

MEASUREMENT OF ACOUSTIC VELOCITIES AT WOODWIND INSTRUMENT TONEHOLES USING PARTICLE IMAGE VELOCIMETRY

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ABSTRACT

The timbre and playability of a woodwind instrument is significantly affected by the velocity field near its tone holes. Effects have been widely studied and are complex, varying subject to conditions such as tone hole geometry and separation, intensity level and frequency. Non-linear phenomena such as acoustic streaming and vortex shedding become important at low frequencies and play important roles in the interaction between tone holes.

Particle Image Velocimetry (PIV) is an invaluable tool for the quantitative determination of instantaneous velocity fields. This work investigates velocity fields in single and multiple tone hole situations using PIV. Experimental results will be presented and discussed in comparison with theory.

INTRODUCTION

The behaviour of acoustic fields in the vicinity of a tube termination has been the subject of much experimental and theoretical investigation. The interaction of the flow with the walls at an opening in the tube has important implications for the study of woodwind instruments, since the sound produced can be strongly influenced by the acoustical behaviour near tone holes. Studies by Keefe [1] have shown that the acoustical behaviour of a woodwind instrument is strongly influenced by the position, geometry and separation of toneholes along the main duct, both from the point of view of the listener and the player.

The aim of this paper is to provide a quantitative investigation into the variation of acoustic velocities with frequency at short side ducts on a cylindrical tube of geometry and dimensions similar to those found on a modern Boehm flute. PIV is used to obtain instantaneous velocity maps of the region surrounding the tone holes, from which the acoustic streaming velocities are ascertained. Further analysis of the velocity maps is then undertaken to examine the non-linear effects such as vortex shedding, internal and external hole interactions.

ACOUSTIC BEHAVIOUR AT TONE HOLES

Theoretical work by various authors [2, 3] showed that the acoustical behaviour of a woodwind instrument can be generally represented by a transmission line, with the effects of each tone hole represented by series and shunt impedances. Additional internal and external corrections due to the presence of the tone holes were experimentally investigated by Benade and Murday [4], Coltman [5] and Keefe [1]. The corrections were also theoretically determined using modal decomposition by Keefe [6, 7] and Dubos et al [8], which was supported by experimental measurements, and using a finite difference method by Nederveen et al [9]. Keefe showed in a detailed experimental investigation [1] that the internal and external interactions between tone holes are most important for large diameter holes separated by a short distance compared to the diameter of the main bore. He also showed that for a woodwind instrument under normal playing conditions, the strength of non-linearities generated by the sound fields is determined by the geometry and separation of the toneholes and can have very prominent effects on the tone produced by the instrument, especially for notes in the lower register.

EXPERIMENTAL METHOD

The apparatus used in this experiment can be seen in Figure 1. A Perspex tube, 500mm long, internal diameter 21mm, with a side hole of diameter 15mm located centrally along its length was mounted onto a loudspeaker and enclosed within a Perspex box to contain the seeding particles and to minimise disturbance of the air around the tube by external draughts.

Incense smoke particles were then introduced into the Perspex box and a sound field, generated by the loudspeaker, was applied. The frequency of the sound field was set to the first resonant frequency of the tube and the sound intensity was increased to a level at which an air jet was clearly seen exiting the tone hole. This corresponded to a sound pressure level of approximately 125 dB inside the main tube opposite the hole. The tone hole sound pressure level was measured at three positions; flush with outer wall of the tube hole and at distances of 6mm and 12mm inside the tone hole, using the probe microphone. Additional sound pressure level measurements were taken at the base of the tube using a pressure transducer.

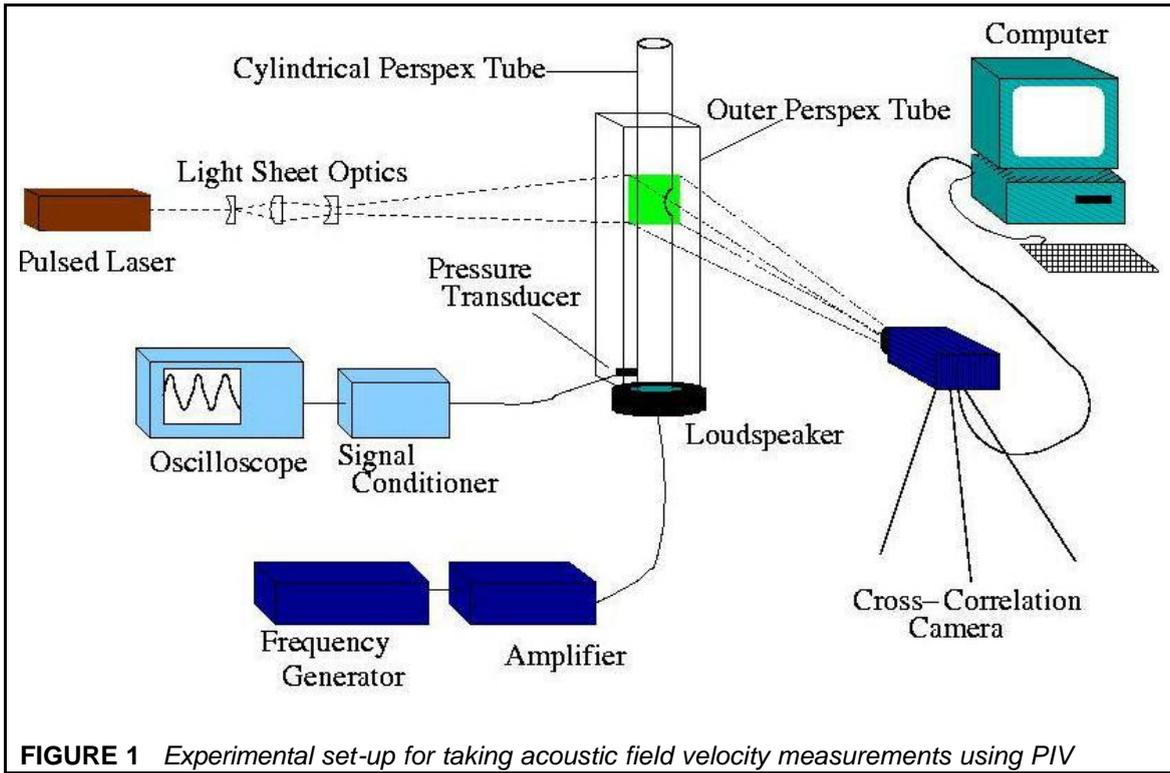


FIGURE 1 *Experimental set-up for taking acoustic field velocity measurements using PIV*

The beam from the copper vapour laser was optically expanded into a two dimensional light sheet of width 50mm and was projected through the tube axis. The timing box was used to synchronise the pulses generated by the laser with the exposure times of the digital CCD camera. The streaming pattern was allowed to stabilise and images of duration 15-30ns and separation 1ms were taken using the CCD camera and recorded onto a PC through an image capture device.

Changing the separation time between the two images allowed two velocity regimes to be measured; the acoustic particle velocity due to the to-and-fro motion of the fluid in the sound field, and our main concern in this paper, the slower non-zero mean motion generated due to viscosity in the fluid, known as the acoustic streaming velocity.

The acquired image pairs were cross-correlated using software on the PC to produce two-dimensional velocity maps. These maps were subsequently validated using a computational algorithm to remove spurious vectors, and contour maps of flow speed were plotted.

Measurements were taken at a range of frequencies on either side of the first resonant mode of the tube. This was repeated for two tubes of the same length but with two tone holes of diameter 15mm, separated by a centre-to-centre distances of 34mm and 27.6mm respectively, and mounted symmetrically on either side of the tube centre.

RESULTS AND DISCUSSION

Contour maps of flow speed with vectors corresponding to acoustic streaming velocities for the single tone hole can be seen in Figure 2. Figures 2(a) and 2(c) respectively show the jets produced for frequencies below and above resonance. Figure 2(b) shows the same configuration at resonance. As can be seen, the direction of the jet is strongly affected by frequency.

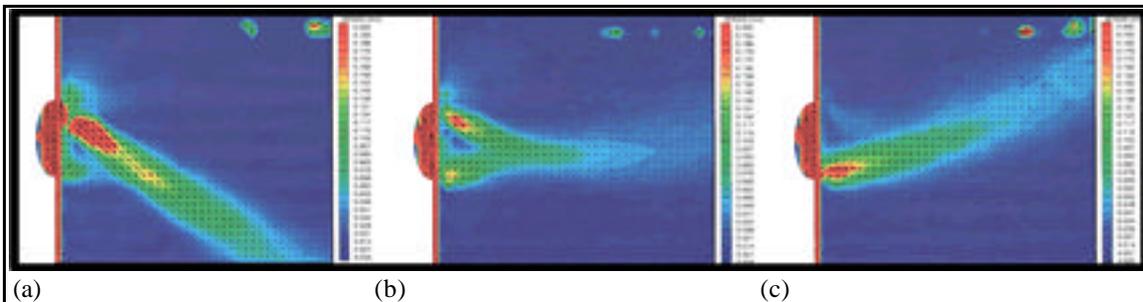


FIGURE 2 Contour maps of flow speed, with acoustic streaming velocities indicated, for a single tone hole at frequencies (a) $f < f_0$ (b) $f = f_0$ (c) $f > f_0$, where f_0 is the resonant frequency. The position of the tube is shown in white on the left of each map. Red areas represent 20 cm/s.

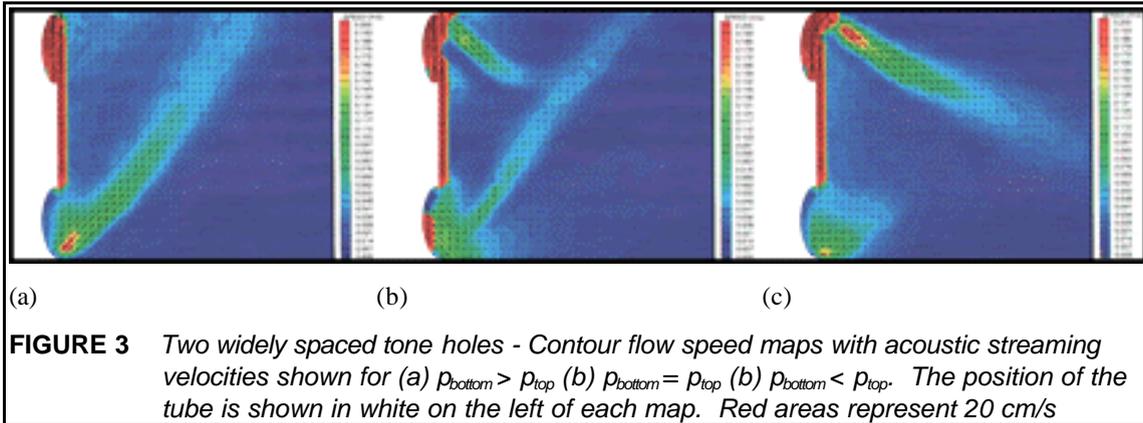


Figure 3 shows the contour maps of flow speed with vectors corresponding to acoustic streaming velocities for the case of two widely spaced tone holes. As can be seen in figure 3(a), a jet emanates out of the bottom hole for the case where the pressure in the bottom hole exceeds that in the top hole. The converse occurs in figure 3(c). Under resonance conditions the pressure in both holes is equal and a symmetrical flow pattern is observed (figure 3(b)).

Figure 4 shows the results of the sound pressure level measurements corresponding to the contour maps shown in figure 3. There are clearly two frequencies for which the pressure is equal in both the upper and the lower tone holes. The arrow in figure 4 marks the first of these

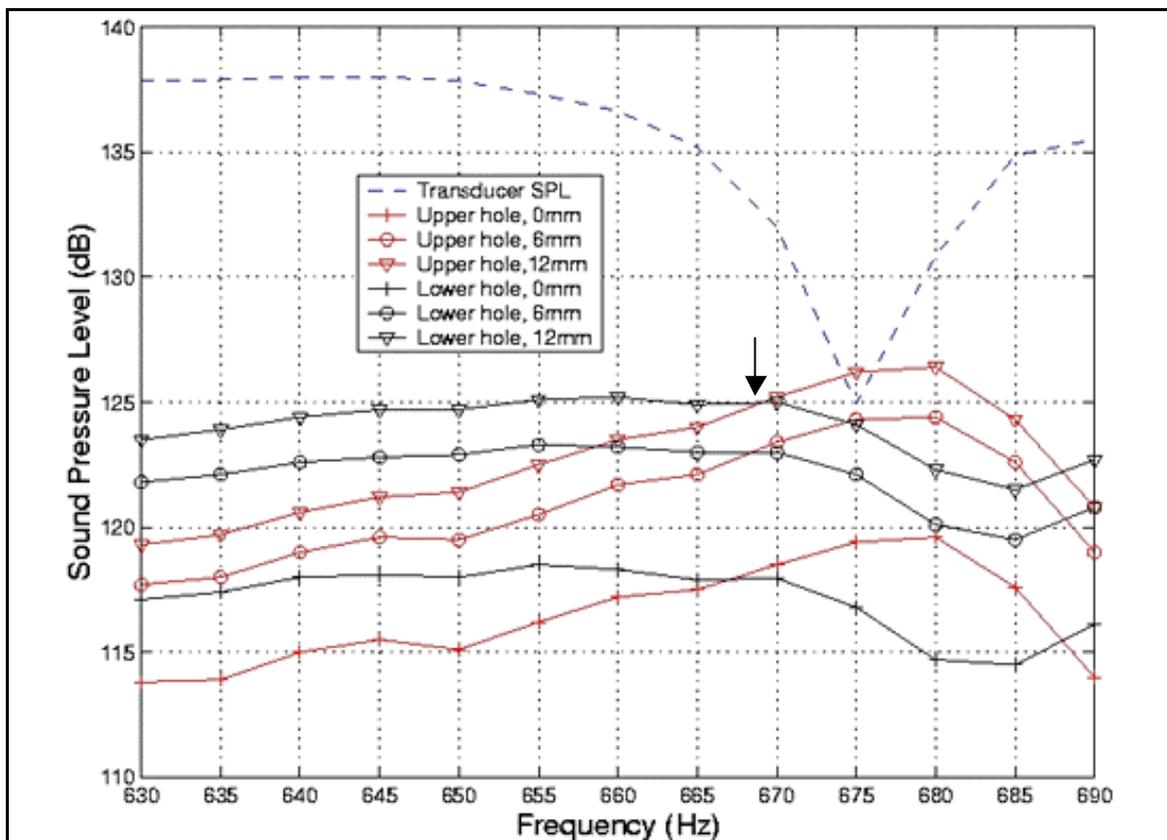


FIGURE 4 Plot of sound pressure level variation at the tone holes with frequency for the double tone holes with separation 34mm. The arrow indicates the frequency at which the pressure in the top and bottom holes are equal (see figure 3(b)).

and is the frequency at which the PIV map shown in figure 3(b) was taken. At lower frequencies than this the pressure is higher in the lower hole than the upper hole. For a small range of frequencies between the two points where the tone hole pressures are equal the pressure is higher in the upper hole than the lower.

These preliminary observations show that the jet produced by the single hole is affected by inter-hole interactions when a second hole is present and therefore the double tone hole configuration is not a direct extension of an array of single tone holes.

It is clear from these results that observations of acoustic streaming velocities are necessary to investigate the non-linearities and inter-hole interactions at high sound intensities such as those corresponding to the levels found inside a woodwind instrument under playing conditions. Further results will be presented and discussed.

ACKNOWLEDGEMENTS

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