PIV STUDY OF STANDING WAVES IN A RESONANT AIR COLUMN

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ABSTRACT

Particle Image Velocimetry (PIV) is a non-invasive, whole-field technique for visualising fluid flow. Images of a seeded flow are captured in rapid succession and analysed to produce a velocity vector map. Due to advances in digital camera technology, it has recently become possible to capture images sufficiently quickly to enable the measurement of acoustic particle velocities.

In this paper, PIV measurements of standing waves generated in an air column are presented and discussed.

INTRODUCTION

Particle Image Velocimetry (PIV) is a non-intrusive, whole-field technique used in fluid dynamics for flow visualisation. The method consists of capturing two images of an illuminated, seeded flow in rapid succession and analysing them to produce a velocity vector map. The analysis involves cross-correlating small regions, called *interrogation areas*, of the first image with corresponding regions of the second image. Each interrogation area correlation results in a displacement vector which can be converted to a velocity vector, assuming the time interval between images captures is known. Repeating for the whole image leads to a velocity vector map.

The particles used to seed the flow under investigation must follow the flow faithfully. When applying PIV to the measurement of acoustic fields in air, particles with a size of the order of 1ì m or less must be used. The particles must also have good scattering characteristics to ensure maximum image contrast in the illuminated region. Smoke particles fulfil these required conditions and have proved to be acceptable for seeding sound fields.

PIV measurements have previously been carried out to investigate acoustic streaming in an air column [1, 2]. Acoustic streaming is the generation of mean flow in a fluid disturbed by a sound field. In these investigations, an image capture rate of 33 frames per second was sufficient to measure the streaming velocities, which were found to be of the order of several mm/s.

To use PIV to measure the oscillatory motion of particles in acoustic fields, images must be captured at a much higher rate. For example, in a 1 kHz resonant sound field, to measure the particle velocity over 1/10th of an acoustic cycle requires an image capture rate of 10000 frames per second. That is, a time separation between images of 100 µs. Recent advances in high-speed imaging technology have now made it possible to use the technique to measure the fluctuating particle velocities found in sound fields. For example, Bamberger et al [3, 4] have used PIV to measure jet velocities in flute-like instruments.

In this paper, a PIV study of oscillatory particle motion in a resonating air column during one acoustic cycle is presented.

EXPERIMENTAL PROCEDURE

Figure 1 shows a schematic diagram of the experimental set up. A 620-mm long, vertically mounted, transparent duct of square cross-section (34mm x 34 mm) is seeded using smoke particles. The duct is rigidly terminated at the top end by a metal plate and coupled to a loudspeaker at the bottom end. The total air column (comprising the transparent duct and the coupling to the loudspeaker) has a first resonance frequency of 225 Hz. A laser sheet of width 5mm, produced by passing the beam from a 532 nm Yag-Nd laser through three cylindrical lenses (with focal lengths of 19 mm, 200 mm and 60 mm), is used to illuminate a region approximately half way up the air column. The square geometry of the duct reduces optical flare, which is a particular problem when illuminating a transparent curved flow passage. A *PCO DoubleShutter Sensicam* high-speed digital camera is focussed on the illuminated region.

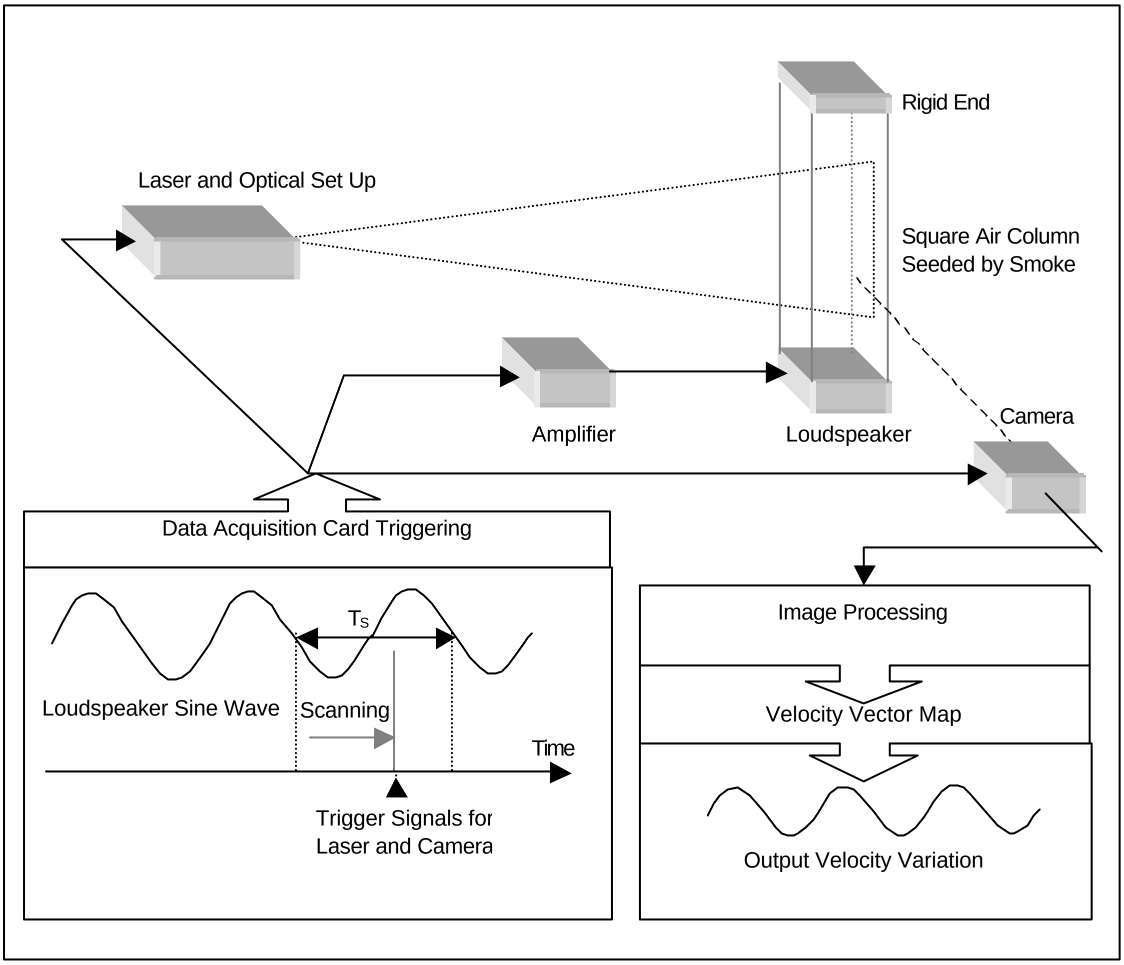

Figure 1. Schematic diagram of experimental set-up and analysis procedure.

This hardware set up is controlled by self-written software using a data acquisition card as the interface. The card simultaneously sends the following signals to the loudspeaker, laser and camera:

a. A 225 Hz sinusoidal electrical signal is amplified and used to drive the loudspeaker. (The period of the sine wave is T_s = 1/225 = 4.4 ms). The air column is excited at the first resonance frequency to maximise the amplitude of oscillation of the smoke particles half way along its length.

b. Two 100 µs duration voltage pulses separated by 200 µs are sent to the laser, causing it to flash twice.

c. The camera is triggered by a TTL signal resulting in the acquisition of two images. The TTL signal is synchronised with the voltage pulses sent to the laser, to ensure that the two laser flashes occur during the two exposures.

After triggering the hardware in the way described above, a pair of PIV images is stored digitally and cross-correlated to produce a velocity vector map.

A 2-mm diameter probe microphone, located at the rigidly terminated end, is used to monitor the sound pressure level in the air column during the PIV measurement.

The above procedure is repeated 22 times. After each repetition, the signals sent to the camera and laser are advanced by 200 µs relative to the signal sent to the loudspeaker. This ensures that 22 image pairs are captured covering one complete 4.4 ms cycle of the smoke particles' sinusoidal motion (see the Data Acquisition Card Triggering section of Figure 1).

RESULTS

Figure 2 shows six of the twenty-two velocity vector maps measured during one 4.4 ms cycle of the particles' motion. The sound pressure level in the air column was 160 dB (re 20 µPa). The sequences of the figure show that the variation in velocity is clearly non-sinusoidal. This can be seen more clearly in Figure 3, which plots the change in acoustic particle velocity during one acoustic cycle. The plotted values were determined by averaging the velocity vectors in each vector map.

Figure 4 shows the result of performing an FFT on the velocity variation of Figure 3. The FFT reveals that, in addition to a 225 Hz component, odd harmonics of this frequency are also present. The even harmonics are not seen at this measurement region (half way along the air column) because it coincides with a velocity nodal position common to all even modes.

The observed harmonic distortion was found to be due to the loudspeaker behaving non-linearly. The experiment was repeated with the amplification of the electrical driving signal reduced (the new sound pressure level in the air column was 150 dB). Figure 5 shows six of the resulting vector maps. The variation in velocity is now much more sinusoidal, a fact that is clearly demonstrated in Figure 6

CONCLUSIONS

The PIV technique has been successfully applied to a resonant air column to measure the changes in particle velocities during one acoustical cycle. The ability of the technique to measure the sinusoidal variation in velocity in a linearly driven air column has been demonstrated. In addition, harmonic distortions introduced when the air column is driven non-linearly have been detected using the technique.

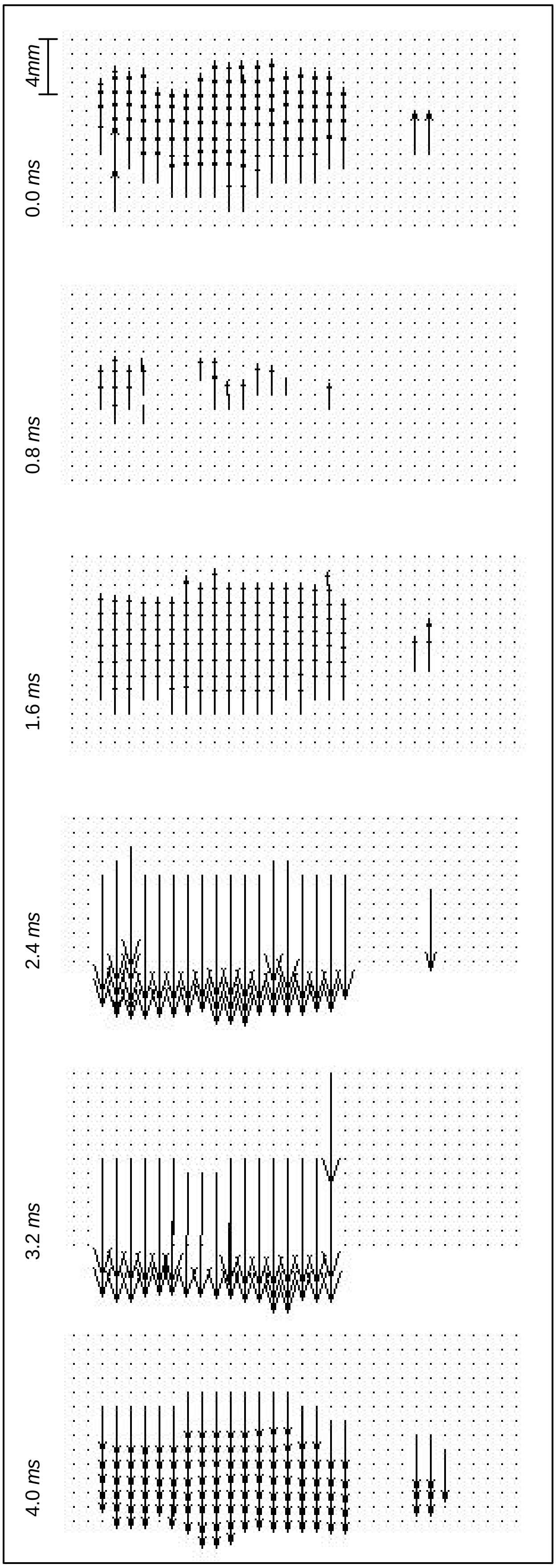

Figure 2. Selection of six velocity vector maps taken during one 4.4 ms cycle (SPL = 160 dB).

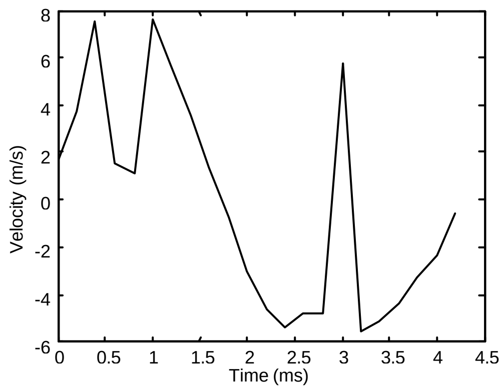

Figure 3. Average particle velocity within illuminated region during one 4.4 ms cycle (SPL = 160 dB).

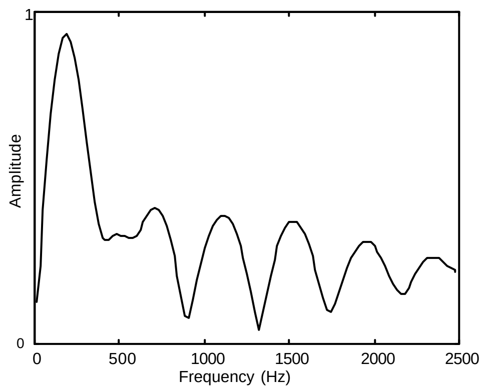

Figure 4. FFT of average particle velocity during one 4.4 ms cycle (SPL = 160 dB).

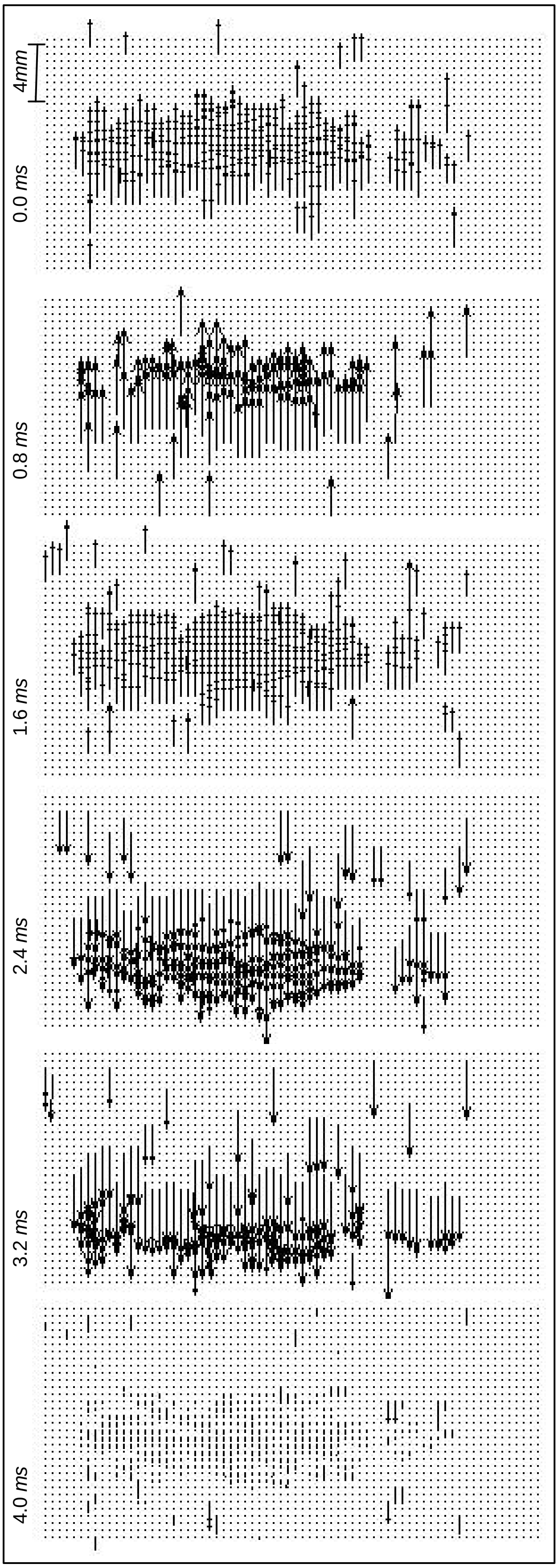

Figure 5. Selection of six velocity vector maps taken during one 4.4 ms cycle. (SPL = 150 dB).

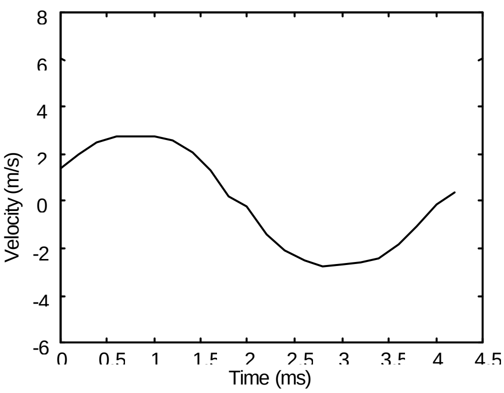

Figure 6. Average particle velocity during one 4.4 ms cycle
(SPL = 150 dB).

REFERENCES

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