chin, and the shoulder holding the violin body [3].

Marshall [2] analyzed the vibration behavior of a violin and found that the neck participates strongly in the lower order modes [2]. He suggested that these low order resonances must be related to the coveted "feel" of the great violins. Later, Askenfelt and Jansson [3] presented an extensive series of measurements at the contact points of string instruments and compared the results to the vibration sensation thresholds for the finger reported by Verrillo [1]. For the violin, the measurements were made with an accelerometer and for excitation the lowest note G3 (194 Hz) was played on the violin at fortissimo level. In a comparison experiment with four violins they found that there is no clear relationship, such as higher neck vibration levels indicate higher quality.

Extending on the work of Askenfelt and Jansson, Wollman et al. [5] investigated the vibrotactile feedback of the left hand in violin playing. He showed that the perception thresholds for the left hand in violin playing are lower than those reported by Verrillo, due to the greater contact area of fingers and thumb holding the neck, as well as the influence of the applied pressure. In the same study, based on the expert judgment of an experienced professional violinist, several violins were categorized into "vibrating" and "non-vibrating" instruments. The differences of the neck vibrations were investigated and they found that the "vibrating" violins vibrate significantly more in the frequency range from 600 Hz to 1 kHz. They suggest that these differences in vibration behavior might lead to the perceived characteristics of the individual instrument.

However, quality classification of violins based on vibrational properties remains limited and might depend on how perceptual criteria are individually evaluated by violinists during assessment, as pointed out by Saitis et al. [7].

To measure vibrations during violin playing and to further explore the role of vibrotactile feedback, we are developing a measurement method to measure vibrations at the contact points between violinist and the instrument during realistic playing scenarios. In this paper we evaluate a miniature accelerometer with a laser Doppler vibrometer and demonstrate the potential of the approach by presenting a measurement of the horizontal and vertical neck vibrations during playing of a chromatic scale.

2. SENSOR EVALUATION

To evaluate the miniature accelerometer for vibration displacement measurements of a violin, we compared it to a laser Doppler vibrometer (LDV). We focus on vibration displacement because perception data is reported as displacement values (e.g. see [1]). In the first experiment two examples of the accelerometer are compared to the LDV by measuring the motion of a loudspeaker driver membrane. Thereafter, the acceleration sensor is evaluated with vibration measurements on the top plate of a violin, where the violin was held in a fixed position. The violin used for the experiments is a professional quality instrument that was made by O. Spidlen in 1946 (Prague).

2.1. Equipment

We also tried piezo disc elements and piezo thinfilm sensors to measure vibrations at the contact points of a violin. The miniature accelerometer we evaluate hereafter was most promising with regard to resolution, mass, and size. The miniature accelerometer is a Knowles BU-21771-000 piezo-based miniature 1-axes accelerometer designed for vibration transduction. The size of the accelerometer is 7.9 x 5.5 x 4 mm and its weight is 0.28 g. According to the data sheet[1] the sensor has a sensitivity of -45 $\pm$ 4.5 dB relative to 1 V/g at 1 kHz. The frequency response of the sensor is flat up to 2 kHz. The accelerometer is connected to a preamplifier that we designed with a gain of 21 dB. The battery driven preamplifier also supplies the sensor. The accelerometer is attached to the vibrating surface with double-sided tape.

The performance of the miniature accelerometer was compared to an LDV consisting of a single-point laser head, a controller, and a velocity decoder[2]. The precise alignment of the laser beam is crucial for LDV measurements, because only the projection of the vibration velocity vector from the target surface onto the laser beam is captured. To increase reflection and to improve signal-to-noise ratio (SNR), we used pieces of retroreflective tape with a size of 5 $\times$ 5 mm that were attached to the target surface. The measurement range of $\pm$ 50 mm/s with a resolution of 0.6 μm/s proved to be a good compromise for the measurements presented in this paper.

A computer with an external soundcard[3] recorded the signals from the velocity decoder and the miniature accelerometer synchronously. The soundcard has a sampling rate of 48 kHz and a resolution of 16 bit. The measurements were analyzed with computer software we specifically made for this purpose.

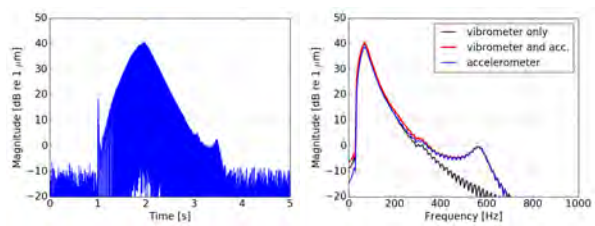
2.2. Evaluation with a loudspeaker

In the first experiment, the accelerometer and the LDV measured the motion of the 8-inch woofer membrane of a 3-way hi-fi loudspeaker[4]. The setup is shown in Fig. 1.

Two configurations were measured. In the first configuration the accelerometer was attached to the loudspeaker membrane and the LDV was measuring the motion of the accelerometer. In the second configuration only the LDV was measuring the vibration of the membrane to assess the influence of the added mass of the accelerometer on the loudspeaker membrane. The loudspeaker was fed with a swept sine signal from 20 Hz to 20 kHz and the frequency response of the loudspeaker was estimated with the method presented in [8]. The results are shown in Fig. 2. For displacement calculation, the accelerometer signal was integrated twice and the vibrometer signal was integrated once[5]. To remove offset and low frequency noise, the signal was filtered using a fourth order high pass filter with a cutoff frequency of 20 Hz after each integration.

Figure 1. Setup for the sensor evaluation on the 8-inch woofer of a hi-fi loudspeaker. The accelerometer and the vibrometer are measuring the motion at the center of the membrane. Operation frequency range of the woofer is 20 Hz to 650 Hz.

Despite a level deviation of 1.6 dB the frequency response of the accelerometer and the LDV match perfectly. A deviation was expected from the manufacturing tolerance of the accelerometer sensitivity. We repeated the same measurement for a second example of the miniature accelerometer, where the level difference was 2.7 dB. The noise level after displacement calculation for the accelerometer is around -10 dB (see Fig. 2). This implies a resolution of approximately 0.3 μm. Note that due to the integration, the cumulated noise level in the displacement time values depends on the cutoff frequency of the high pass filter. By increasing the cutoff frequency to 50 Hz, the noise level was pushed below -20 dB resulting in a resolution of 0.1 μm.



(a) Displacement time signal calculated from the accelerometer. (b) Extracted frequency responses from the swept sine measurements.

Figure 2. Results of the woofer membrane measurement. A swept sine from 20 Hz to 20 kHz was played back through the loudspeaker.

Comparing the vibrometer measurement with and without the accelerometer in Fig. 2, the responses start to diverge above 400 Hz. The presence of the accelerometer influences the motion of the loudspeaker membrane, which in this case results in an additional resonance around 600 Hz. In the following, the cutoff frequency of the high pass filter applied after each integration was set to 50 Hz and the measured level differences of the accelerometers were taken into account. To restrict the comparison to the relevant frequency range for vibration sensation and to include a fair margin, the signals were also low pass filtered with a cutoff frequency of 2 kHz.

[1] `http://www.knowles.com/download/file?p=BU-21771-000.pdf`

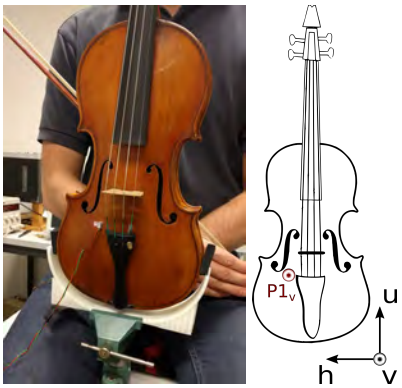
[2] Polytec OFV-303 head, OFV-3001 controller, OVD-01 decoder

[3] Sound Devices USBPre 2 audio interface

[4] Philips 22AH587, Manual: `http://docs.mfbfreaks.com/um/User_Manual_22AH587.pdf`

[5] For integration the scipy.integrate.cumtrapz function from the SciPy library 0.14.0 was used

2.3. Evaluation with a violin in a fixed position



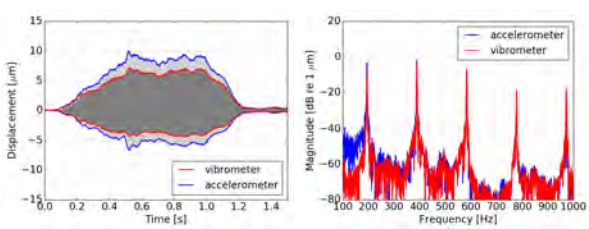
(a) (b)

Figure 3. Setup picture (a) and measurement position (b) for the evaluation of the accelerometer. Open strings were bowed from behind. The index v refers to vibrations measured along the vertical axis.

For an application based evaluation we created a setup to measure the vibrations of a violin during playing. The violin was held in a fixed upright position by the use of a 3D printed stand, such that the vibrations could be measured with the LDV and the violinist could bow open strings with downstroke from behind the instrument. The violinist was instructed to bow the strings in mezzo-forte (mf), although this setup is obviously not a realistic playing scenario. The purpose of this experiment is to exclude deviations due to the small added mass of the accelerometer, as well as to compare the sensitivity and the frequency range of the acceleration sensor and the LDV.

Measurement setup and measurement position $\mathrm{P1_v}$ are illustrated in Fig. 3. The measurement position was chosen because the top plate might be most sensitive to added mass. The distance between the laser measurement point and the accelerometer was roughly 1 cm.

The vibration displacement signals for the open G string (G3, 196 Hz) are shown in Fig. 4.



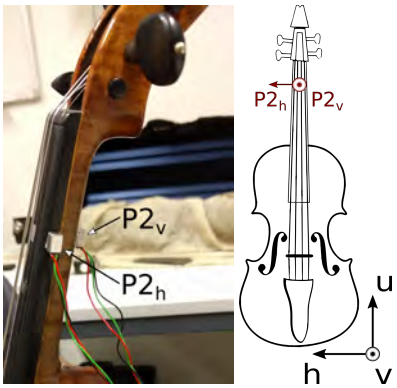
(a) Time signals with highlighted envelope (b) Frequency spectra

Figure 4. Comparison of laser Doppler vibrometer and accelerometer measurement on position $\mathrm{P1_v}$. The time signal shows the measured displacement when the lowest note G3 was played by the violinst. The frequency plot shows the corresponding spectrum.

The level difference of the time signals in Fig. 4 is around 12 % with regard to the displacement signal calculated from the accelerometer. The major deviations in the frequency spectrum are that the level of the LDV is 6 dB lower for the first partial and 2 dB lower for the second partial. The deviations arise from the laser beam misalignment in this case, but apart from the mentioned deviations, the frequency spectra closely match each other. We also calculated the Pearson correlation coefficient of the displacement signals. The correlation coefficient is above 0.96. Therefore it seems safe to conclude, that the accelerometer captures the vibrations up to 1 kHz. The accelerometer mass of 0.28 g attached to the violin body and the cables do not influence the vibration.

Summarizing, the accelerometer can measure vibration displacement with a resolution of 0.1 μm in the frequency range from 50 Hz to 1 kHz. We were surprised that the accelerometer performs comparable to the vibrometer for the desired application. In contrast to the LDV, the accelerometer is suited for measurements at the violin under realistic playing conditions, which is demonstrated in the following section.

3. VIBRATION MEASUREMENT DURING A REALISTIC PLAYING SCENARIO



(a) (b)

Figure 5. Setup picture (a) and measurement positions (b) to measure the vibrations at the neck. In a realistic playing scenario, a chormatic scale was played in mf. The index h or v refers to vibrations measured along the horizontal or vertical axis. Position P2 corresponds to the finger pressing position of a minor third on the fingerboard.

To unveil the potential of the mobile measurement setup, we measured the vibrations of the violin neck during a playing scenario. We attached two BU-21771-000 accelerometers to the neck of the violin as shown in Fig. 5. The accelerometer at position $\mathrm{P2_v}$ measured the vertical vibrations of the neck on the opposite side of the fingerboard and the accelerometer at position $\mathrm{P2_h}$ was attached to the side of the fingerboard to measure the vibrations in horizontal direction. The location alongside the fingerboard that corresponds to the sensor positions is the finger pressing position of a minor third. In contrast to before, the violinist was now performing in a real-

istic playing scenario and played a chromatic scale in mf from G3 (196 Hz) to A#5 (932 Hz) with downstroke. The sensors minimally disturb the violinist, because the violinist usually does not touch these positions of the neck with the fingers.

The calculated displacement time signals from the accelerometer signals are shown in Fig. 6. For the majority of the played notes the levels of the horizontal vibrations are higher than those of the vertical vibrations. For example, the level of the lowest note (G3, 196 Hz) is more than two times (6 dB) higher in the horizontal than in the vertical direction. This is consistent with the result from [3], where the horizontal displacement levels for this note were 5-10 dB higher than the vertical ones. The signal levels in Fig. 6 vary quite substantially depending on the played note, although the chromatic scale was played with the same dynamics. The vibrations generated by notes played on the D string have the lowest levels. For the horizontal vibrations the notes with the highest displacement levels are B3 (247 Hz) and A#4 (466 Hz) and for the vertical vibrations C4 (262 Hz).

These maximum values must be related to the body modes of the violin. According to [2, 3] these are typically found around 200 Hz and 300 Hz. Also the first acoustic mode (or Helmholtz mode) is expected around 300 Hz [2], which is close to the fundamental frequency of the open D string (D4, 293 Hz). However, the relation of the modes and the results in Fig. 6 has to be clarified in further measurements.

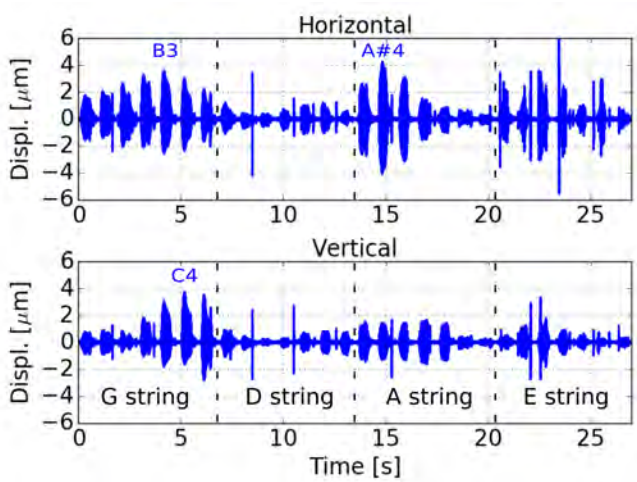


Figure 6. Time signals of the horizontal and vertical vibrations measured at positions $P2_h$ and $P2_v$, when the violinist was playing a chromatic scale from G3 (193 Hz) to A#5 (932 Hz) in mf. The levels vary substantially depending on the note. Notes, where the vibration levels are highest are indicated.

4. CONCLUSION

We demonstrated that the evaluated miniature accelerometer can be used to measure the vibrations of a violin in the relevant frequency range of human vibration sensation. With the vibrometer as reference, we found that the acceleration sensor measures with an accuracy of 0.1 μm from 50 Hz to 1 kHz. Further, it was showcased that multiple sensors can be used in a realistic playing scenario to record vibrations simultaneously.

Future work will be headed towards applying the method to study the vibrations on the fingerboard and also to measure the influence of finger touch, along with further investigations on the vibration behavior of the instrument. The method will be applied also to study vibrations of other string instruments and instruments that were augmented with actuators.

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