THE USE OF LASER DOPPLER VELOCIMETRY IN THE MEASUREMENT OF ARTIFICIALLY INDUCED WALL VIBRATIONS IN A WIND INSTRUMENT

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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 a simple brass instrument are described. In section 2, by using a mechanical source to excite the instrument through a range of frequencies and measuring the velocities induced in the walls, the instrument's structural modes are identified. In section 3, with an artificial mouth used to blow the instrument, the vibrational responses under different clamping conditions are measured and compared. Measurements are then presented in section 4, which verify that the velocities induced in the walls of the instrument when artificially blown are comparable to those induced by a human player. Finally, the mechanism by which the wall vibrations are excited is investigated.

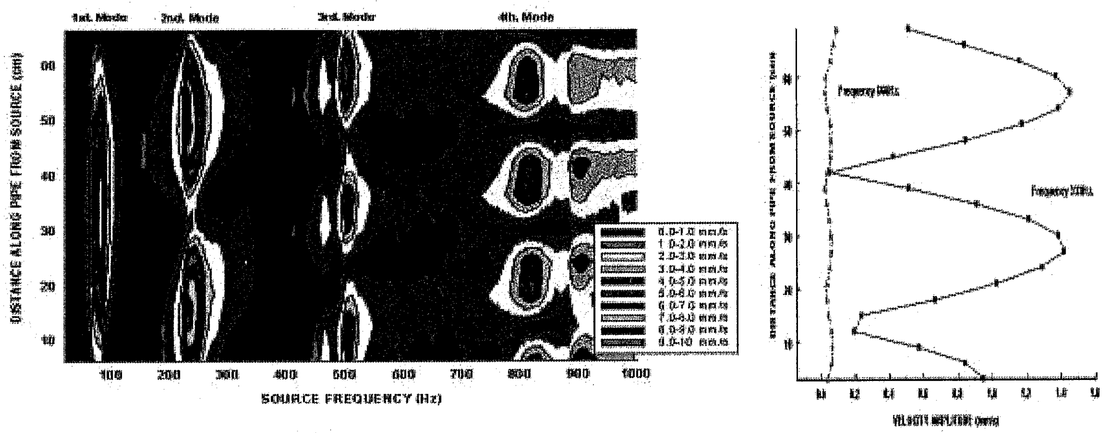
The vibrational velocity measurements were obtained using Laser Doppler Vibrometry (LDV). LDV is a non-invasive optical measurement technique, so any vibrational changes due to loading through conventional sensors are avoided. An artificial mouth was used to play the instrument to ensure repeatability and a constant output. This is with a view to future experimentation where the effect of differing wall thicknesses and materials on the sound produced by the instrument will be investigated using both LDV measurements and psychoacoustical tests.

2. DETERMINATION OF STRUCTURAL MODES

2.1 Experimental Method

A section of brass pipe (length 70 cm, outside radius 0.7 cm 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 clamp was then removed from the open end of the pipe and the procedure repeated with the end loosely suspended in a loop of cotton.

2.2 Structural Mode Results



The results of the experiments undertaken on the artificial mouth/brass pipe combination can be seen in Figures 1 and 2. Figure 1(a) shows a 2D contour plot of the variation in velocity amplitude with frequency along the length of the pipe with both ends clamped. 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.

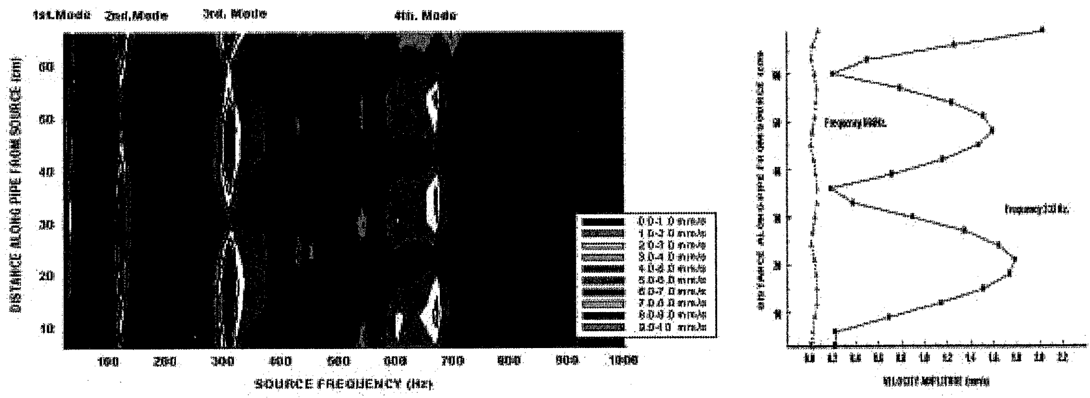


Figure 1 (a) 2D contour plot of velocity amplitude variation with frequency along the pipe with both ends clamped. (b) Velocity amplitude variation along the pipe at 333 Hz and 666 Hz when it is artificially blown with both ends clamped.

Figure 2 (a) 2D contour plot of velocity amplitude variation with frequency along the pipe with one end loosely suspended. (b) Velocity amplitude variation at 333 Hz and 666 Hz when pipe is artificially blown with one end loosely suspended.

Figure 2(a) shows a 2D contour plot taken from the same pipe with one end loosely suspended. Once again the plot clearly shows distinct modal patterns at the natural frequencies of vibration but the first four bending modes have been shifted in frequency to approximately 30 Hz, 130 Hz, 300 Hz and 640 Hz. The positions at which the nodes and antinodes occur along the pipe have also changed, as the open end is now able to vibrate freely.

3. DETERMINATION OF THE WALL VIBRATION INDUCED THROUGH ARTIFICIAL BLOWING

Before embarking on experiments which involved artificially blowing the instrument, an input impedance measurement was carried out to give an indication of the instrument's playing frequencies. Figure 3 shows the measured impedance curve. The second peak can be seen to occur around 330Hz. By adjusting the embouchure of the artificial mouth, a stable note could be played at approximately this frequency.

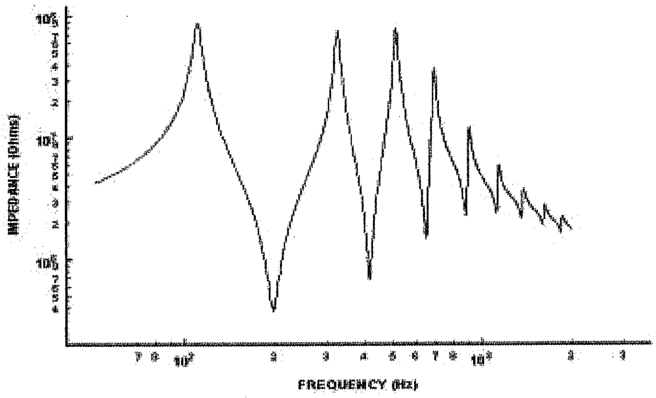


Figure 3. Impedance Curve for the Pipe under Investigation.

3.1 Experimental Method

The shaker was removed from the set-up described in section 2.1 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, a second harmonic at 666 Hz and a third at 1000 Hz. The velocity amplitudes at 3 cm intervals along the pipe at these three frequencies were measured using the LDV.

This procedure was performed with both ends of the pipe clamped and then repeated with the far end loosely suspended. The pressure and embouchure were maintained constant throughout to allow the amplitudes of vibration to be compared.

3.2 Induced Wall Vibration Results

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.

Figure 2(b) shows the velocity amplitude variations induced by the artificial mouth at the same two frequencies under the second clamping condition of a loosely suspended end. Comparison with Figure

2(a) again shows a match to the bending mode shapes of the pipe. However, in this case the two harmonics of the played note are closer in frequency to structural resonances of the pipe.

The importance of the agreement between the harmonic frequencies of the played note and the frequencies of the instrument's structural modes to the amplitude of the induced wall vibrations is investigated in Figure 4.

Figure 4(a) compares the velocity amplitude variations along the pipe induced by the artificial mouth at 333 Hz under the two clamping conditions. At the antinodes, the velocities are slightly larger when the pipe is loosely suspended at one end. This is consistent with Figures 1(a) and 2(a) which show that when the pipe is clamped at both ends the closest structural resonance to 333 Hz is the bending mode centred on 230 Hz, whereas when the pipe is suspended at one end the closest structural resonance to 333 Hz is the bending mode centred on 300 Hz.

Figure 4(b) compares the velocity amplitude variations along the pipe induced by the artificial mouth at 666 Hz under the two clamping conditions. In this case, at the antinodes, the velocities are approximately the same whether the open end of the pipe is rigidly clamped or loosely suspended. However, at the nodes, the velocities are lower when the pipe is loosely suspended. Again, this is consistent with Figures 1(a) and 2(a) which show that at 666 Hz, although the structural responses under the two clamping conditions are similar, in the loosely suspended case there is a well defined bending mode centred close by which may explain the deeper troughs.

Figures 4(c) compares the velocity amplitude variations along the pipe at 1000 Hz under the two clamping conditions. Here, at the antinodes, the velocities are significantly larger when the pipe is clamped at both ends. Examination of Figures 1(a) and 2(a) reveals that under rigid clamping conditions the effect of the fourth bending mode is still evident at 1000 Hz. When the pipe is loosely suspended at one end the structural response at 1000 Hz is much lower.

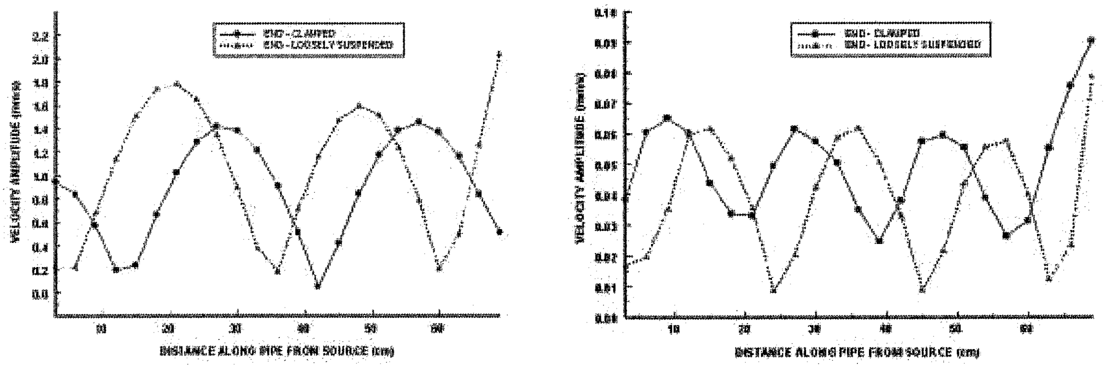


Figure 4 (a) Velocity amplitude response at 333Hz. Pipe with clamped and loosely suspended end. (b) Velocity amplitude response at 666Hz. Pipe with clamped and loosely suspended end.

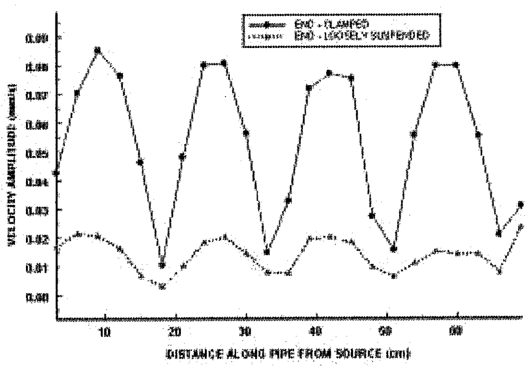


Figure 4 (c). Velocity amplitude response at 1000Hz. Pipe with clamped and loosely suspended end.

4. COMPARISON OF ARTIFICIAL MOUTH WITH HUMAN PLAYER

To check that the velocities induced in the walls of the instrument when artificially blown are comparable to those which would be induced by a musician, a human player attempted to attain a note of similar frequency and loudness to that used in the artificial mouth experiments. The instrument was clamped at both ends and wall velocity measurements were made as described previously.

Figure 5(a) shows the velocity amplitude variation along the pipe induced when blown by a human player. For comparison purposes, Figure 5(b) shows the variation induced by the artificial mouth. In both cases, the velocity variations at the fundamental and second harmonic of the played note are shown.

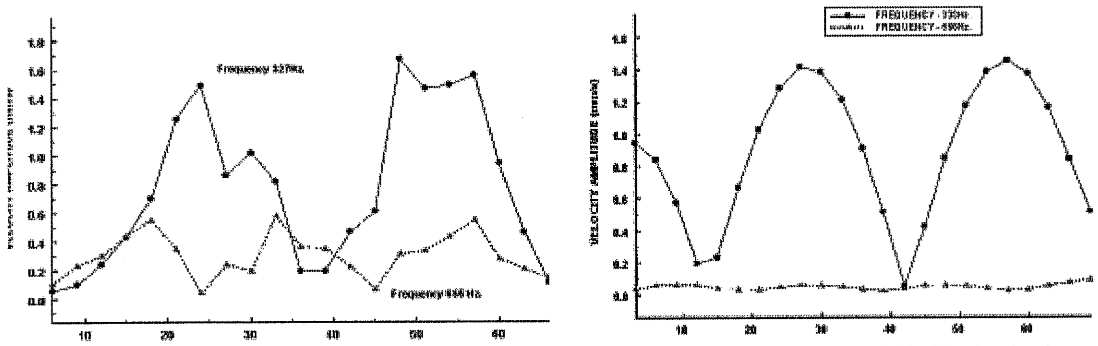


Figure 5 (a) Velocity amplitude variation produced by a human player. (b) Velocity amplitude variation produced by artificial mouth under similar conditions

The two graphs show good agreement in shape and amplitude, especially at the fundamental frequency of the played note. This would appear to confirm the acceptability of using the artificial mouth when measuring the wall vibrations induced when an instrument is blown. The difficulty that the player had in producing notes of similar loudness and quality is evident when Figures 5(a) and 5(b) are compared. The constant output of the artificial mouth results in the much smoother variation in velocity amplitude along the pipe seen in Figure 5(b). The artificial mouth removes the problems encountered when using a human player, such as the introduction of unavoidable movement into the system and the inability to repeat and sustain notes over long periods.

5. INVESTIGATION OF 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.

5.1 Experimental Method

To help determine the dominant excitation mechanism, a short length of flexible tubing was inserted between the 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.

To monitor the motion of the lips when a note is being played, a separate experiment was carried out in which a photodiode was positioned at the far end of the pipe and a light source placed behind the artificial mouth. The interruption in the passage of light caused by the movement of the lips was recorded as changes in voltage from the photodiode.

5.2 Coupled/Decoupled Induced Wall Vibration Results

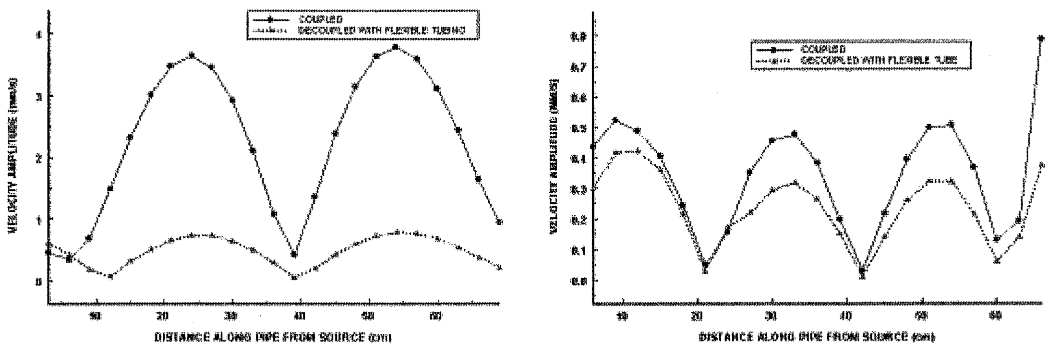


Figure 6 Velocity amplitude variation of pipe when artificially blown - with and without flexible tubing present. Measured at (a) 327 Hz (b) 653 Hz.

Figure 6 Velocity amplitude variation of pipe when artificially blown - with and without flexible tubing present. Measured at (c) 975Hz.

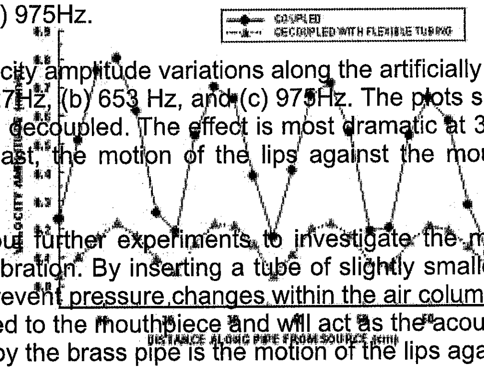


Figure 6 shows the velocity amplitude variations along the artificially blown pipe with and without flexible tubing inserted at (a) 327Hz, (b) 653 Hz, and (c) 975Hz. The plots show a reduction in vibration velocity when the mouthpiece is decoupled. The effect is most dramatic at 327Hz and 975 Hz indicating that, at these frequencies at least, the motion of the lips against the mouthpiece is the dominant excitation mechanism.

It is planned to carry out further experiments to investigate the mechanism by which the instrument walls are excited into vibration. By inserting a tube of slightly smaller diameter inside the brass pipe, it should be possible to prevent pressure changes within the air column from acting on the outer pipe. The interior tube will be joined to the mouthpiece and will act as the acoustic resonator ensuring that the only excitation experienced by the brass pipe is the motion of the lips against the mouthpiece.

5.3 Photodiode Lip Motion Results

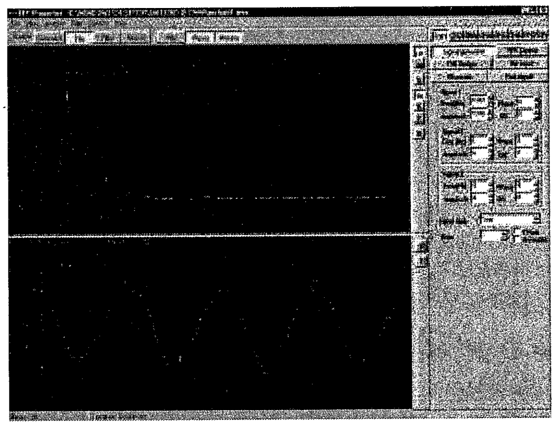


Figure 7 shows the photodiode signal and its frequency spectrum. The variation in voltage, and hence the motion of the lips, is nearly sinusoidal although higher harmonics can be picked out. The fundamental frequency is 344 Hz. Analysis of a recording of the note produced during this experiment confirmed that the playing frequency was also 344 Hz.

Figure 7 Photodiode signal and its frequency spectrum

6. SUMMARY

Experiments have shown that when a simple wind instrument, consisting of a mouthpiece and section of brass piping, is artificially blown mechanical wall resonances are excited. The strength of these induced wall vibrations is dependent on how close in frequency the air column resonances and the structural resonances are. As clamping conditions significantly affect the structural resonance frequencies, this will have to be taken into consideration when comparing resonators of different materials and making recordings for psychoacoustical tests.

The artificial mouth has been shown to be a more than suitable substitute for a human player when measuring induced wall vibrations. The ability of the artificial mouth to repeat and sustain notes at a given loudness should make it an excellent tool when comparing the vibrations induced in pipes of different materials and wall thicknesses.

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.

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. REFERENCES

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