An investigation into wall vibrations induced in wind instruments constructed from different metals

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Abstract

A series of experiments has been carried out in which a simple instrument (a trombone mouthpiece coupled to a section of metal pipe) was blown using an artificial mouth and the induced wall vibrations measured using a scanning Laser Doppler Vibrometer. The pipe’s natural resonant frequencies and mode shapes were established and compared to the velocity amplitude variation of the vibrations induced by an artificially blown note. The variations in these velocity amplitudes were shown to occur at similar frequencies to, and match the shapes of the bending modes of the pipe. Results indicate that it is the motion of the lips against the mouthpiece, rather than air pressure changes within the pipe, that is the dominant mechanism in exciting wall resonances. The measurements were repeated for pipes of identical dimensions but manufactured from different metals and the results compared.

1. Introduction

Although the most significant resonances in a wind instrument are associated with the air column, the question of whether the structural resonances have an effect on the tonal quality of the instrument remains a subject of debate. Instrument makers and researchers have claimed the ability to distinguish between sounds produced by instruments manufactured from different materials [1,2]. However, psychoacoustical studies have so far failed to demonstrate that this is the case [3, 4].

In this paper, experiments designed to study the wall vibrations of wind instruments constructed from different metals are described. These simple instruments comprise a trombone mouthpiece coupled to a section of pipe made of either brass, titanium, copper, aluminium or steel. In section 2, by using a mechanical source to excite a simple brass instrument through a range of frequencies and measuring the velocities induced in the walls, the instrument's structural modes are identified. In section 3, an artificial mouth is used to blow the brass instrument, and the vibrational response is measured and compared with the pipe's structural mode shapes and frequencies. In section 4, the mechanism by which the wall vibrations are excited when the brass instrument is artificially blown is investigated. Finally, in section 5, the velocities induced in the walls of instruments constructed from five different types of metal when artificially blown are measured and discussed.

The vibrational velocity measurements were obtained using Laser Doppler Vibrometry (LDV). LDV is a non-invasive optical measurement technique, so any vibrational changes due to loading through conventional sensors are avoided. An artificial mouth was used to play the instruments to ensure repeatability and a constant output.

2. Determination of the structural modes of a simple brass instrument

A section of brass pipe (length 70 cm, external diameter 14 mm and wall thickness 0.5 mm) of the type used in musical instrument manufacture was rigidly clamped at each end around the entire circumference to prevent movement perpendicular to the length of the pipe. The pipe was fixed horizontally on an anti-vibration optic table housed in an anechoic chamber with one end attached via a Denis Wick trombone mouthpiece to an artificial mouth; a mechanical blowing device comprising a pair of water-filled latex rubber lips contained within a hermetically sealed box. In order to excite the mechanical resonances, the pipe was driven at a position close to the mouthpiece using a shaker with a fine pointed screw attachment. The vibrometer laser beam was reflected and focussed on to the top of the pipe using a silver-sided mirror angled at 45° to the light path. To determine the mechanical resonances the shaker was driven at discrete frequencies over a range of 20 Hz - 1 kHz in 10 Hz steps, and at each frequency the velocity amplitude (in m/s) was measured using the LDV. Readings were taken along the pipe at 6 cm intervals.

The results of the experiments undertaken on the artificial mouth/brass pipe combination can be seen in Figure 1. Figure 1(a) shows a 2D contour plot of the variation in velocity amplitude with frequency along the length of the pipe. The natural vibrational frequencies are clearly distinguishable in the plot, as are the shapes and positions of the first four modes (bending modes) located at 80 Hz, 230 Hz, 500 Hz and 830 Hz.

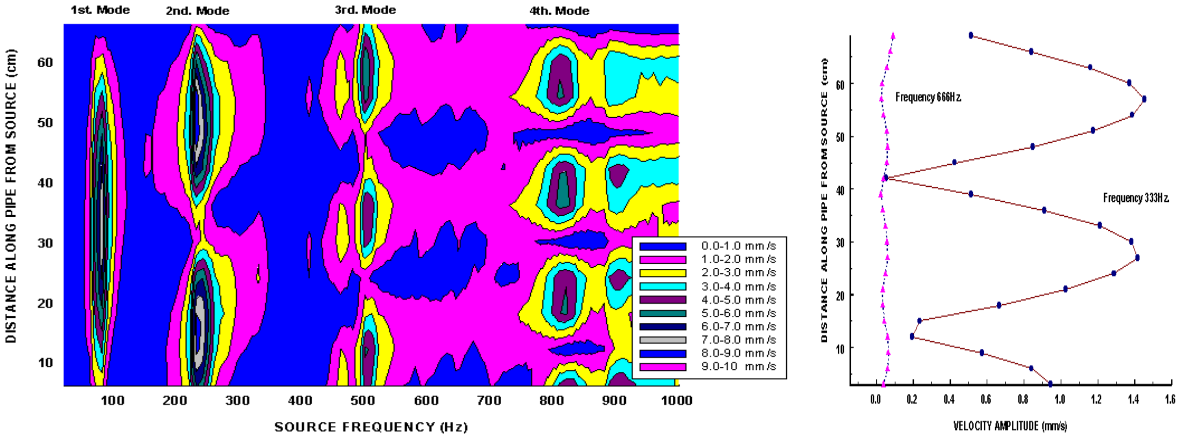

Figure 1 (a) 2D contour plot of velocity amplitude variation with frequency along the pipe with both ends clamped. (b) Velocity amplitude variation along the pipe at 333 Hz and 666 Hz when it is artificially blown with both ends clamped.

3. Determination of the wall vibrations induced in a simple brass instrument through artificial blowing

The shaker was removed from the set-up described in section 2 and the air-supply to the artificial mouth activated. The lips were adjusted until a discernible stable note was heard in the selected frequency region. This note was recorded and frequency analysis revealed a fundamental frequency of 333 Hz and a second harmonic at 666 Hz. The velocity amplitudes at 3-cm intervals along the pipe at these two frequencies were measured using the LDV.

Figure 1(b) shows the velocity amplitude variation along the length of the pipe induced by the artificial mouth at 333 Hz and 666 Hz. Comparison with Figure 1(a) shows that the variation in the velocity amplitude at the fundamental frequency of the played note (333 Hz) matches the natural bending mode shape centred on 230 Hz. Similarly, the plot for the second harmonic of the played note (666 Hz) corresponds to the natural bending mode shape centred on 500 Hz.

4. Investigation of the Excitation Mechanism

It is clear that using the artificial mouth to blow the brass pipe has excited wall resonances. This could be caused by the oscillation of the lips, which are in contact with the pipe through the mouthpiece. However, it could also be a result of coupling between the air column resonances and the structural resonances. That is, the air pressure changes within the pipe might be providing a driving force to excite the wall resonances. This is only likely to be significant when the air column resonances are close in frequency to the structural modes.

4.1 Decoupling the lips from the brass pipe

To help determine the dominant excitation mechanism, a short length of flexible tubing was inserted between the brass pipe and the mouthpiece. It was anticipated that this would reduce any vibration transmitted from the lips to the pipe without altering the strength of the air column resonances. The instrument was then artificially blown and the velocity amplitude variation along the pipe was measured as before.

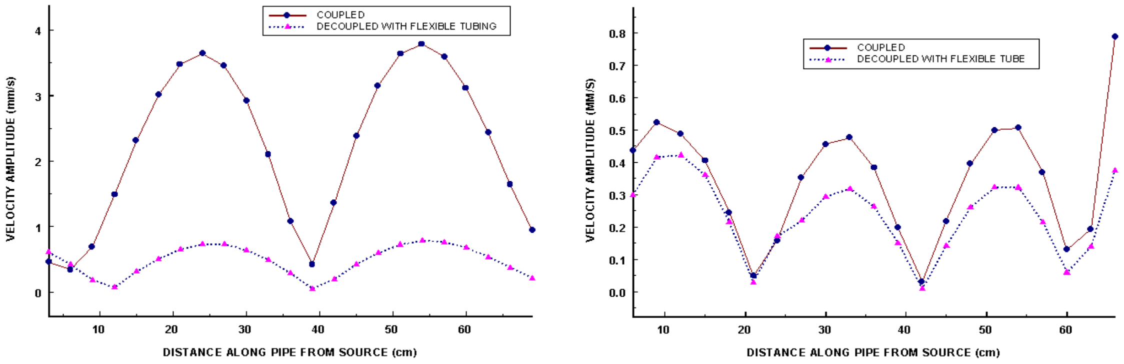

Figure 2 Velocity amplitude variation of pipe when artificially blown - with and without flexible tubing present. Measured at the first two harmonics (a) 327 Hz and (b) 653 Hz

Figure 2 shows the velocity amplitude variations along the artificially blown pipe, at (a) 327Hz and (b) 653 Hz, with and without flexible tubing inserted. The plots show a reduction in vibration velocity when the mouthpiece is decoupled. The effect is most dramatic at 327Hz indicating that, at the fundamental frequency especially, the motion of the lips against the mouthpiece is the dominant excitation mechanism.

4.2 Decoupling the air column from the brass pipe

With the flexible tubing removed and the brass pipe recoupled to the mouthpiece, an aluminum pipe (9.5mm external diameter) was inserted inside the brass pipe. This inner pipe was connected to the mouthpiece so that it behaved as the acoustic resonator. This ensured that pressure changes within the air column were prevented from acting on the outer pipe meaning that the only excitation experienced by the brass pipe was the motion of the lips against the mouthpiece. In this new configuration, the instrument was again artificially blown and the velocity amplitude variation along the pipe remeasured.

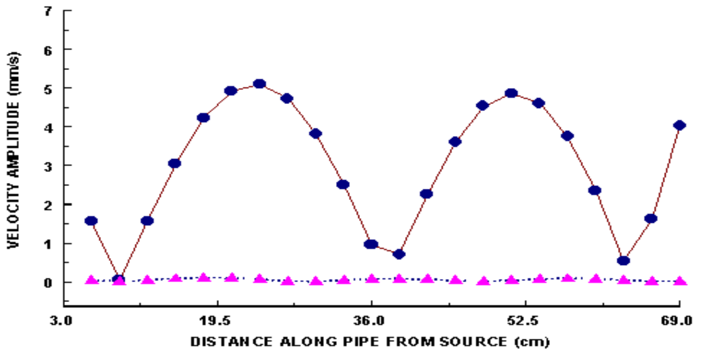

Figure 3 Velocity amplitude variation of pipe isolated from the air column. Measured at the first two harmonics, 330 Hz and 660 Hz

Figure 3 shows the velocity amplitude variations along the artificially blown pipe at 330Hz and 660 Hz. At the fundamental frequency, the plot shows velocity amplitudes similar to those measured when the pipe is normally coupled to the mouthpiece (Fig.2 (a)), despite there being no interaction with the air column. Again, this provides a strong indication that the interaction of the lips with the mouthpiece is the dominant excitation mechanism.

5. Comparison of Velocity Amplitude Measurements in Pipes of Different Materials

The experiments described in section 4 imply that it is the movement of the lips against the mouthpiece which is the dominant excitation mechanism. Artificially blowing the instrument causes the walls to vibrate, with the lips acting as a mechanical source (a mini shaker) positioned at the pipe end.

In principle, therefore, the magnitude of the vibrations induced when a pipe is artificially blown should depend on the strength of the pipe's structural response at the frequency of the blown note. Pipes of identical dimensions but manufactured from different metals have different structural resonance properties. Therefore, when artificially blown, pipes made from different metals should exhibit different magnitudes of induced wall vibration.

The structural resonance properties of five pipes of identical dimensions (length 1m, external diameter 12.7mm and wall thickness 0.7mm) but manufactured from different metals (steel, titanium, brass, copper and aluminium) were measured using the same basic procedure as in section 2. In this case, however, the shaker was driven with a CHIRP signal of range 3 Hz – 1 kHz. For comparability and repeatability, the shaker was controlled by a potentiometer system ensuring an equal degree of loading on each pipe.

Artificial blowing measurements were made on the five pipes using the same basic procedure as in section 3. A pressure gauge was positioned at the open end of the pipe and the artificial mouth firmly attached on a slideway ensuring the mouthpiece insertion was repeatable both in terms of angle and pressure. When artificially blown, the note produced by each pipe had a fundamental frequency of 409Hz.

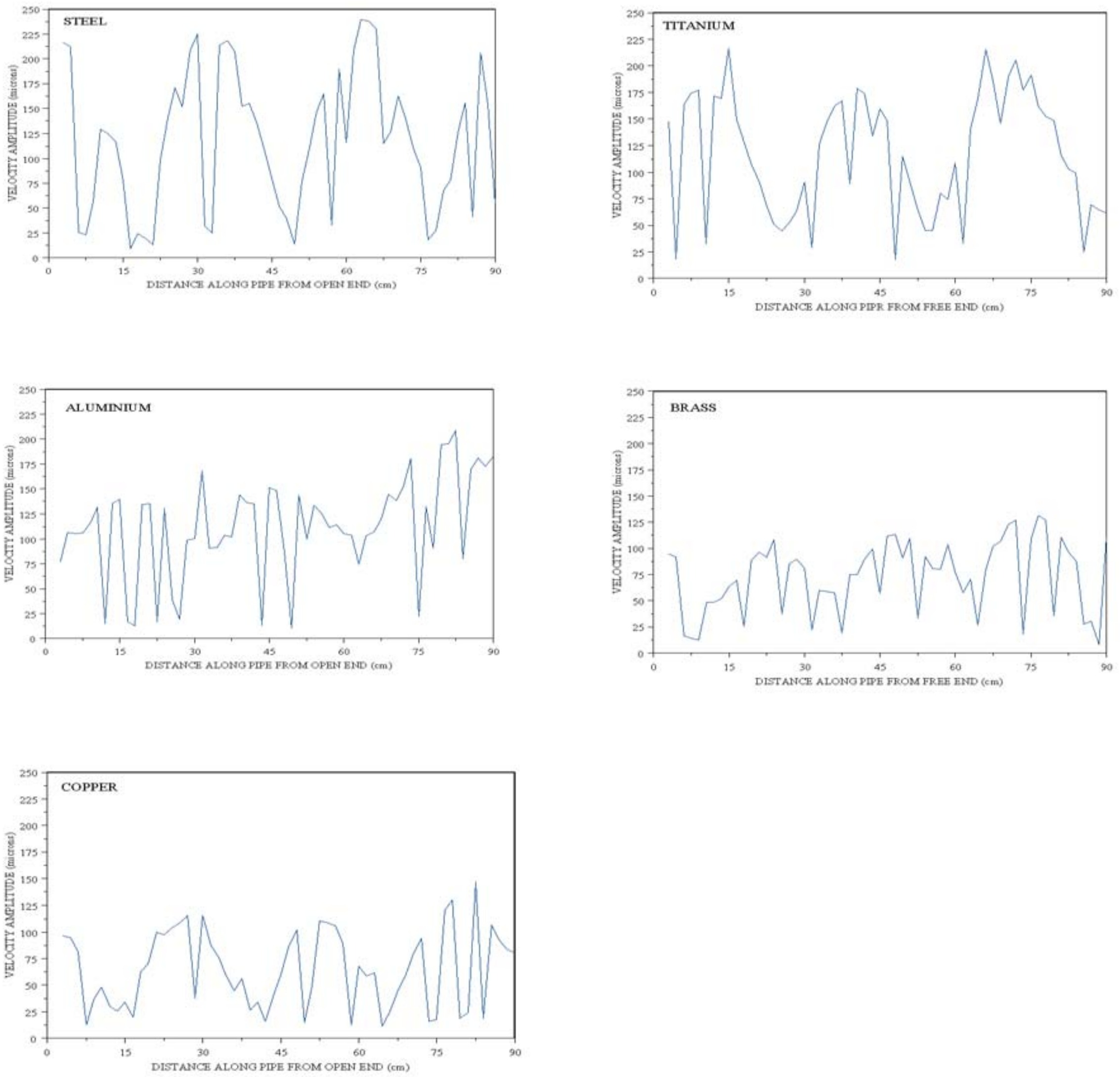

Figure 4 Structural velocity amplitude variation along the five pipes at 409Hz

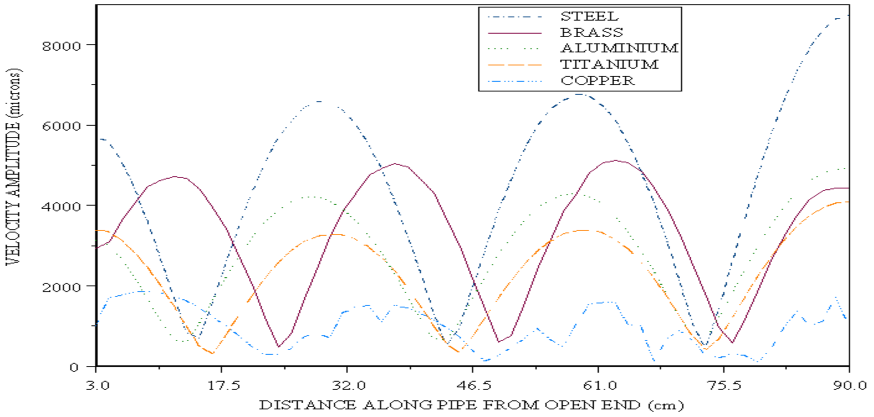

Figure 5. Velocity amplitude variation when artificially blown for the five pipes at the fundamental frequency of 409Hz.

Figure 4 shows the structural responses of the five metal pipes at 409 Hz. Steel has the strongest response followed, approximately, by titanium, aluminium, brass and copper. Aluminium and titanium show velocity amplitude variations of similar magnitudes, as do brass and copper, making ordering difficult.

Figure 5 shows the velocity amplitude variation along the length of pipe, for each of the five metals, when artificially blown. As one might expect from the structural responses of Figure 4, steel exhibits the greatest velocity amplitudes with copper having the lowest. In this case, however, relatively large wall vibrations are induced in the brass pipe despite it appearing to have a weak structural response at 409Hz.

On the whole, there appears to be a reasonable correlation between the magnitudes of the wall vibrations induced when the pipes are artificially blown and the strengths of the pipes' structural responses at 409 Hz. It is intended to repeat the measurements to determine the structural resonance properties of the pipes using a sinusoidal excitation signal rather than the CHIRP signal. This should maximise the signal-to-noise ratio at the 409 Hz frequency of interest, improving the accuracy of the measurements.

6. Summary

Experiments have shown that when a simple wind instrument, consisting of a mouthpiece and section of metal piping, is artificially blown mechanical wall resonances are excited. The strength of these induced wall vibrations is dependent on how close in frequency the artificially blown resonances and the structural resonances are.

The experimental results presented suggest that it is the motion of the lips against the mouthpiece, which is the main cause of the wall vibrations when the instrument is blown. The material of the pipe affects the position of the structural modes and hence its response to a particular note.

Further experiments, both physical and psychoacoustical, are planned to assess the effect of differing materials and wall thicknesses on the tonal quality of wind instruments.

7. Acknowledgements

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8. References

[1] Angster, J., Paal, G., Garen, W., Miklos, A., “The Effect of Wall Vibrations on the Timbre of Organ Pipes”, Proceedings of the 16th. Int. Congress on Acoustics and 135th JASA Meeting. Seattle, Vol. 3, pp 753-754, 1998.
[2] Pyle, R.W., “The Effect of Wall Materials on the Timbre of Brass Instruments”, Proceedings of the 16th. Int. Congress on Acoustics and 135th JASA Meeting. Vol. 3, Seattle, pp 751-752, 1998.
[3] Coltman, J.W., “Effect of Material on Flute Tone Quality”, *J. Acoust. Soc. Amer.*, **49** (2), pp.520-523, 1971.
[4] Widholm, G., Linortner, R., Kausel, W., Bertsch, M., “Silver, Gold, Platinum-and the Sound of the Flute”, Proceedings of the Int. Symposium on Musical Acoustics, Perugia, Vol.1, pp 277-280, 2001.