Determination of Vibro-Acoustic Properties of Brass Instruments

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I. Introduction

The question whether the material and manufacturing process influence the sound produced by brass instruments has been discussed extensively, yet some of the questions related to the influence of manufacturing techniques, material selection, and design remain unanswered. Karl Liskovius reported the effect of vibrating walls lowering the pitch of pipes in 1842.[1] In 1909 Dayton C. Miller constructed a double-walled flue pipe that could be filled with water in order to investigate experimentally the effect of the coupling/damping between the two walls of the pipe and the subsequent effect on the sound quality.[2] A change in amplitudes of partials by up to 3 dB was observed, but the changes could not clearly be attributed to the change in material dynamics surrounding the air column. Instead, the differences were explained by variations in material properties or geometrical imperfections. A summary of the different results and opinions concerning the effect of the wall material on the radiated sound of flue pipes was published by Boner and Newman.[3] Experiments performed by Klaus Wogram in 1976 on wall vibrations of trombones resulted in the conclusion that the differences, quantified by means of the subjective assessment of the quality of sound and based on objective measurements using artificial lips originate from the varying responses of instruments built from different wall materials.[4]

After a number of publications on the effect of the material on the radiated sound, focusing in particular on the bell section of brass wind instruments,[5] Moore et al. presented results in 2005 from an attempt to exclude the influence of the human being in the experimental setup by using artificial lips to study the effect of bell vibrations on the spectrum of the radiated sound of modern trumpets. The results showed that the bell vibrations affected the spectrum of the radiated sound significantly.[6] Kausel et al. showed similar results for bell vibrations of a French horn[7] and for a trumpet.[8] One of their main conclusions was that a significant portion of the acoustical effects can be attributed to strain oscillations (axially symmetric motion of the wall) in the bell section and therefore strain oscillations in cylindrical pipes and damping parts of the instrument away from the bell section will not result in measurable effects. Gautier et al. proposed an adaptation of the Miller experiment to the case of a trombone bell and concluded that the input impedance was significantly influenced by the water level surrounding the trombone bell.[9]

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A recent theoretical/numerical study of axial vibrations of brass wind instruments and their acoustical influence (Kausel et al.[10]), complemented by an experimental investigation (Moore et al.[11]), focused primarily on the coupling of axial bell vibrations of a trumpet to the internal air column. Modeling results that could be validated by experiments showed that axial resonances have a measurable effect on the sound of brass wind instruments. It is concluded that these effects probably explain the sensitivity to details of construction often reported by musicians and instrument makers.

II. Motivation and scope

Previous studies have identified the significance of bell vibrations on the radiated sound of brass wind instruments. However, very little is known about the fluid-structure interactions in cylindrical sections and their effect on the radiated sound.

Nederveen et al. experimentally studied pitch and level changes in (cylindrical) organ pipes due to wall resonances.[12] They observed audible changes of 6 dB and frequency shifts of 20 cents in the case of a coincidence of an air column resonance with a wall resonance. Nief et al. investigated vibroacoustic interactions of a simplified wind instrument, i.e., an oval brass tube connected to a clarinet mouthpiece.[13] However, the authors mention that the geometrical parameters used in the experiments were unusual in comparison to a real instrument. Whitehouse investigated cylindrical tubes made from different materials attached to a trombone mouthpiece.[14] The internal air column was excited by an artificial mouth. The resulting structural dynamic response was captured by a scanning laser Doppler vibrometer.

In the present paper, representative geometrical parameters of cylindrical sections and realistic excitation amplitudes of the air column were used to study the vibroacoustic interactions within brass wind instruments. Investigations were performed on straight cylindrical tubes of 810 mm length, an outer diameter of 12 mm, and a

Figure 1: Tubes of identical geometry but made from different materials (brass and nickel silver).

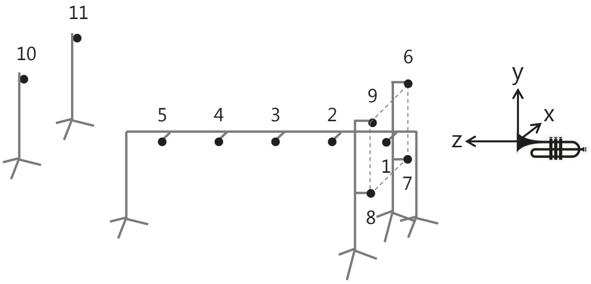
wall thickness of 0.5 mm, made from two different standard materials for brass wind instrument construction (see Figure 1). The effect of changes in the material properties on the interaction between the internal air column and the surrounding structure were investigated experimentally as well as numerically.

III. Experimental setup

Mouthpiece pressure measurements

A quantitative assessment of the fluid-structure interaction within a brass wind instrument requires the ability to artificially excite the air column at realistic pressure fluctuation levels and with correct excitation characteristics. As a first step, time-resolved pressure fluctuation measurements were performed for a variety of brass wind instruments and with different players, varying pitches, volume levels, etc. These measured pressure fluctuations were later reproduced by an artificial excitation mechanism for the air column.

The resulting radiated sound field was captured simultaneously by several microphones. The microphone setup for brass wind instrument types that predominantly radiate in the horizontal direction is illustrated in Figure 2 and the exact location coordinates are listed in the table of Figure 2. Eleven microphones were used to capture the radiated sound field.



Mic No.	x	y	z
1	0	0	240
2	0	0	330
3	0	0	420
4	0	0	510
5	0	0	600
6	70	70	240
7	70	-70	240
8	-70	-70	240
9	-70	70	240
10	190	0	660
11	300	0	580

Figure 2: Microphone setup for mouthpiece pressure measurements and coordinates of microphone positions [cm].

Mouthpieces were fitted with a flush-mounted piezoresistive pressure transducer, similar to the one shown in Figure 3, applied to a tuba mouthpiece. All the measurement channels were synchronously acquired by a multi-channel system with a sampling rate of 40 kHz at a resolution of 24 bits.

Vibroacoustic investigation of tubes

The investigation of the fluid-structure interactions within the cylindrical tubes was performed by exciting the internal air column with an artificial excitation source.

This consisted of an active speaker within a housing and an aperture to mount brass instrument mouthpieces equipped with a pressure transducer to monitor and control the required excitation pressure fluctuations. The system is capable of reproducing the pressure fluctuation corresponding to the real playing situations as recorded during the mouthpiece pressure measurements. For the results presented in this paper, the amplitude of the fundamental frequency measured in the experiments was reproduced by the artificial excitation source as a sine wave.

Figure 3: Tuba mouthpiece equipped with pressure transducer.

The vibroacoustic response of the tubes was captured by a scanning laser Doppler vibrometer. Scans along the tubes were performed to determine the structural dynamic response (surface-normal vibration velocity levels). Figure 4 shows the elastically suspended cylindrical tube attached to the artificial excitation source.

IV. Numerical approach

Numerical investigations were performed on the basis of coupled fluid-structure interaction simulations. The simulations were accomplished with the commercial finite element modeling (FEM) software tool ANSYS.[15] A schematic section cut of the numerical model for the straight tubes is given in Figure 5. The 3D finite element model consists of the straight tube coupled with a fluid-structure interaction (FSI)

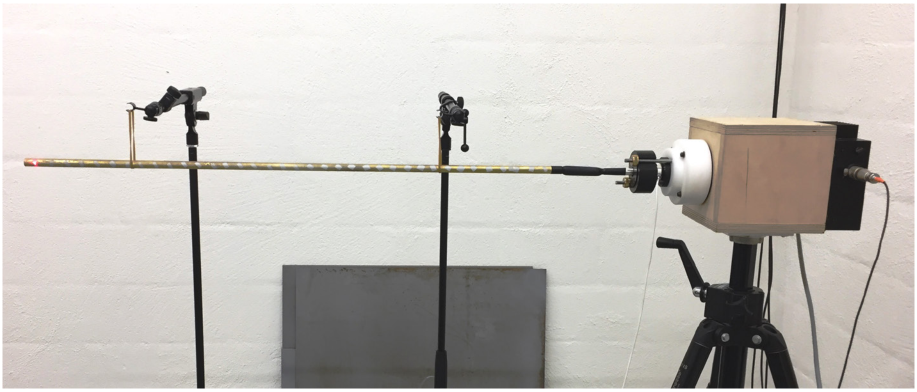


Figure 4: Excitation of tube with an artificial source, tube elastically suspended.

interface to the internal air column. At the inlet of the tube the air column is excited asymmetrically by plane waves. The asymmetry is required in the numerical model to excite bending modes of the tube. The excitation frequency was set to coincide with structural resonances of the tube. The pressure amplitude was adjusted to match realistic fluctuations of the fundamental frequency measured in the mouthpiece in the real playing situation. The outlet of the tube was surrounded by an acoustic enclosure to simulate sound radiation into the free-field. The material properties of the two different tubes were derived based on the experimental modal analysis results. Fluid-structure interaction simulations were used to quantify the amount of energy that is transferred from the vibrating internal air column into the surrounding tube material as a function of the material properties.

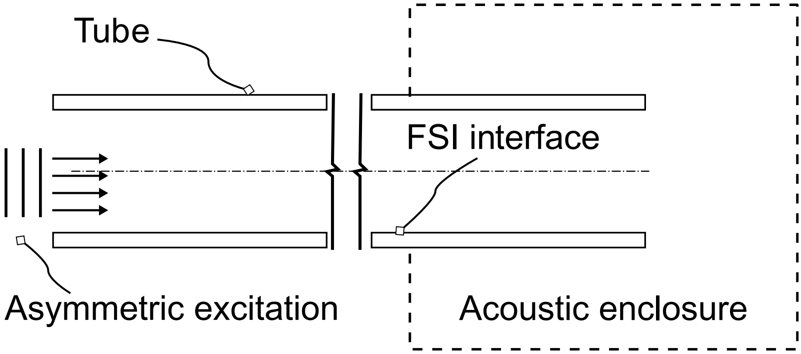


Figure 5: Schematic section cut of numerical model (3D FEM).

V. Results

Mouthpiece Pressure Measurements

Mouthpiece pressure measurements were conducted according to the setup illustrated in Figure 2. Signals were acquired for different pitches (several octaves) and varying volume (*pp–ff*). Table 1 gives an overview of the different instrument types and the number of players who participated in the mouthpiece pressure recording sessions.

For some instrument types (e.g., flugelhorn, bass trombone, or F tuba) the database, at the moment, is rather small. However, a continuous extension of the database is planned for the future. In Figure 6 the measured pressure in the mouthpiece as a function of time on a tenor trombone (*B♭*, *pianissimo*) is illustrated. The measured values are normalized by using the maximum measured amplitude as a reference. The pressure signal is slightly asymmetric and does not show a clean sinusoidal shape but contains harmonics.

Instrument Type	No. of Players
E♭ cornet	2
B♭ cornet	16
B♭ trumpet	8
B♭ flugelhorn	2
E♭ alto horn	6
B♭ baritone	3
B♭ euphonium	6
B♭ tenor trombone	5
bass trombone (B♭)	2
E♭ tuba	3
BB♭ tuba	2
F tuba	1
French horn (B♭)	6
Baroque trumpet	6

Table 1: Instrument types and number of players for mouthpiece pressure measurements.

The mouthpiece pressure for the same tone as illustrated in Figure 6 (*B♭*) was acquired, but for the volume level of *fortissimo*. The normalized resulting pressure signal is shown in Figure 7. The signal becomes even more asymmetric with respect to the y-axis. Finally, the measured normalized pressure in a mouthpiece of a tenor trombone is illustrated in Figure 8 for the tone *b♭*^{1} played *fortissimo*. The signal becomes symmetric with respect to the y-axis and can be characterized as a sinusoidal function. Similar trends as presented for a tenor trombone were found for all the different instrument types investigated. At higher pitches the signals become more symmetric with respect to the y-axis and approach a sinusoidal shape, meaning that harmonics gradually disappear.

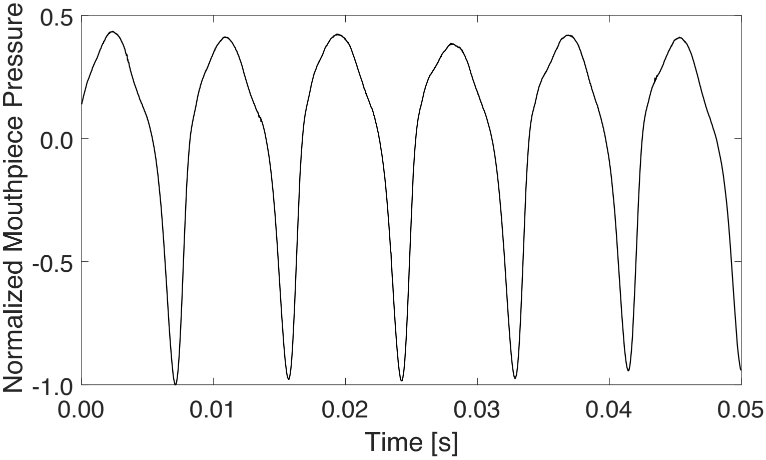


Figure 6: Measured time-resolved mouthpiece pressure, B♭ tenor trombone, playing the note *B♭, pianissimo.*

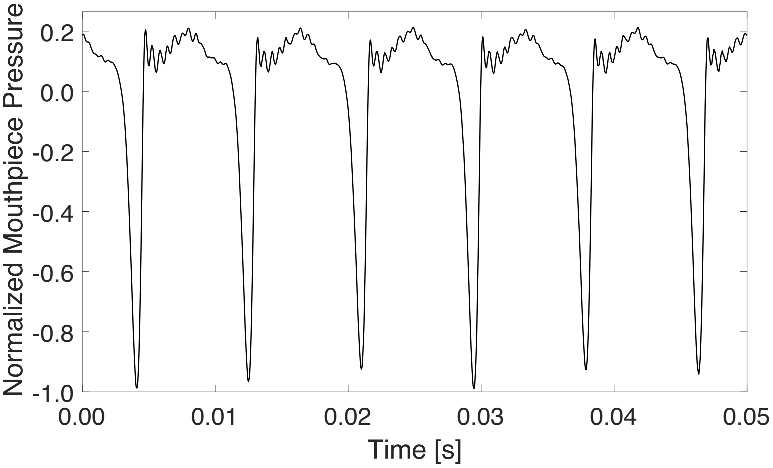


Figure 7: Measured time-resolved mouthpiece pressure, B♭ tenor trombone, playing the note *B♭*, *fortissimo.*

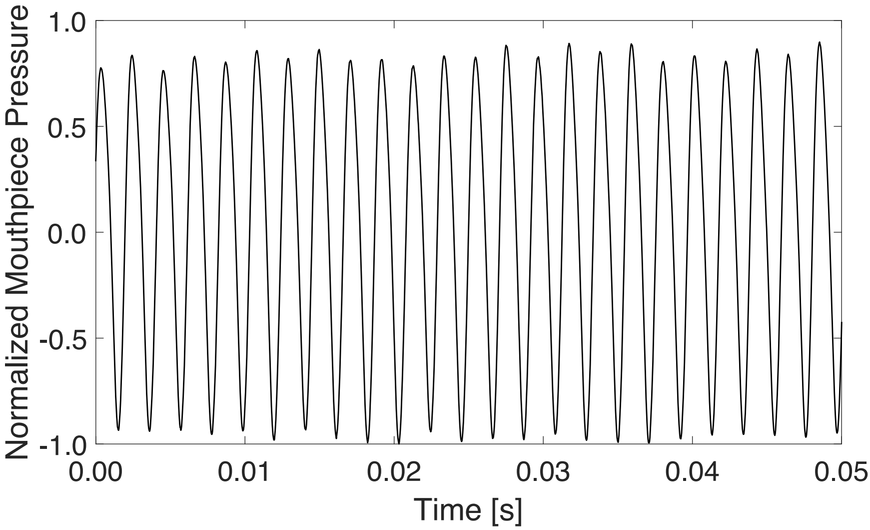


Figure 8: Measured time-resolved mouthpiece pressure, B♭ tenor trombone, playing the note *b♭*^{1}*, fortissimo.*

These findings are in agreement with results based on imaging methods focusing on the investigation of lip vibrations of brass players during extremely loud playing. Stevenson et al. concluded that the spectral enrichment of the mouthpiece pressure observed at loud playing is not based on a change of the lip open area but is mainly caused by non-linear propagation effects.[16]

An artificial excitation of the air column must be performed with realistic pressure fluctuation characteristics. The harmonic content of the pressure fluctuations is to be taken into account especially for the quantitative investigation of fluid-structure interaction mechanisms between the internal air column and the surrounding structure of the brass wind instrument. The measured pressure fluctuations in the mouthpieces of different instruments can be correlated with the measured radiated sound pressure levels at different microphone positions, according to Figure 2. In Figure 9 the correlation between the root mean square (RMS) pressure in the mouthpiece and the averaged radiated sound pressure level is illustrated for thirteen B♭ cornet players.

The averaged sound pressure level is derived from microphones 2, 6, 7, 8, and 9, representing a half-sphere around the cornet bell as the source location. An almost linear relation between the pressure fluctuations in the mouthpiece and the resulting pressure levels of the radiated sound was found. Although every player used the same instrumented mouthpiece, the conversion from mouthpiece pressure to radiated sound pressure by the instrument were found to differ significantly. Therefore, lower conversion rates may be related to differences in the cornet types played by the musicians or

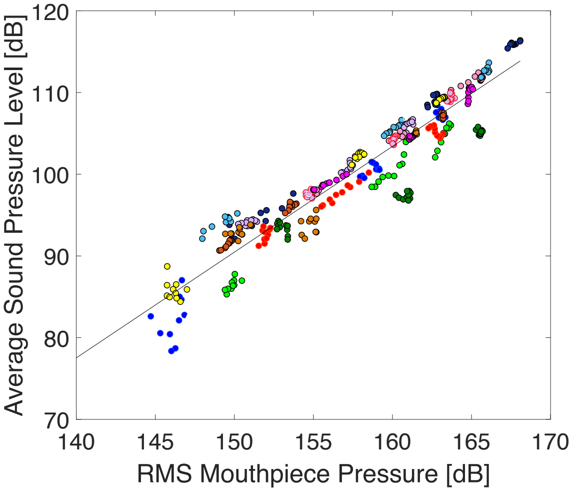


Figure 9: Measured correlation between RMS mouthpiece pressure and radiated sound pressure level, B♭ cornets.

to the response of the musicians to the instrumented mouthpiece that could not be perfectly matched to individual needs and preferences.

In Figure 10 the correlation between the RMS mouthpiece pressure and the radiated sound pressure level is shown for three different baritone players. Again, the correlation between the mouthpiece pressure and the level of the averaged radiated sound is linear. The variation among the different musicians seems to be smaller but was probably also influenced by the small sample size. However, in contrast to the results for cornets, the three baritone players used exactly the same type of instrument.

The reduction in the sample-to-sample variation might well be a first indicator of the varying conversion efficiency from pressure fluctuation in the mouthpiece to radiated sound pressure level of different instrument types, which is affected by design and also by material selection.

Linear correlations were found for all the different instruments investigated in this study. Therefore, in a simplified experimental setup, realistic excitation levels in the mouthpieces of brass instruments can be derived based on the experimentally determined linear relations. But this simplification does not consider the exact temporal evolution of the pressure fluctuations influenced by volume and pitch.

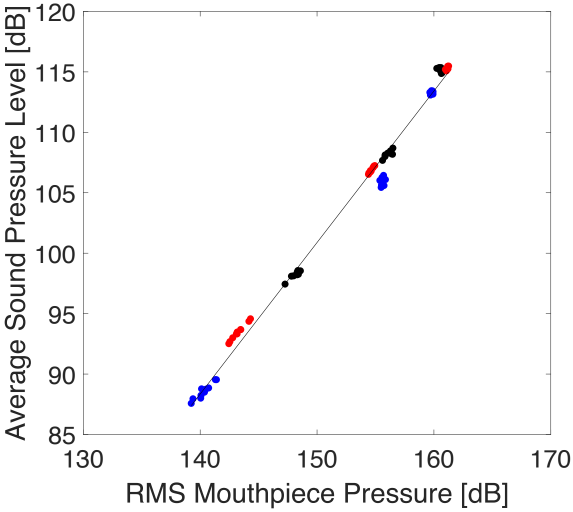


Figure 10: Measured correlation between RMS mouthpiece pressure and radiated sound pressure level, B♭ baritones.

Vibroacoustic investigation of tubes

In the vibroacoustic experiments, the modal properties (eigenfrequency, mode shape, and modal damping) of the cylindrical tubes made from two different materials were determined for very low as well as for realistic excitation levels of the internal air column, derived from measurements in the mouthpieces. Measurements were performed with a continuous sweep across the eigenfrequency of interest.

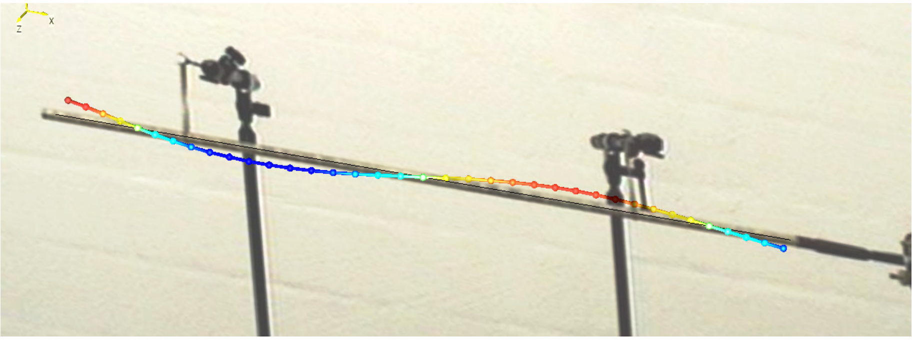


Figure 11: Measured second bending vibration of cylindrical tube (picture from scanning laser Doppler vibrometer).

Figure 11 shows the detected second bending vibration mode of one of the cylindrical tubes. The results were used to develop a 3D Finite Element Method (FEM) model of the tube structure coupled to the internal air column. In Table 2, a comparison between the measured and predicted eigenfrequencies for the two different tube materials is given. In the 3D FEM model the material properties were defined to match the measured modal properties. A maximum of 0.58% deviation between experiment and prediction was found for the first five modes. The overall agreement of the numerical prediction with the experimental results justifies the use of the model to perform coupled fluid-structure interaction simulations to study the energy flows from the air column into the structure and vice versa. Three different cases were numerically investigated: (1) an infinitely rigid tube with identical geometrical properties as in the experimental investigation with a representative excitation of the air column at the inlet of the tube (see schematic cross-section view of numerical model in Figure 5); (2) the same simulation set-up as for case (1) but with a tube material corresponding to Tube Material 1 in Table 2 and a fluid-structure interaction interface between air column and tube; and (3) the same simulation set-up as for case (2) but for Tube Material 2 in Table 2.

Tube material 1			
Mode	Exp. [Hz]	Num. [Hz]	Diff. [%]
1	79.35	79.55	0.25
2	218.20	218.70	0.23
3	425.70	427.00	0.31
4	701.90	702.03	0.02
5	1039.00	1041.70	0.26
Tube material 2			
Mode	Exp. [Hz]	Num. [Hz]	Diff. [%]
1	82.40	82.63	0.27
2	225.80	227.10	0.58
3	442.50	443.51	0.23
4	726.30	729.23	0.40
5	1076.00	1081.20	0.48

Table 2: Comparison of eigenfrequencies, experimental versus numerical, tube materials 1 and 2.

Mode No.	Energy Difference [%]
1	-87.0 %
2	-93.5 %
3	-93.0 %
4	-91.8 %

Table 3: Relative comparison of energy transferred from air column to surrounding material, Tube Material 1 as reference.

Numerical predictions were used to quantify the amount of energy that is fed from the air column to the surrounding material of the tubing. Table 3 shows a comparison of the predicted total energy flows into the tubes. The total energy transferred into Tube 1 was taken as the reference for the comparison. The overall trend of the total energy differences is in agreement with the material properties for the two tubes. The material of Tube 2 has higher stiffness values and lower material damping properties. Therefore, a significantly lower amount of energy was transferred from the internal fluid column into the surrounding solid. This difference not only affects the acoustic transfer function from inlet to outlet of the tubing but also may change the efficiency of the brass wind instrument and may affect the characteristics of the radiated sound.

VI. Summary and conclusions

Experimental as well as numerical investigations were performed on straight tubes made from different materials in order to quantify the coupling between the artificially excited air column and the surrounding wall material. The excitation was done at realistic pressure amplitudes, based on experimentally determined mouthpiece pressure fluctuations for varying pitch and volume levels for different brass wind instrument types. The results showed a linear correlation between the mouthpiece pressure and the measured average radiated sound pressure level for all the different instrument types investigated.

Significant differences, in terms of energy that is transferred from the fluid to the surrounding structure, were found in the FEM simulations. For the tube material with higher stiffness and lower material damping, a difference of about -90% in total energy was found as compared to the other tube material for vibration modes 1–4. These differences affect the acoustic transfer functions of the two tubes. Translated onto a brass wind instrument, these differences may result in a change in the efficiency of the instrument and may also change the characteristics of the radiated sound.

It is clear that an investigation of possible effects of the material selection, manufacturing techniques, and the design on the acoustic characteristics of the brass wind instrument need to be performed using realistic pressure fluctuations within the internal air column. Additional effort is required and currently ongoing to use the approach presented for the determination of acoustic properties of historic brass instruments. A detailed insight into the fluid-structure interaction mechanisms should be of significant value in enhancing the quality of historically informed reproductions of brass wind instruments.

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Rainer Egger took over the business from his father and founder Adolf Egger in 1972. Egger Instruments in Basel, Switzerland, is specialized in making historically informed reproductions of Baroque brass instruments. The Historic Brass Society honored his achievements in period brass instrument craftsmanship with the Christopher Monk Award in 2012.

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