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LASER MEASUREMENT OF RANDOM AND PERIODIC SOUND FIELDS

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ABSTRACT

In this paper the application of Laser Doppler Anemometry (L.D.A.), which is both absolute and non-instrusive, to the measurement of acoustic particle velocities is described. Reasons for the photon correlation method of signal analysis are outlined and a gating technique, which allows the relative phase of the velocity and pressure to be deduced is described.

INTRODUCTION

To obtain a full description of a sound field at any point the pressure, velocity and phase relationship between the two must be determined. The pressure is quite easily measured using microphones but velocity measurements are considerably more difficult. Several methods have been proposed of which one of the more recent is the pressure gradient microphone [1,2]. Such methods suffer however from the need for calibration, the application of empirical correction factors depending on distance from the sound source etc. and the fact that they intrude into and hence distort the field.

The technique of L.D.A. though can overcome these difficulties [3,4]. It provides an absolute measurement of the velocity and, since it relies on the scattering of light from very small particles suspended in the medium under investigation, it is essentially non-intrusive. The actual experimental arrangements of L.D.A. systems are numerous, as are the methods for analysing the intensity fluctuations of the scattered light [5]. In this work the Gaussian crossed beam setup employing the photon correlation method of signal analysis is used. The photon correlation method is best suited to the low density of scattering particles generally available in air flows and also seems to be more robust and versatile than say frequency tracking systems.

In this paper we present results for the form of the correlation function due to periodic, and band limited noise fields and discuss the form of the correlation function when the Doppler signal is gated.

Measurements made in a travelling wave tube are presented and compared to those made with a microphone. Further extensions of the work are proposed and limitations of the technique discussed.

LASER MEASUREMENT OF RANDOM AND PERIODIC SOUND FIELDS

REVIEW OF L.D.A. TECHNIQUE

L.D.A. relies on the scattering of light from small particles suspended in, and faithfully following the motions of the fluid under investigation.

In the Guassian crossed beam setup light from a laser is split into two beams which are then focussed down to a point in the fluid (see Fig. 1). At he intersection of these two beams a fringe pattern is set up, as shown.

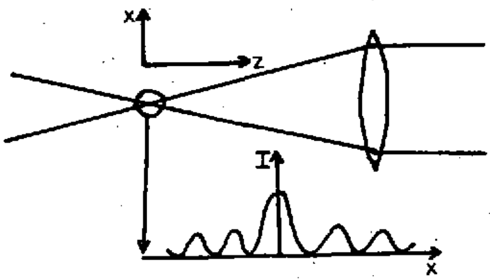

Figure 1. Production of L.D.A. fringe pattern. I is light intensity.

Particles passing through this pattern will scatter light in a manner depending on their velocities and the geometrical form of the fringe pattern. Thus it is possible to deduce the fluid velocity by collecting the scattered light and analysing it. The method of analysis is dictated by the density of seeding particles in the fluid, parameters of the flow to be measured and various other factors. Photon correlation (which analyses signals in the time domain) is found to be easy to use though other workers have made measurements using frequency analysis systems [3].

THEORY

In this section is it stated how the velocity and average velocity amplitude of the sound field can be deduced from the observed characteristics of the correlation function. The effect of gating (to determine the phase relationship between the pressure and velocity fluctuations) on the correlation function is also described.

<u>Periodic Sound Fields</u>
It has already been shown [4] that the correlation function due to a sinusoidal oscillation with no mean flow takes the form

$$R(\tau) = A + B\,J_0(a_m D\tau) \qquad (1)$$

where A and B are constants, J_0 is the zero order Bessel function a_m is the velocity amplitude of the vibration, D is the frequency to velocity conversion factor and τ is the lag time on the correlator. D depends only on the wavelength of the laser light used and the geometry of the L.D.A. system so it is possible to deduce the velocity amplitude of the sound field at any point by measuring some parameter of the autocorrelation function (we use the first minimum) and using the tabulated values of the Bessel function.

Another approach is to use the autocorrelation function for frequency modulation which is essentially what is happening here - the sinusoidal intensity distribution of the fringe pattern due to the laser beams is being modulated by the sinusoidal oscillations of the sound field. This yields [6]

$$R(\tau) = \frac{A_0}{2} J_0 \left(2\mu \sin \frac{\omega_m \tau}{2}\right) \cos \omega_0 \tau \qquad (2)$$

Where A_0 is the amplitude of the frequency modulated signal, μ is the modulation index, ω_m is the frequency of the modulating signal and ω_0 is the carrier frequency. For no mean flow ($\omega_0 = 0$) and for

$\frac{\omega_m \tau}{2} << 1$ equation (2) reduces to equation (1). However the latter

condition does not always obtain in practice and affects the correlation function in the regimes of low intensity and high frequency. Discussion of this and possible remedies will be deferred until the conclusion.

Noise Fields.

The effect of narrow band noise on the autocorrelation function was studied because of the occurrence of this type of noise in many situations (e.g. resonance set up in ducts by noise). The correlation function was deduced by integrating the correlation function for a single tone sound field over the probability density function for the amplitude distribution of band limited white noise [7]. This gave the form of the autocorrelation function as a Gaussian and the average velocity amplitude of the sound field to be deduced as

$$\bar{a}_m = \sqrt{\frac{\pi}{2(D\sigma_n)^2}} \qquad (3)$$

where σ_n is the standard deviation of the correlogram.

LASER MEASUREMENT OF RANDOM AND PERIODIC SOUND FIELDS

The gating technique

To implement the gating technique the signal from a microphone in the sound field is fed to a microcomputer which supplies a pulse of preset width at a preset delay time from the zero upcrossings of the signal. These pulses are then fed to the photomultiplier and only for their duration is the Doppler signal analysed. Thus, by varying the delay time, the velocity at different portions of the acoustic cycle is sampled. Furthermore, by incorporating a frequency or phase shifting device into the optics the sign of the velocity can be deduced. This would then allow the phase relationship between the velocity and pressure to be determined.

The gating however affects the correlogram by causing it to be damped and ride on a sloping base line [8]. The degree of damping is increased as the pulse width is decreased and generally some compromise must be reached between damping of the correlogram and velocities to be sampled.

APPARATUS

A schematic diagram of the apparatus is shown in figure 2.

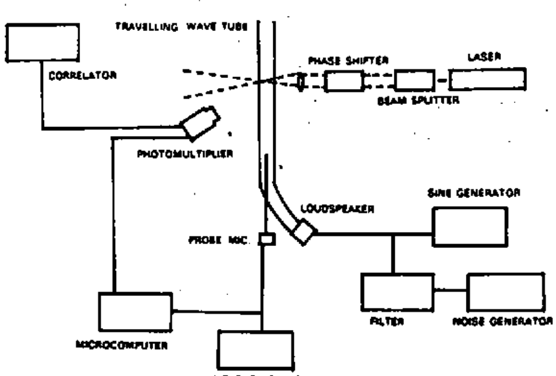

Figure 2. Diagram of apparatus.

The sound field is fed into a tube of length 1.5 m, diameter 2 cm, the final metre of the tube being filled with absorbing material to prevent the reflection of sound and hence the production of standing waves. A probe microphone could be inserted into the tube to monitor the sound field and thus make comparisons with the laser measurements. This arrangment was chosen because of the particularly simple relationship between the pressure and velocity fluctuations. The sound field could be chosen as either single tone or band limited white noise.

On the optical side a 32 mW He-Ne laser was used. After splitting and passing through a phase shifter the beams were focussed down into the tube from a separation of 2 cm using a 200 mm focal length lens. A small quantity of tobacco smoke was generally introduced into the tube for seeding purposes.

MEASUREMENTS AND RESULTS

Periodic Sound Fields

To measure the velocity amplitude of a single tone sound field the microcomputer gating system and the phase shifter were made inactive. A sound frequency of 1260 Hz was used, the probe microphone having been calibrated at this frequency to an accuracy of about 0.5 dB. Figure 3 shows a typical correlogram and compares its estimate of the velocity amplitude to that of the probe microphone. It was found that over the range of sound intensity from about 95 dB to 120 dB the L.D.A. system and probe microphone agreed with each other to within about 5%.

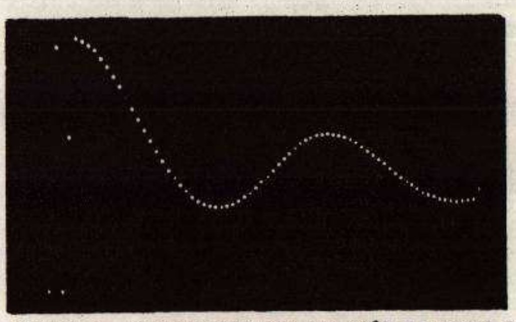

Figure 3. Correlogram due to 1260 Hz sound field.
Velocity amp from correlogram = 80.4 mm/sec.
From probe mic. = 80.6 ± 2 mm/sec. τ = 2μs.

Band limited noise field

For these measurements white noise was filtered about 1260 Hz and passed into the tube. A typical correlogram is shown in figure 4. These measurements showed rather more deviation than those for the single tone case, but this would have been expected considering the difficulty of estimating the standard deviation of the correlogram, the irregular pressure fluctuations in the tube and the fact that the microphone response is non-linear over frequency. All measurements however agreed to well within 10%.

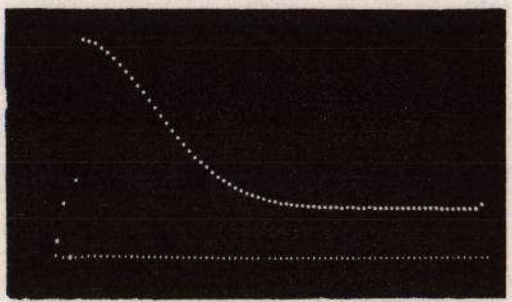

Figure 4. Correlogram due to noise filtered about 1260 Hz.
Average velocity amp. from correlogram = 51.2 mm/sec.
From probe mic. = 49.1 mm/sec. τ = 2μs.

Gating the sound field

These measurments followed the procedure outlined in the theory section. The sound frequency was again 1260 Hz and the phase shifter was set at 50 kHz. This later provided a velocity pedestal of 0.317 m/sec against which to measure the velocity at any particular position in the acoustic cycle. Figure 5 shows an oscillogram of the pressure and gating pulses while figures 6(a) and (b) show correlograms obtained using different delay times. Measurments such as these allowed the velocity time history to be plotted as in Figure 7. As can been seen the graph indicates a velocity ampliutde of about 85 mm/sec while measurements with ungated correlograms and the probe microphone indicated velocity amplitudes of 86 mm/sec and 85 mm/sec respectively. It is encouraging that the three procedures show such close agreement.

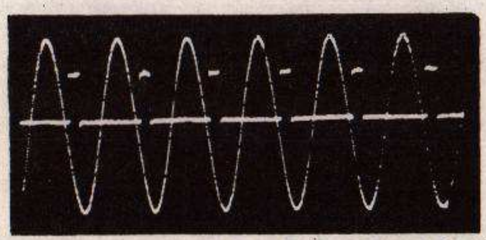

Figure 5. Gating pulses and sinusoidal pressure fluctuation.
Delay time = 400 μs. Pulse width = 100 μs.

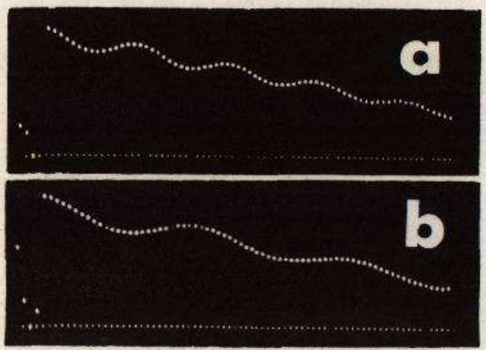

Figure 6. Gated correlograms for different delay times in 1260 Hz cycle.
Frequency shift = 50 Hz. τ = 1μs. Pulse width = 100 μs.
(a) Delay = 300 μs. (b) Delay = 700 μs.

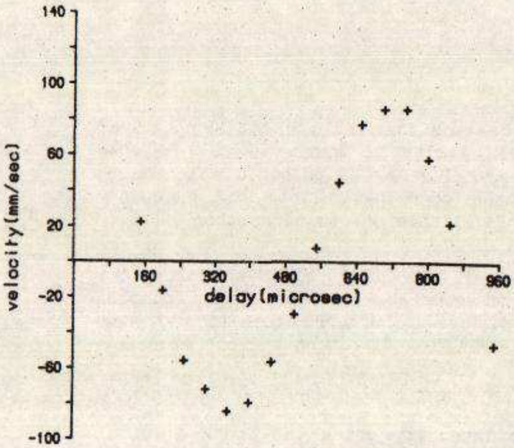

Figure 7. Velocity vs. delay time using gating technique.

DISCUSSION

It has been seen that L.D.A. can provide accurate measurement of acoustic velocity flutuations in the regime of intensities from about 90 dB to 120 dB. In itself this is quite useful but, as mentioned earlier, the method begins to fail at lower intensities and higher frequencies (- 3 kHz). This is due to the $\omega_m\tau/2$ term in equation 2. For example, if intensity is low then the correlator lag time must be increased so that the first minimum of the Bessel function can be measured. This causes the correlogram to become modulated by the sin function (see fig. 8) and hence makes it difficult or impossible to estimate the velocity amplitude. This effect can be reduced to some extent

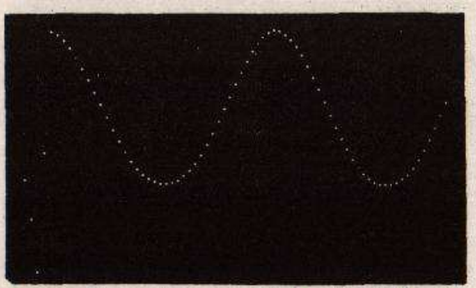

Figure 8. Correlogram obtained with τ = 20 µs.

by altering the optical arrangement (increasing the angle of intersecton of the beams) which would decrease the lower limits to about 80 dB. Higher frequencies have a similar effect on the correlogram. A possible solution to these problems may be tranformation of the correlogram into the frequency domain, a facility which is not at present available on our correlator.

It is imagined however that the technique will be of interest to laboratory acousticians and present research is directed towards measuring complex acoustic impedances using the gating technique. Further extensions of the work include the investigation of superimposed flow fields on the correlogram.

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