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An active-system approach for eliminating the wolf note on a cello

Philipp Neubauer,[a] Johannes Tschesche, Joachim Bös, and Tobias Melz
System Reliability, Adaptive Structures, and Machine Acoustics SAM, Technische Universität Darmstadt, Magdalenenstraße 4, 64289 Darmstadt, Germany

Holger Hanselka
Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany

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Wolf notes are generally undesirable sounds that occur in string instruments, particularly in cellos. State-of-the-art passive wolf note eliminators affect the whole cello sound and can become ineffective when environmental conditions and, therefore, the cello's structural properties change. In this paper, an approach is presented that uses smart materials to eliminate the wolf note with little effects to the cello's sound. Based on preliminary measurements, a mathematical model of the cello for generating the wolf note and for developing a wolf note elimination controller is set up. The controller consists of a wolf detection criterion that triggers a velocity feedback controller to actively induce damping into the cello's body whenever a wolf note is detected. The controller setup is experimentally validated by an implementation on a test cello. The velocity feedback to induce the active damping is implemented by means of a piezoelectric patch actuator attached to the cello's body. Both the results of the mathematical model and the results of the experimental investigation show a good performance in eliminating the wolf note on a cello.
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I. INTRODUCTION

In acoustics of musical instruments, a wolf note is a phenomenon that occurs in string instruments. The sound of a wolf note is characterized by intense beats and the shifting of the tone to higher harmonics. The beats typically occur with modulation frequencies of 4–10 Hz, which, from a psychoacoustic point of view, is considered annoying.[1,2] Furthermore, the wolf note has a substantial impact on the playability of a cello.[3,4] Since the frequency at which a wolf note occurs depends on the structural characteristics of the individually manufactured instrument and the variable mechanical properties of the wooden body, wolf notes can be found at different frequencies for various cellos. Usually the frequencies of wolf notes for cellos are between 147 and 185 Hz.[2,5] Conventional wolf eliminators are based on tuned mass dampers, which must be tuned to a fixed frequency.[1,5] Therefore, they are only capable of eliminating that single wolf note at the specific frequency to which they are tuned. The mechanical properties of cellos and other classical string instruments made of wood are very sensitive to the environmental conditions to which they are exposed. These conditions primarily are the ambient temperature and the humidity. If these environmental conditions change, the structural properties of the instrument, such as the stiffness, for example, will also change and, therefore, alter the frequency of the wolf note. The frequency shift may render the conventional mechanical wolf eliminators ineffective.[6,7]

This paper presents a universal smart material wolf note eliminator that is compatible with conventional designs of cellos and is able to adjust to changes in its surrounding environment. The elimination device consists of a piezoelectric patch actuator and a demand-actuated velocity feedback controller. After a brief introduction to the wolf note (Sec. II), a description of selected conventional mechanical wolf note eliminators and active approaches by other researchers is presented (Sec. III). This is followed by preliminary measurements (Sec. IV), the mathematical modeling of the cello with the development of an approach to detect the wolf note and of the controller design (Sec. V), and the results of the implementation with an experimental validation (Sec. VI).

II. CHARACTERISTICS OF THE WOLF NOTE

Since Raman, one of the first scientists who worked on the subject, investigated the processes of how a wolf note occurs from cellos at the beginning of the 20th century,[8] there have been many different approaches to explain this phenomenon from various points of view. However, the consensus is that a strong coupling between the string and the body (similar values for the input admittances) as well as a lightly damped body mode may result in wolf notes.[1,2,5–10] Schelleng developed a theoretical criterion for the occurrence of a wolf note on a violin, which consists of the body's damping, the point of bowing, as well as the ratio of the string's and the body's effective masses.[11] This criterion was confirmed by Gough.[9,10] The body and the strings are mechanically coupled by the bridge, which acts as the main

[a]Electronic mail: neubauer@sam.tu-darmstadt.de

energy transducer and as an admittance transformer.[6,7,9,10] Due to the asymmetric design of the cello's body with the sound post connecting the top and the bottom of the cello below the higher strings and the bass bar found below the lower strings, the bridge begins to rock strongly if a frequency close to a wolf note is excited. This is described by Rossing as the "rocking motion" of the bridge.[12] The connection points between the bridge and the body are subsequently referred to as *left bridge foot* and *right bridge foot*, as indicated in Fig. 1. The strong coupling allows for the well-known double-slip motion of the bowed string and the periodic collapses of the body's vibration to occur, which subsequently leads to the acoustic phenomenon called the wolf note.[1,2,6,7,13,14] Inácio and co-authors have developed a very accurate mathematical model of a cello and were able to extensively study and understand the interactions of string and body as well as the parameters that influence the occurrence of the wolf note such as the bow force and the bowing velocity.[15–17]

III. WOLF NOTE ELIMINATION STRATEGIES

Experienced cellists can suppress the wolf note by increasing the bow force, changing the point of bowing, or even squeezing the cello between their legs.[6,7,13] These methods, however, rely on the expertise of the player and still affect the sound of the cello.

The conventional wolf note elimination devices available on the market today aim at passively reducing the vibration amplitudes so that the coupling between the string and the body is reduced. Most of the available conventional wolf note eliminators are designed as mechanical tuned mass dampers in order to limit their influence on the cello's sound solely to the frequency of the wolf note. The effectiveness of these devices was investigated and discussed for example by Gidion.[18] High quality handmade cellos can come already equipped with such a mechanical tuned mass damper, which is mounted to the inside of the cello's top plate and is tuned to the exact frequency of the wolf note in order to reduce the vibration amplitudes at this specific frequency.[2,6] Another type of passive elimination device can be installed by the players themselves. This device consists of an attachable mass and must be positioned at a specific spot on the string between the tailpiece and the bridge in order to reduce the vibration amplitudes of the bridge at the frequency of the wolf note. Once the device is fixed in its position, the operation frequency is fixed as well. This wolf note elimination device requires the player to properly tune it.[2,6] Although the presence of these conventional wolf note eliminators still affects the cello's sound, most musicians can tolerate this drawback because the wolf note is eliminated. The biggest problem with this type of wolf note eliminator is that the effective frequency of the mechanical tuned mass damper is fixed once it is attached, which means the eliminator can become ineffective if the wolf note's frequency shifts.[7] Therefore, the convenience of these simple mechanically tuned mass dampers comes with design and reliability drawbacks.

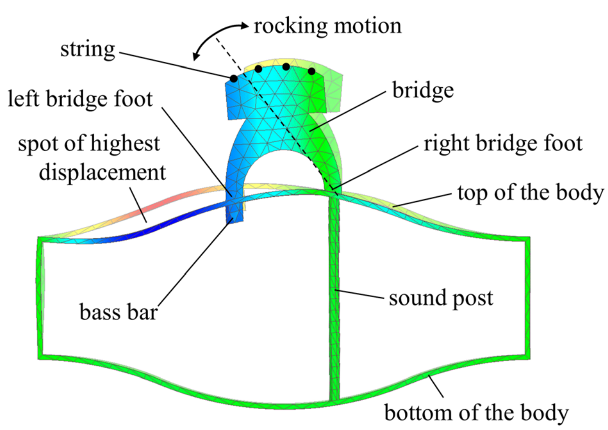

FIG. 1. (Color online) Relevant parts of a cello (cross section, view from the tailpiece) with the rocking motion of the bridge at the main body resonance, qualitative illustration.

Benacchio and Mamou-Mani present a way to actively adjust the modal parameters of a simplified musical instrument in order to modify its radiated sound. They use an active system with an electrodynamic actuator and a piezoelectric sensor in a closed loop, controlled by a time-dimensionless algorithm, called *modal active control*.[19–21] Such combinations of musical instruments with sensors and actuators are called *smart musical instruments*.[20] By changing the modal parameters of a cello, the elimination of a wolf note is generally possible.

In previous works a semi-active approach in form of piezoelectric shunt damping was investigated. Unfortunately, the conversion from mechanical to electrical energy and vice versa between the cello's body and the piezoelectric patch actuator was too low to effectively eliminate the wolf note. To increase the amount of energy induced into the cello's body, active approaches were investigated.[22–24]

The active approach presented in this paper shall be compatible to different cellos and varying environmental conditions. The use of a demand-actuated velocity feedback controller allows for an active increase of the cello's body mechanical damping. The approach includes the control of the amount of damping to fully suppress the wolf note while affecting the sound of the instrument as little as possible.

IV. PRELIMINARY MEASUREMENTS

Preliminary measurements on a test cello were necessary to estimate both the technical feasibility and the requirements for the used actuators, sensors, and the controller. Furthermore, this allowed for the development of a wolf note detection strategy.

A. Experimental setup

The test cello is a handcrafted high class cello of full size (4/4) that strongly suffers from a wolf note. The strings are medium sized and have a standard tuning (C-G-d-a). Since the wolf note is more likely to occur with heavier strings, the C string is excited. All other strings are muted using plastic foam. Adjusting the natural frequency of the C string is achieved by pushing the string against the fingerboard with a metal clamp in a defined and reproducible way. The cello is excited by a cellist bowing it constantly with medium velocity and medium bow force. The cello is held by the cellist in a standard position. During the experiments, the environmental conditions were held constant at 21 °C (70 °F) and 50%–60% relative humidity to prevent the cello from detuning. Two miniature lightweight accelerometers are applied to the cello's body next to each bridge foot. The airborne sound pressure is measured by a microphone that is elastically mounted to the tailpiece. Furthermore, an electric guitar pickup (conventional Humbucker) is applied to the bottom end of the fingerboard to qualitatively analyze the string oscillations at the typical point of bow excitation. All sensor positions can be taken from Fig. 2.

B. Experimental results

For the following results, the C string is tuned to two representative frequencies using the metal clamp. The strongest occurrence of the wolf note on the given test cello is at 154 Hz (subsequently referred to as *wolf state*), while a tuning frequency of the string of 130 Hz represents a state without a wolf note occurrence (subsequently referred to as *regular state*). In Fig. 3, all sensor signals in wolf state and in regular state are compared in the time domain. In the regular state (Fig. 3, left), the measured signals are not modulated. In the wolf state (Fig. 3, right), a strong and characteristic amplitude modulation occurs in the sound pressure as well as in the acceleration at the left bridge foot. In comparison to the regular state, the maximum peak-to-peak amplitudes of the sound pressure approximately double, whereas the peak-to-peak amplitudes of the acceleration on the left bridge foot almost triple. The acceleration amplitudes at the right bridge foot do not change significantly. In the wolf state, the string does not noticeably change its peak-to-peak displacement amplitudes, but experiences a disturbance in its waveform caused by the high vibration amplitudes of the body at the left bridge foot. This shows how strong the string and the body are coupled near the left bridge foot at the wolf note.

In the frequency domain, the same measurements of the regular state and the wolf state are compared. The sound

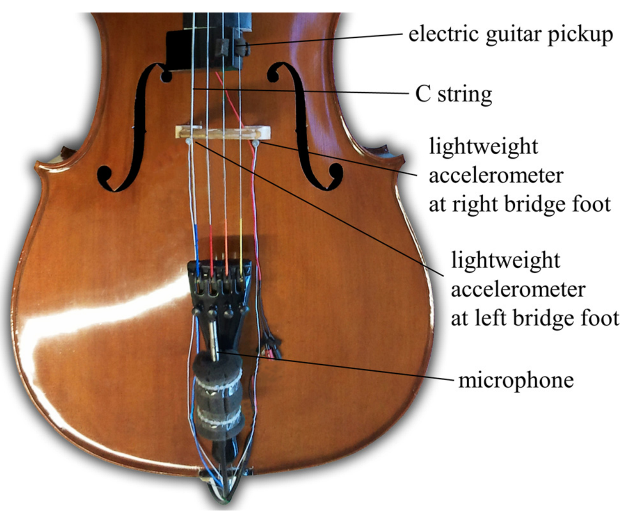

FIG. 2. (Color online) Sensor positions at the cello used for the preliminary measurements.

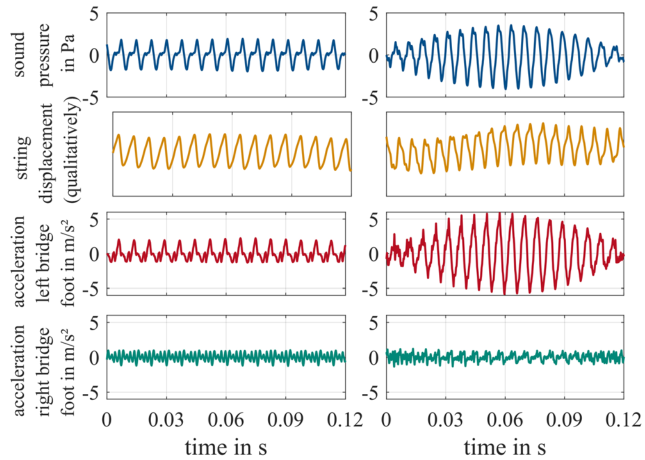

FIG. 3. (Color online) All sensor signals in regular state (left) and in wolf state (right) in the time domain.

pressure level spectra are given in Fig. 4. Although the excitation of the string is a single peak at exactly its tuning frequency in the regular state, this cannot be confirmed for the wolf state. There is a local minimum at the string's nominal tuning frequency of 154 Hz surrounded by two peaks. This is the characteristic double-peak of the wolf note in the frequency domain. The actual 154 Hz tuning frequency of the string becomes instable and splits up into two peaks, one of which is lower and one of which is higher in frequency. This behavior is described intensively in the literature.[4,9,10,12,13]

A more common method to identify frequencies at which wolf notes may occur is to determine the input admittance (driving point mobility) of the bridge.[5,6,9,10,12,17,25] A high value of the input admittance for a certain frequency means a high "willingness to vibrate," which, in the case of the cello's body, may lead to a wolf note. The input admittances at the left and the right bridge foot are determined using a small impact hammer to excite the top plate of the cello in its normal direction close to the bridge feet. The accelerometers marked in Fig. 2 are used to measure the response of the cello's body in the same direction. The results are shown in Fig. 5. The highest peak of the input admittance at the left bridge foot is at the frequency at which the wolf note occurs (about 154 Hz). At this frequency, there is a strong coupling to a body mode, which can only be observed at the left bridge foot. The input admittance of the right bridge foot is about 13 dB lower at this frequency. At

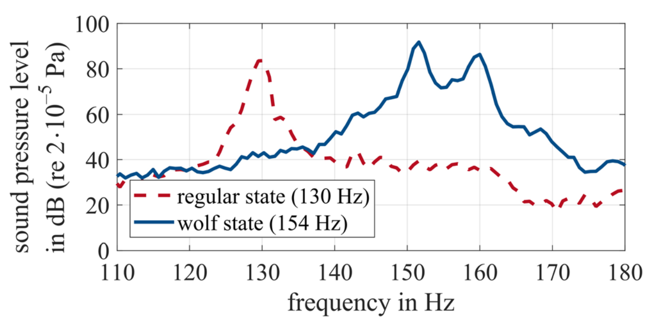

FIG. 4. (Color online) Sound pressure levels of the regular state and the wolf state in the frequency domain.

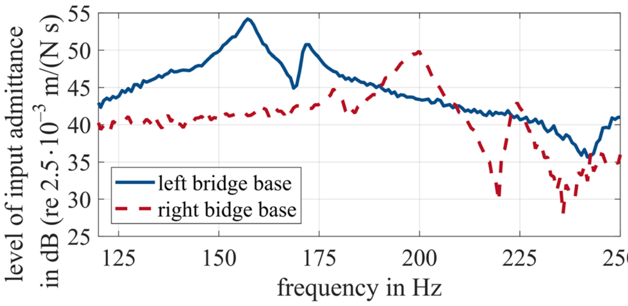

FIG. 5. (Color online) Input admittances of the cello at the left and the right bridge foot.

most other frequencies, the differences of the input admittance levels at the left and the right bridge foot are much smaller. At the right bridge foot the maximum input admittance can be found at approximately 200 Hz, where there is a strong coupling to another body mode.

V. MATHEMATICAL WOLF NOTE MODELING AND CONTROLLER DESIGN

In 1963 Schelleng modeled a cello as an electric circuit and was, therefore, able to describe the parameters that influence the wolf note.[11] Later, other authors modeled the string and the body of a cello with simple mechanical or electrical elements such as single mass oscillators or idealized strings.[4,9,10,26] In more recent works the cello has been modeled using modal approaches.[17,21] For the research presented in this paper a linear model for generating the wolf note and for developing the controller is set up. A combination of three coupled single mass oscillators, representing the string and the body at the two bridge feet, is used. The modeling of two parts of the body is necessary to reflect the asymmetric properties of the cello's body and to evaluate the *wolf criterion*, which is described in Sec. V D. Even though a cello is not a perfect linear structure, particularly the bowed string, the linearized model is assumed to approximate the structural properties close enough. Moreover, other authors have already been able to use similar linear models to simulate the cello's body[4,7,9,10,26] or even the bowed string,[27] so it can be assumed that the linearized model provides appropriate results.

A. Mathematical model

The block diagram of the mathematical model used in this paper is shown in Fig. 6. The string is excited by an initial displacement of $x_s(t=0) = 0.001\,\text{m}$, which corresponds to a plucked string and which is much easier to model than a bowed string, but is still able to generate the wolf note behavior in the linear model. The string, which is represented as a single mass oscillator (subscript s), excites the single mass oscillator at the left bridge foot (subscript l) as well as the single mass oscillator at the right bridge foot (subscript r). Note that the two single mass oscillators represent the two body modes at 154 and 200 Hz (which can be interpreted from Fig. 5) rather than representing two independent bodies. The reaction forces at the two bridge feet in turn work at the string's single mass oscillator. However, the couplings between the string and the oscillators at the bridge feet must be multiplied by the coupling factor c in order to match the model's behavior to the test cello's behavior. The values of the mechanical elements used in this model are determined from experiments performed on the test cello and from further estimations. The mass of the string's oscillator m_S and the effective masses of the body's oscillators m_l and m_r are estimated by calculating their effective masses at the frequency of the wolf note. The spring rate at the two bridge feet k_l and k_r are determined by setting the natural frequency at the left bridge foot to 154 Hz and at the right bridge foot to 200 Hz (see peaks of the input admittance in Fig. 5). The spring rate of the string k_S is kept variable to change the string's natural frequency. The damping coefficients of the string's oscillator d_S as well as the damping coefficients of the body's oscillators d_l and d_r are determined by means of experimental measurements taken on the test cello. The coupling factor c is empirically determined and represents the behavior of the bridge and other properties of the cello that are neglected. The derived equations of motion are given in Eq. (1),

$$\boldsymbol{M}\begin{bmatrix}\ddot{x}_s(t)\\ \ddot{x}_l(t)\\ \ddot{x}_r(t)\end{bmatrix} + \boldsymbol{D}\begin{bmatrix}\dot{x}_s(t)\\ \dot{x}_l(t)\\ \dot{x}_r(t)\end{bmatrix} + \boldsymbol{K}\begin{bmatrix}x_s(t)\\ x_l(t)\\ x_r(t)\end{bmatrix} = \boldsymbol{F}. \tag{1}$$

The mass matrix $\boldsymbol{M}$, the damping matrix $\boldsymbol{D}$, the stiffness matrix $\boldsymbol{K}$, and the force excitation vector $\boldsymbol{F}$ are given as follows:

$$\boldsymbol{M} = \begin{bmatrix} m_s & 0 & 0\\ 0 & m_l & 0\\ 0 & 0 & m_r\end{bmatrix}, \tag{2}$$

$$\boldsymbol{D} = \begin{bmatrix} d_s + c\,(d_l + d_r) & c\,d_l & c\,d_r\\ c\,d_l & d_l & 0\\ c\,d_r & 0 & d_r\end{bmatrix}, \tag{3}$$

$$\boldsymbol{K} = \begin{bmatrix} k_s + c\,(k_l + k_r) & c\,k_l & c\,k_r\\ c\,k_l & k_l & 0\\ c\,k_r & 0 & k_r\end{bmatrix}, \tag{4}$$

$$\boldsymbol{F} = \begin{bmatrix}0\\0\\0\end{bmatrix}. \tag{5}$$

The corresponding physical values are given in Table I.

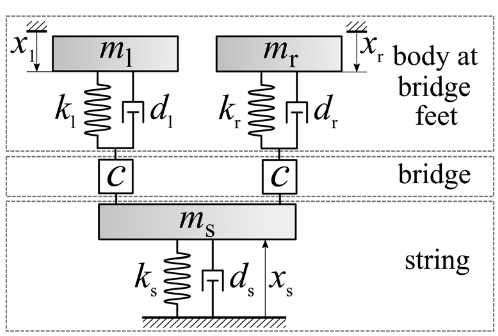

FIG. 6. Block diagram of the mathematical model of the cello.

TABLE I. Physical values for the mathematical model.

mass	stiffness	damping	coupling factor
$m_S = 0.00157\,\mathrm{kg}$	$k_S =$ variable	$d_S = 0.0038\,\mathrm{Ns/m}$	$c = 0.01$
$m_l = 0.0134\,\mathrm{kg}$	$k_l = 12546\,\mathrm{Ns/m}$	$d_l = 0.33\,\mathrm{Ns/m}$	
$m_r = 0.0103\,\mathrm{kg}$	$k_r = 16265\,\mathrm{Ns/m}$	$d_r = 0.38\,\mathrm{Ns/m}$	

B. Results of the mathematical model

The results of the mathematical model are compared with experimental results. The natural frequency of the string is set at every 1 Hz interval from 140 to 160 Hz for both the mathematical model and the test cello. In the experiment, the string is excited with the bow, while in the mathematical model it is excited by an initial displacement $x_s = 0.001\,\mathrm{m}$, which simulates a plucked string. For each of the string's natural frequencies the response of the level of body accelerations at the left bridge foot is determined and the spectrum is calculated. In Fig. 7, the response surfaces at the left bridge foot are shown as determined from both the numerical simulation and the experiment. In both response surfaces the acceleration of the body at the left bridge foot develops the characteristic double-peak for the natural frequency of the string in the wolf state (154 Hz). For strings tuned to frequencies higher and lower, the levels of both peaks differ, which means the wolf note becomes less intense. The presented mathematical model is in good agreement with the experimental results for response frequencies close to the wolf note. For response frequencies higher than 180 Hz and lower than 130 Hz the acceleration levels match only qualitatively, which suggests a limited validity for the presented model. These results conform to those of the coupled vibrating systems of Fletcher and Rossing.[6]

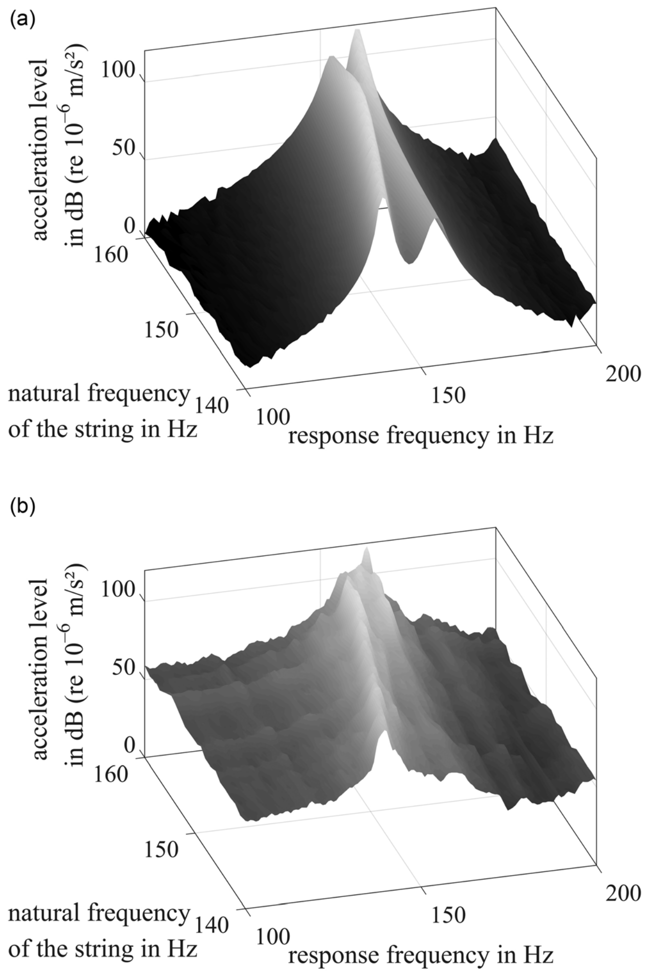

FIG. 7. Response surfaces of the level of body accelerations for the results of the mathematical model (a) and for the experimental results (b), left bridge foot.

C. Wolf note elimination in the mathematical model

The goal is to eliminate the wolf note while changing the instrument's sound as little as possible. The effective mass and the stiffness are mechanical parameters that are difficult to alter. Furthermore, the resonance frequencies and, therefore, the sound of the cello, will be influenced on a large scale when these parameters are changed. Since the damping coefficient is a mechanical parameter that primarily affects the amplitude of an oscillation and furthermore is easy to control by a velocity feedback control algorithm, this parameter is chosen as an adequate parameter to affect the wolf note, as is confirmed in the literature.[2,7,13] In the mathematical model, the value of the damping coefficient of the body at the left bridge foot d_l is varied in a range between 0 and 2.5 Ns/m, while all other mechanical parameters are kept constant. The string is tuned to a fixed natural frequency of 154 Hz (wolf state). The calculation results are illustrated as a surface plot in the frequency domain in Fig. 8, where the acceleration response of the body at the left bridge foot is a function of d_l. With increasing values of the damping coefficient d_l, the characteristic double peak of the wolf note decreases. Of course, as the damping coefficient increases, the dissipation of vibration energy becomes higher, causing the sound to fade out faster. Finding the optimal damping coefficient is a trade-off between fully eliminating the wolf note and minimizing the influence of the additional mechanical damping on the sound of the cello. The experimentally determined damping coefficient of the unmodified test cello (0.33 Ns/m) is marked with the black line. The required damping coefficient for the mathematical model, at

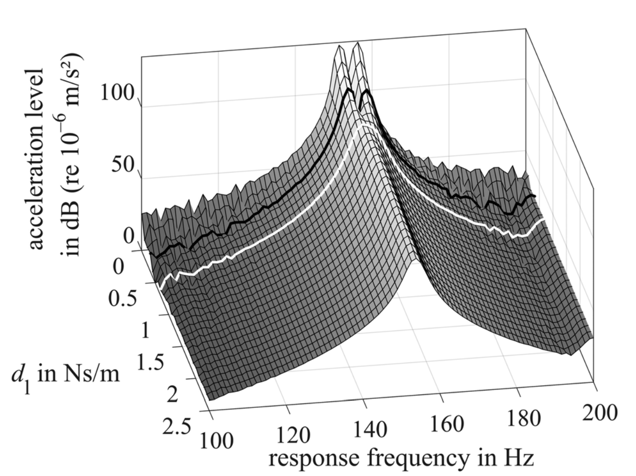

FIG. 8. Influence of the damping coefficient of the body at the left bridge foot $\boldsymbol{d_l}$ on the occurrence of the wolf note.

which the double peak fully disappears, can be found at $d_{\mathrm{l,req}} = 0.7\,\mathrm{Ns/m}$ (white line in Fig. 8).

D. Wolf note detection

To detect a wolf note, a criterion is necessary that can be experimentally determined at the test cello. Furthermore, it needs to work in real time and it should enable the determination of the amount of additional damping necessary to suppress the wolf note. A criterion based on the measurement of airborne sound is presumed to be unreliable since, in the context of a musical play, there are many other sources of airborne sound that may lead to false detections. Hence, the measurement of structure-borne sound is assumed to be more suitable.

As a conclusion from the experimental results shown in Fig. 5, a great difference of input admittances between the left and the right bridge foot at the excited frequency is assumed to indicate a high risk of a wolf note occurrence. Since the input admittance $Y(f)$ is defined as the ratio between the resulting vibration velocity $v(f)$ and the force excitation $F(f)$,

$$Y(f) = \frac{v(f)}{F(f)}, \tag{6}$$

a high input admittance at a certain frequency results in high vibration velocities. Assuming the bridge to be rigid and forces induced by the string into the bridge to work equally on the left and the right bridge foot, in the wolf state (154 Hz) the vibration velocities at the left bridge foot $v_{\mathrm{l}}\,(154\,\mathrm{Hz})$ will significantly exceed those at the right bridge foot $v_{\mathrm{r}}\,(154\,\mathrm{Hz})$. But high vibration amplitudes at the left bridge foot alone do not necessarily indicate a wolf note since a regular non-wolf note tone can be heavily bowed and a wolf note can be lightly bowed, both resulting in similar vibration amplitudes at the left bridge foot. However, the ratio between the vibration amplitudes at the left and the right bridge foot as a relative measure is a reliable wolf criterion $C_{\mathrm{w}}(t)$ to detect the wolf note in the time domain,

$$C_{\mathrm{w}}(t) = \frac{v_{\mathrm{l}}(t)}{v_{\mathrm{r}}(t)}\,. \tag{7}$$

Based on the assumption made before [see Eq. (6)], this criterion implicitly represents the ratio between the input admittances and can be calculated as a time-dependent scalar value since a vibration velocity only exists if a corresponding force excitation by the string is given. So, if, for example, the string is tuned to 130 Hz and excites the cello's body via the bridge, the vibration velocities at the bridge feet will take amplitudes according to their input admittances at the excited frequency. In reality, of course, the force excitation by the string will not only consist of the string's tuning frequency, but also of several harmonics, which might reduce the wolf criterion's performance.

However, in practice it is not easy to experimentally determine vibration velocities, particularly regarding the implementation on a cello during a musical play. Vibration accelerations are much easier to determine since they can be measured using lightweight accelerometers, as used in the preliminary measurements. The required velocities can be determined by an integration of the acceleration signals $a_{\mathrm{l}}(t)$ and $a_{\mathrm{r}}(t)$ of the accelerometers at both bridge feet. Assuming the time signals to be harmonic functions, it can be shown that the ratio of the velocities from Eq. (7) equals the ratio of the accelerations except for the constant phase shift of $\pi/2$. The angular frequency is assumed to be identical for the left and the right bridge foot since both are excited by the same string and it can, therefore, be canceled,

$$\begin{aligned}\frac{\hat{v}_{\mathrm{l}}\,\sin(\omega t)}{\hat{v}_{\mathrm{r}}\,\sin(\omega t)} &= \frac{\int \hat{a}_{\mathrm{l}}\,\sin(\omega t)\mathrm{d}t}{\int \hat{a}_{\mathrm{r}}\,\sin(\omega t)\mathrm{d}t} = \frac{-\omega\,\hat{a}_{\mathrm{l}}\,\cos(\omega t)}{-\omega\,\hat{a}_{\mathrm{r}}\,\cos(\omega t)}\\ &= \frac{\hat{a}_{\mathrm{l}}\,\sin(\omega t + \pi/2)}{\hat{a}_{\mathrm{r}}\,\sin(\omega t + \pi/2)}\,.\end{aligned} \tag{8}$$

Hence, $C_{\mathrm{w}}(t)$ is calculated as the ratio of $a_{\mathrm{l}}(t)$ and $a_{\mathrm{r}}(t)$.

The ratio between two time signals yields very unsteady values for $C_{\mathrm{w}}(t)$ since time signals, of course, contain positive values, negative values, and values close to zero. Therefore, the RMS values of the time signals are used to calculate the final wolf criterion $C_{\mathrm{w}}(t)$, where Δt is the instantaneous averaging time, $\tilde{a}_{\mathrm{l}}(t)$ is the RMS acceleration signal measured at the left bridge foot, and $\tilde{a}_{\mathrm{r}}(t)$ is the RMS acceleration signal measured at the right bridge foot. False detection of the wolf note by unexpected short-time incidents such as a knock on the cello's body must be prevented, so the time averaging interval Δt is a crucial parameter. Experiments show that $\Delta t = 0.75\,\mathrm{s}$ is a useful instantaneous averaging time as a trade-off between a reliable and a fast detection of the wolf note even though the real-time character of the wolf criterion is reduced by high values for the averaging interval,

$$C_{\mathrm{w}}(t) = \frac{\tilde{a}_{\mathrm{l}}(t)}{\tilde{a}_{\mathrm{r}}(t)} = \frac{\sqrt{\dfrac{1}{\Delta t}\displaystyle\int_{t-\Delta t}^{t} (a_{\mathrm{l}}(t))^2 \mathrm{d}t}}{\sqrt{\dfrac{1}{\Delta t}\displaystyle\int_{t-\Delta t}^{t} (a_{\mathrm{r}}(t))^2 \mathrm{d}t}}\,. \tag{9}$$

In the case of a wolf note, $\tilde{a}_{\mathrm{l}}(t)$ takes much higher values than $\tilde{a}_{\mathrm{r}}(t)$ and, therefore, the wolf criterion is $C_{\mathrm{w}} \gg 1$. In the case of a regular note $\tilde{a}_{\mathrm{l}}(t)$ and $\tilde{a}_{\mathrm{r}}(t)$ take less differing amplitudes (independently from the bowing intensity) which results in lower wolf criterion values.

An experimental validation is performed. The value of the wolf criterion is calculated from measured acceleration signals for various tunings of the C string. A rather big step size is chosen far away from the frequency of the wolf note since a high value is not expected, considering the results of the measured input admittance in Fig. 5. Close to the wolf note a much smaller step size of only 1 Hz is chosen. Additionally, C_{w} is calculated from acceleration signals in the mathematical model. The experimental and the calculated results are shown in Fig. 9. In both the experimental

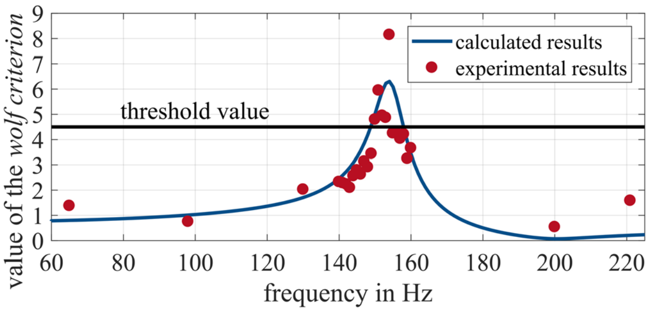

FIG. 9. (Color online) Value of the wolf criterion $\boldsymbol{C}_{\mathrm{w}}$ for various tuning frequencies of the C string, calculated results and experimental results.

results as well as the calculated results the wolf criterion takes higher values if the string is excited at a frequency close to the wolf note. Based on the results it is assumed that on the test cello as well as in the mathematical model the wolf note occurs for $C_{\mathrm{w}} > 4.5$. Hence, this value is set as the threshold value $C_{\mathrm{w,t}}$.

E. Controller design

To eliminate the wolf it is necessary to increase the mechanical damping of the body near the left bridge foot. A velocity feedback controller is suitable for this purpose. The controller must be enabled to actively increase mechanical damping if a wolf note is detected while otherwise staying disabled to ensure that the wolf note elimination system affects the cello's vibrations only when necessary. The activation of the controller is made possible by using the wolf criterion. The block diagram of the controller is shown in Fig. 10. The acceleration signals gathered at the left and the right bridge foot are used to calculate the single value wolf criterion $C_{\mathrm{w}}(t)$ as introduced in Eq. (9). The next block contains a threshold function set to the value $C_{\mathrm{w,t}} = 4.5$. Hence, the control deviation is only a non-zero value if $C_{\mathrm{w}}(t)$ exceeds the threshold value. The deviation value is amplified with the gain factor g. This gain factor determines the amplification of the velocity feedback and, therefore, the amount of active damping added at the left bridge foot. The acceleration signal at the left bridge foot is integrated to obtain the velocity. The result is the feedback force F_{vf}, which acts as active damping since it is proportional to the velocity. Note that F_{vf} is not an additional excitation force since the model is still excited by an initial displacement of the string, as described in Sec. V A.

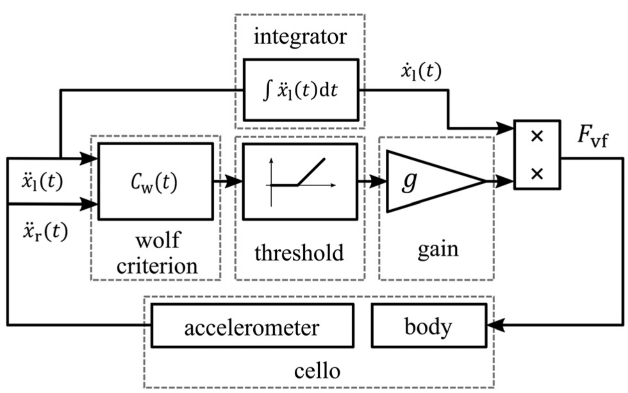

FIG. 10. Implemented velocity feedback controller using the wolf criterion.

The velocity feedback controller is integrated into the mathematical model. Therefore, F_{vf} must be added to the force excitation vector $\boldsymbol{F}$ on the right hand side of Eq. (1),

$$\boldsymbol{F} = \begin{bmatrix} 0 \\ F_{\mathrm{vf}} \\ 0 \end{bmatrix} \tag{10}$$

with

$$F_{\mathrm{vf}} = \begin{cases} (C_{\mathrm{w}} - C_{\mathrm{w,t}})\, g\, \dot{x}_{\mathrm{l}}(t) & \text{for } C_{\mathrm{w}} > C_{\mathrm{w,t}}, \\ 0 & \text{else,} \end{cases} \tag{11}$$

where g is the gain factor that is necessary to set the amount of velocity feedback in order to achieve a resulting damping coefficient of $d_{\mathrm{l,req}} = 0.7\,\mathrm{Ns/m}$. The difference $C_{\mathrm{w}} - C_{\mathrm{w,t}}$ is used to calculate the control deviation. To meet the requirement for the damping, in the mathematical model g can be calculated from

$$(d_{\mathrm{l}} + (C_{\mathrm{w,154\,Hz}} - C_{\mathrm{w,t}})\, g)\, \dot{x}_{\mathrm{l}}(t) = d_{\mathrm{l,req}}\, \dot{x}_{\mathrm{l}}(t), \tag{12}$$

which represents the sum of the mechanical damping at the left bridge foot d_{l} and the additional damping of the velocity feedback. This leads to

$$g = \frac{d_{\mathrm{l,req}} - d_{\mathrm{l}}}{C_{\mathrm{w,154\,Hz}} - C_{\mathrm{w,t}}} = \frac{0.7 - 0.33}{6.3 - 4.5} \approx 0.21, \tag{13}$$

where $C_{\mathrm{w,154\,Hz}}$ is set to 6.3, which is the value of the wolf criterion in the wolf state (154 Hz) in the mathematical model, see Fig. 9.

F. Results of the mathematical model

By analogy with the computations in Fig. 7, the natural frequency of the string is varied from 140 to 160 Hz and the string is excited by an initial displacement of $x_{\mathrm{s}}(0) = 0.001\,\mathrm{m}$. The results from the mathematical model with the included velocity feedback controller and the wolf criterion are shown in Fig. 11. With the included wolf eliminator the double peak completely disappears at natural frequencies of the string around 154 Hz (white line). Of course, when damping is actively added to the system, the amplitudes of the accelerations decrease. Therefore, the volume of the instrument slightly decreases when the wolf note is being eliminated. This, however, might be an acceptable drawback compared to a wolf note actually occurring. At frequencies without a wolf note, the active wolf eliminator has no influence on the vibrations of the system since the controller is deactivated. The goal to eliminate the wolf note by actively adding damping to the body by means of the velocity feedback principle is achieved in the mathematical model. The demand to only affect the sound of the instrument when a wolf note occurs is also satisfied.

VI. EXPERIMENTAL IMPLEMENTATION AND RESULTS

The active wolf elimination is experimentally validated. Therefore, the real test cello, the applied accelerometers, and a piezoelectric patch actuator take the place for the

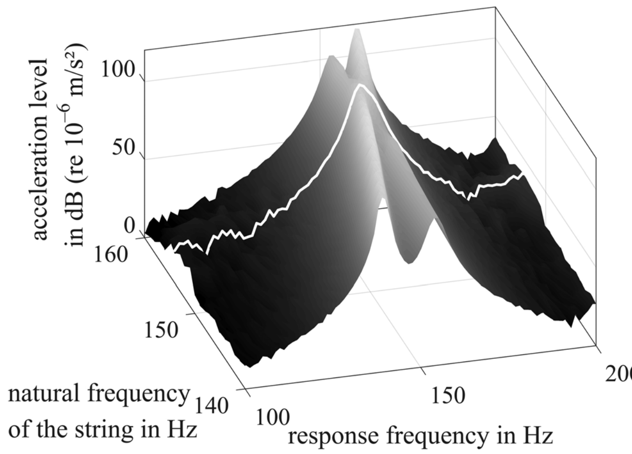

FIG. 11. Response surface of the level of body acceleration for the results of the mathematical model with included control algorithm, left bridge foot.

mathematical model of the cello, its acceleration outputs, and the velocity feedback input, respectively. A dSPACE rapid control prototyping system is used to implement the velocity feedback control algorithm in real time.

A. Application of the smart wolf note eliminator and experimental setup

Compared to the experimental setup described in Sec. IV A, a piezoelectric patch actuator (PI Ceramic, Type DuraAct P 876.A12) is applied to the cello's body, while the guitar pickup was dismounted. Figure 12 shows the experimental setup. The mounting of the piezoelectric patch actuator is a difficult task since the wood of the body is very soft compared to the material of the piezoelectric actuator. In order to maximize the transmission of flexural waves from the actuator into the body, the actuator is fixed by double-sided adhesive tape and is edge-supported by superglue. For further improving the transmission of bending moments, the longer side of the actuator is orientated along the fiber direction of the wood, where it has the highest stiffness.[6] The actuator is positioned at the spot of the highest displacement amplitudes of the body's top plate found in the wolf state (see Fig. 1). The experimental wolf note elimination system is shown as a block diagram in Fig. 13. The two accelerometers, positioned near the bridge feet, measure the vibrations of the cello's body. After preamplifying, the signals are converted from analog to digital and the controller is implemented in the dSPACE system. If a wolf note is detected,

FIG. 12. (Color online) Experimental setup of the validation of the smart materials wolf note eliminator.

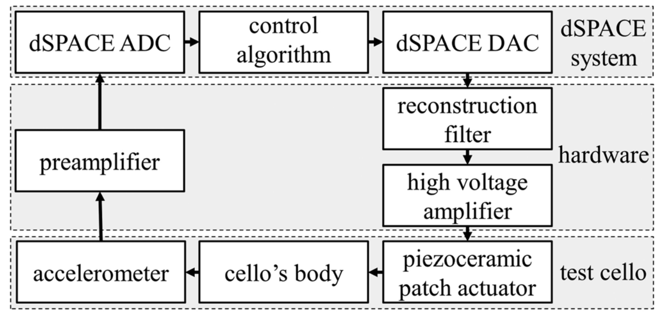

FIG. 13. Signal flow of the experimental setup of the wolf note eliminator.

the velocity feedback controller is activated and an output signal is calculated. This output signal is converted from digital to analog, reconstructed, and high voltage-amplified to drive the piezoelectric patch actuator. The actuator induces the bending moments in the cello's body, which increases the mechanical damping as long as the wolf note is detected and the controller is activated. Since the velocity feedback signal is calculated from the measured acceleration signal, the active wolf eliminator may adapt itself to different cellos and varying environmental conditions. Note that the gain factor g and, therefore, the required amount of active damping induced into the body is empirically determined in the experimental investigations and differs from the calculated value in the mathematical model since the high voltage amplifier and the piezoelectric patch actuator were neglected in the mathematical model.

B. Experimental results

Measurements of the body acceleration signal confirm the effectiveness of the active wolf note eliminator applied to the test cello as depicted in Fig. 14. When the wolf note eliminator is enabled (solid line), a stable single peak occurs right in the center of the former double peak. At frequencies other than the wolf note frequency there are only minor changes. Compared to the preliminary measurements in Sec. IV the frequency of the wolf note changed slightly from 154 to 160 Hz. This may be a result of changing environmental conditions, but is more likely caused by the removal of the guitar pickup. This emphasizes both how sensitively the cello reacts to minor changes in the test conditions and the importance of an adaptive wolf note elimination system. The measured wolf note elimination can also be verified in the

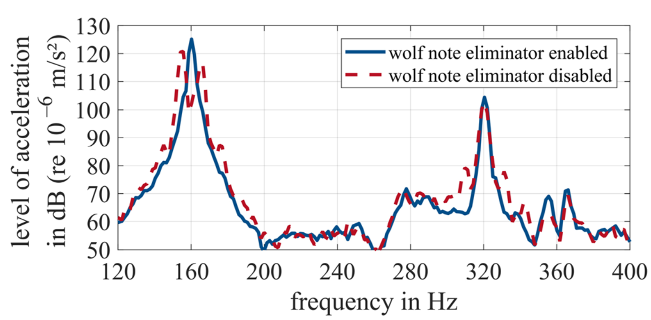

FIG. 14. (Color online) Influence of the wolf note eliminator in the frequency domain, measured body acceleration level at the left bridge foot.

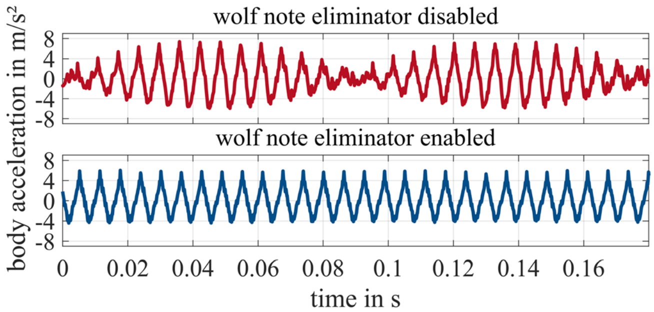

FIG. 15. (Color online) Influence of the wolf note eliminator in the time domain, measured body acceleration level at the left bridge foot.

time domain, see Fig. 15. The strong beats in the body acceleration disappear when the active wolf note eliminator is enabled. Two sound samples, which were recorded from the real test cello with the wolf note eliminator being disabled and enabled, are provided as supplementary material.[28] Their waveforms are shown in Fig. 16. The strong beats of the wolf note are fully suppressed when the wolf note eliminator is activated. However, the instantaneous averaging time of $\Delta t = 0.75$ s of the wolf criterion leads to a relatively slow response of the wolf eliminator with two beats to occur at the beginning of the sound sample. On the one hand this may appear like a reduced performance of the wolf note eliminator, on the other hand this ensures a smooth reaction of the controller so that the cellist will not be disrupted by a sudden intervention of the controller.

VII. SUMMARY AND CONCLUSIONS

This paper presents a smart wolf note elimination system. A demand-actuated velocity feedback controller with a wolf note detection algorithm is set up to work with a piezoelectric patch actuator, which is applied to the cello's body. With this configuration the wolf note can be eliminated while the sound of the musical instrument is influenced as little as possible.

The presented research was carried out under laboratory conditions. Investigations of the wolf note eliminator's behavior in practical use are necessary, particularly in the context of a musical performance. The player's reactions to the wolf eliminator's actions as well as the eliminator's impact on the playability of the cello should be investigated. Furthermore, the system must be tested with different cellos to ensure its universality. It would be interesting to evaluate the wolf criterion also for other cellos. In order to become a real alternative for cello players, the system must be significantly scaled down. The accelerometers, in particular, must be smaller in order to have only negligible effects on the whole cello sound. Another challenge in the future will be the high input voltage of the piezoelectric actuator, which, in case of improper use, could be dangerous for the musician. Maybe other types of actuators can be used. Also, it could be advantageous if violin makers were included to study the possibilities of the full integration of the actuator to avoid a visually unaesthetic topside mounting.

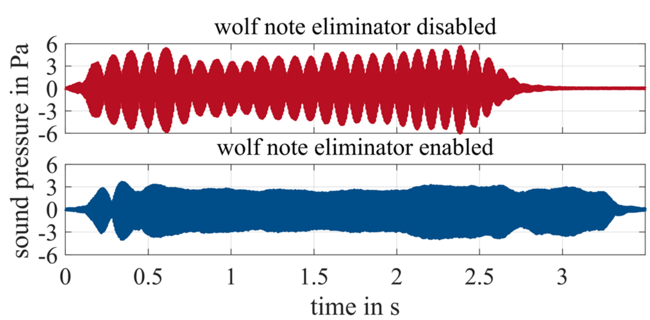

FIG. 16. (Color online) Waveform of the provided sound samples with the wolf note eliminator being disabled and enabled.

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