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THE MEASUREMENT OF HIGH INTENSITY SOUND BY OPTICAL TECHNIQUES

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ABSTRACT

Two optical techniques for measuring sound are assessed; Laser Doppler Anemometry (LDA) using photon correlation signal analysis and Particle Image Velocimetry (PIV). LDA is a point technique, whereas PIV in principle gives complete intensity fields. However LDA turns out to have a wider dynamic range; down to about 60 dB at low frequencies.

1. INTRODUCTION

Traditional techniques of sound measurement are based around the detection of pressure fluctuations using microphones. This is the natural approach since air particle velocities and displacements are microscopically small. If velocities are required then they are inferred from the pressure readings. In the case of high sound intensities, however, direct measurement of velocities become a feasible proposition, since displacements can be quite large; sometimes of the order of a millimetre. This article evaluates two optical techniques for sound measurement which are under investigation at Edinburgh and which have been used with some success in specific laboratory situations. The first method is Laser Doppler Anemometry (LDA) using photon correlation techniques for signal analysis and the second method is Particle Image Velocimetry (PIV).

The techniques to be described have a number of inherent advantages over the microphone. Firstly they are nonintrusive. This can be a major advantage in certain industrial situations, where in some cases it may be extremely difficult to insert even miniature microphones into the sound field. Secondly, if the velocity vector is known, together with the pressure and the correct phase, then the full three-dimensional sound field can be defined. Thirdly, they do not require calibration which, at high intensities, can be a major probelm with microphones.

The output from a pressure gradient microphone, e.g. a ribbon microphone, can be used to predict the velocity but the signal is then a function of frequency and phase lags occur which are often difficult to quantify. A number of attempts in the past have been made to measure acoustic velocities more directly using non-optical probes. An example is the use of a hot wire anemometer, commonly used for flow measurement. The problem here is that in an acoustic field the cooling air stream is not swept continuously downstream but instead oscillates to and fro across the wire so calibration becomes almost impossible. Hot wires and similar instruments are also intrusive and extremely delicate.

2. RELATIONSHIP BETWEEN AMPLITUDE AND PRESSURE

For plane waves and power in W m^{-2} is related to the mean square velocity $\overline{v^2}$ by the expression

$$P = z\,\overline{v^2} \qquad (1)$$

where z is the characteristic impedance, equal to 415 rayl for air at 20C.

The intensity in dB is

$$I = 10 \log 10^{12} P \qquad (2)$$

giving

$$\overline{v^2} = \frac{1}{z}\, 10^{(0.05\,I-12)} \qquad (3)$$

and the amplitude of the sinusoidal velocity fluctuation is then

$$a = \sqrt{2\,\overline{v^2}} = 0.0694 \times 10^{(0.05\,I-6)}\,. \qquad (4)$$

For an acoustic frequency the amplitude of the corresponding displacement is simply a/ω or

$$x = (0.0694/\omega)\, 10^{(0.05\,I-6)}\,. \qquad (5)$$

3. LASER DOPPLER CONFIGURATION

LDA is a point measuring techniques. There are many possible optical configurations (1). In the simplest of these a laser beam is split into two and then focused to the point where the sound is to be recorded. Light scattered by minute particles in the air is then collected by a photodetector (Fig. 1).

Interference between the two beams at the measuring point causes fringes to be formed whose spacing is

$$d = \lambda / (2 \sin \theta) \qquad (6)$$

where θ is the half angle between the beams and λ is the wavelength of the laser illumination.

The most commonly used method of signal analysis in the standard flow situation is frequency tracking. The frequency tracker locks on to the instantaneous frequency, which is proportional to the velocity and so the complete velocity record is obtained. The frequency to velocity conversion factor is

$$D = 2\,\pi/d \qquad (7)$$

In the acoustic situation scattering centres oscillate back and forth through the fringes and displacement amplitudes may be only a few fringe spacings or even a fraction of a fringe spacing. This makes frequency tracking impossible. A further problem is that in air the scattering levels may be extremely low. The photon correlation technique for signal analysis overcomes both of these difficulties. It gives time averaged correlograms which may contain multiple frequency components and is also extremely sensitive optically, to the extent that adequate signals can usually be obtained using very low laser powers.

The simple optical configuration shown in Figure 1 only gives one component of velocity. However, more complex arrangements are possible whereby two or even three components can be measured simultaneously. These generally use three separate beam colours and matching filters on the detectors, or alternatively different polarisations of the laser beams.

4. FORM OF THE CORRELATION FUNCTION

The instantaneous velocity of the air is

$$v = a \sin(\omega t) \qquad (8)$$

where ω is the frequency and a the velocity amplitude.

A general expression for the form of the correlation function is given in (2) but for the limiting case where there are a large number of fringes the simplified form (3) is

$$R(\tau) = J_o\left(\frac{2Da}{\omega}\, sin\left(\frac{\omega\tau}{2}\right)\right) \qquad (9)$$

where τ is the correlation lag and J_0 is the Bessel Function of order zero.

The manner in which Eqn. 9 is applied can be seen with reference to Fig.2, which is a sketch of how $R(\tau)$ appears for typical oscillation amplitudes. The two points marked with a * indicate the positions where the first minimum of the Bessel Function appear. From either the first or the second of these the time lag $\Delta\tau$ at which this occurs may be measured. The velocity amplitude is then given by (3).

$$a = \frac{3.832}{D\,\Delta\tau} \qquad (10)$$

If it is possible to locate the position of the first minimum on the correlogram then the velocity amplitude can be calculated.

If more accurate velocity amplitudes are required then two alternative approaches to analysing the correlograms are possible. Firstly, a curve fitting program can be implemented applying Eqn. 9 in which both D and ω are generally known, leaving the unknown amplitude (a) as the only free parameter. An alternative is to fourier transform the correlogram. The probability density of a sine wave with zero mean is a double peaked function symmetrically places about the zero axis. Therefore the power spectrum shows up as a single peak from which the frequency, and hence the velocity amplitude, may be read.

By gating the photomultiplier in an appropriate phase relationship to a sound pressure measurement it is also possible to obtain the complete velocity record throughout the cycle (4,5). This is particularly useful for the measurement of acoustic impedance (6).

5. COMBINED FLOW AND SOUND FIELDS.

A practical situation occurs when a sound field is combined with a mean flow. In this situation scattering centres have an oscillatory motion superimposed on to a mean velocity. The form of the correlation function has already been calculated for a non-acoustic application (1). In essence it is a cosine wave modulated by a zero order Bessel Function.

If there are n complete cycles between zero lag and the first minimum of the Bessel Function, then the amplitude of the velocity fluctuation is given by

$$a = 0.0383V/n \qquad (11)$$

where V is the constant velocity which has been superimposed onto the sound field.

Fourier transformation of the correlogram leads to a double peaked spectrum of the form shown in Fig. 3. The mean value of the two peak frequencies gives the superimposed velocity, after application of Eqn. 7.

6. PARTICLE IMAGE VELOCIMETRY

PIV is a flow mapping technique which is in essence a development of simple flow visualisation. The region where measurements are to be recorded is seeded with scattering particles, typically from a fine aerosol spray or smoke generator, and then illuminated with a sheet of pulsed laser light. In the system developed at Edinburgh (Fig. 4) the pulsations are generated by deflecting a continuous wave laser off of a rotating multi-sided mirror (7). The region is photographed with a conventional camera, with the shutter speed adjusted such that three or four sweeps of the laser are captured within the one exposure.

For standard fluid flow applications each scattering centre produces a discrete set of points on the negative, whose spacing is proportional to the velocity. There are various different approaches to analysing the film but the one that the author has adopted relies on generating the correlation function for the intensity through a combination of optical and digital fourier analysis (8). The negative is probed by a low power laser which produces a fringe pattern aligned in the flow direction at the point in question. The spacing of the fringes is inversely proportional to the spacing of the scattering centre images on the film. This is captured by a CCD camera and fourier transformed digitally using a 2D FFT routine. The correlation function produced in this way has two distinct peaks whose position give the magnitude and orientation of the velocity vector. The Edinburgh analysis facility automatically scans the films and produces velocity vector maps, typically on a 50 x 50 grid.

PIV has already been used successfully to study acoustic streaming, i.e. the mean motions generated by high intensity sound fields (9). In performing these experiments it was observed that the shape of the fringe pattern altered with the acoustic intensity. By observing this shape it should therefore be possible to measure both the acoustic intensity and the mean velocity simulaneously. The effect on the fringes is shown schematically in Fig. 5. It is assumed here that the exposure time is greater than one whole period of the acoustic oscillation. The image of a single particle then shows as a streak whose length is equal to twice the amplitude of the displacement. The streak is dumbell-shaped, since the scattering centres spend more time at the ends than at the centre. For two exposures the fringe pattern is either squashed or elongated in the direction of the fringes, depending on whether the acoustic waves run in the direction of the mean flow or are perpendicular to it (Fig. 5). The author is planning tests to assess the extent to which this effect can be used for quantitatively mapping the acoustic field.

7. LOWR LIMIT OF APPLICATION

Both of the techniques described can only be used at high intensities, since displacement amplitudes need to be of significant magnitude for optical detection to be feasible. The lowest intensity which can be measured with accuracy is now estimated.

(a) LDA:

An examination of Eqn. 9 shows that at high intensities the Bessel Function term dominates, in which case Eqn. 10 can then be used to evaluate the acoustic amplitude. At high frequencies or low intensities, on the other hand, the sinusoidal term starts to dominate until a situation is reached where the correlogram is entirely determined by the sinusoidal component. Practically speaking, this means that scattering centres are only passing over a small fraction of a fringe; the correlogram is then a cosine wave whose frequency is that of the acoustic oscillation and no amplitude can be determined from its shape. The limit is now evaluated explicity.

The lag time of the first minimum of the Bessel Function must be less than the lag time to the first minimum of the sinusoidal oscillation i.e.

$$\frac{3.832}{Da} \leq \frac{\pi}{\omega} \qquad (12)$$

or

$$\frac{a}{\omega} = \frac{3.832}{\pi D} \tag{13}$$

This may be interpreted more directly in terms of the fringe spacing. Thus

$$x = \frac{a}{\omega} = \frac{3.832}{\pi D} = \frac{3.832d}{2\pi^2} \tag{14}$$

or

$$x = 0.194\ d. \tag{15}$$

From Eqns. 5 and 15

$$x = \frac{0.0694}{\omega} 10^{(0.05\,I-6)} = 0.194\,d \tag{16}$$

The smallest practical fringe spacing obtainable is the laser wavelength when the angle between the focused beams is 60°. Thus writing $d = \lambda$ and $\omega = 2\pi f$, Eqn. 16 becomes

$$\frac{0.0694}{2\pi f} 10^{(0.05\,I-6)} = 0.194\,\lambda \tag{17}$$

After rearrangement this gives the smallest intensity that can be measured as

$$I = 145 + 20\log(f\lambda)\ \text{dB} \tag{18}$$

(f is the optical frequency and λ is the laser wavelength)

As an example, take a laser wavelength of 600 nm, representative of red light. For an acoustic frequency of 1 kHz the limiting intensity is then 81 dB. With the acoustic frequency is reduced to 100 Hz the limit goes down to 61 dB.

(b) PIV:

For PIV the acoustic amplitude must be at least equal to the particle radius (r), otherwise significant streaking will not occur. Thus, from Eqn. 5

$$r = \frac{0.0694}{2\pi f} 10^{(0.05-6)} \tag{19}$$

or rearranging

$$I = 159 + 20 \log (r f) . \qquad (20)$$

As an example take scattering particles of diameter 10μm. At 1 kHz this gives the minimum intensity as 113 dB. At 100 Hz, on the other hand, this drops to 93 dB.

8. CONCLUSIONS

LDA is only a point measuring technqiue but has a much wider range of intensity levels over which it may be applied, with a lower limit of about 60 dB. The PIV method, on the other hand, can potentially be used to give full acoustic maps but can only be used for intensity levels well above 90 dB.

9. REFERENCES

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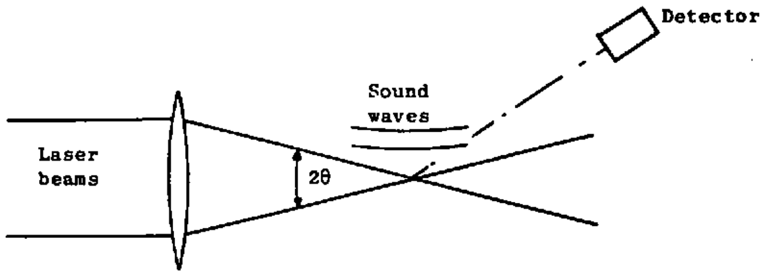

Fig. 1. LDA measuring system

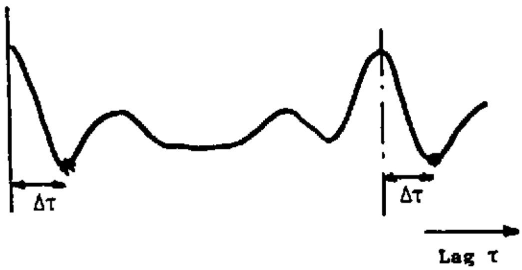

Fig. 2. Typical correlogram in an acoustic field

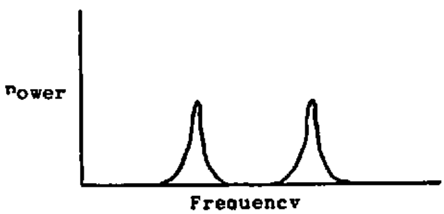

Fig. 3. Double peaked spectrum for combined flow and acoustic fields.

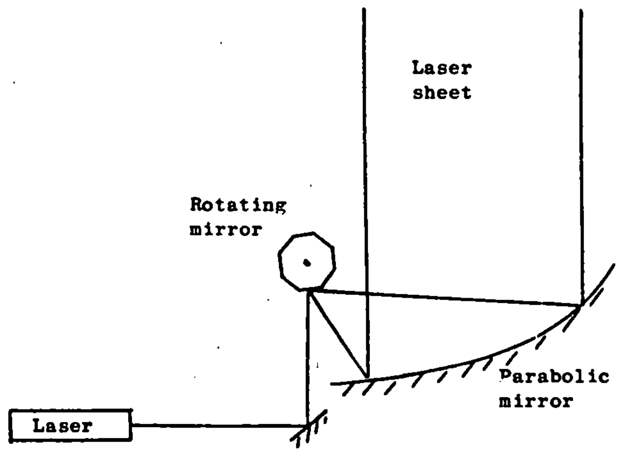

Fig. 4. Scanning beam PIV illumination system used at Edinburgh.

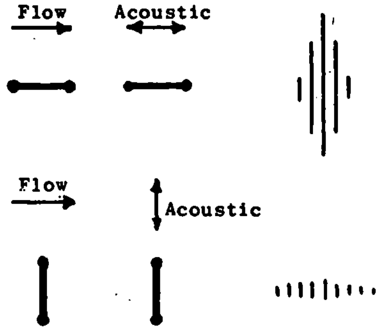

Fig. 5. Fringe patterns produced in PIV analysis for combined flow and acoustic fields.