FLOW OVER A BLUNT FLAT PLATE

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Introduction

It is now recognised that a high Reynolds-number flow around a bluff body separates from the leading edge corner, reattaches downstream and gives rise to regions of concentrated vorticity embedded in irrotational fluid. It has been also found that with such a flow the rate of heat transfer can be as much as 50% greater than that observed with an attached turbulent boundary layer [1].

There have been a number of papers arising from both numerical and experimental studies that have sought to further understand the mechanisms of improved heat transfer and the nature of the instantaneous flow velocities, [2,3,4]. Some of these studies have shown that the reattachment length can be reduced by changing the leading edge geometry, [5], by inclining the plate to the direction of flow, [6], or by the application of sound across the flow, [7]. Using the application of sound [8] it was found that the mean rate of heat transfer increased as the reattachment length was reduced, whilst [7] and [9] have shown that the point of reattachment of the separation bubble oscillates and that a large scale vortex is shed from the separation bubble each acoustic cycle.

Our studies, both numerical and experimental [10], have shown that at some sound pressure levels there is a strong tendency for the large scale vortices to pair. Our objectives are to determine the instantaneous flow velocities, the flow streamlines and to examine the mechanisms of heat transfer under these conditions. It is proposed to use LDA equipment and to phase relate the sampling to the acoustic cycle. Preliminary work has been carried out using hot-wire probes and this paper presents the findings that relate to the large-scale structures in the third or spanwise direction.

Experimental Apparatus

The major component of the test apparatus is a small blow down open jet wind tunnel, Fig.1. The centrifugal fan is powered by a direct current electric motor with variable speed thyristor control. A wide angle diffuser containing four perforated plates connects the fan outlet to a settling chamber which contains a honeycomb and four nylon screens. Air leaving the settling chamber is passed through an 8 to 1 contraction to create a 244mm square open jet working section.

The maximum velocity at the contraction outlet was $15ms^{-1}$ and the profile uniform, within 1%, between the boundary layers, approximately 5mm thick. The centre line longitudinal relative turbulence intensity is 0.3% with spectral components less than 100Hz. The major spectral component occurs at the rotational frequency of the fan. The total volume flow was monitored using a British Standard nozzle connected to the fan inlet.

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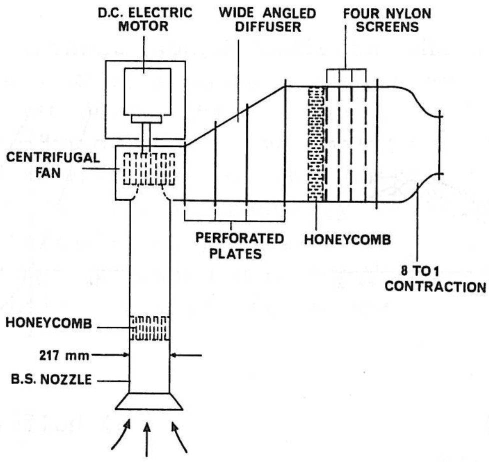


Fig.1 Open jet wind tunnel

The square edged test plate, 13mm thick, 135mm span and 130mm chord, was machined from a block of aluminium. The plate was located midway between the speakers, Fig. 2, and the plate/speaker assembly mounted on a machine table that allowed precise traversing of the assembly in each of the three major axes. The speakers were positioned 350mm apart and connected in anti-phase to generate the equivalent of an acoustic Parker β-mode near the plate [7]. This generated a maximum sound pressure level midway between leading and trailing edges which resulted in zero acoustic velocity at the mid-point of the plate and a maximum acoustic velocity at the leading and trailing edges. Glass endplates at the spanwise extremities ensured a two dimensional sound field.

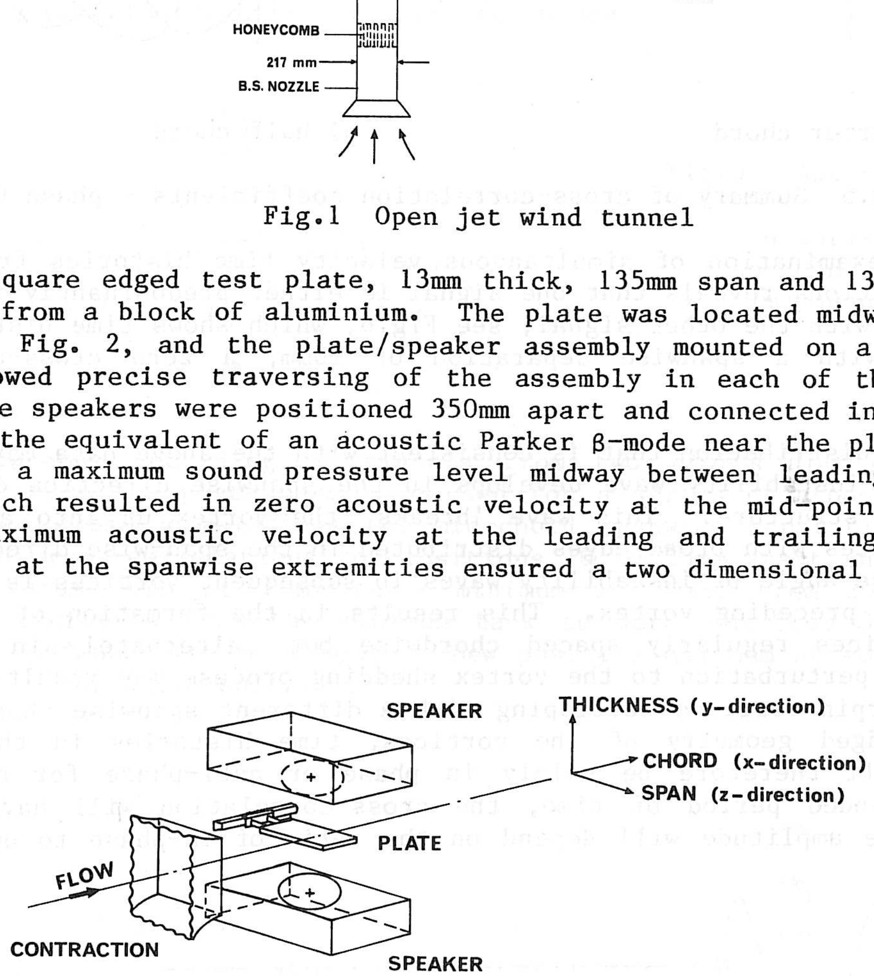
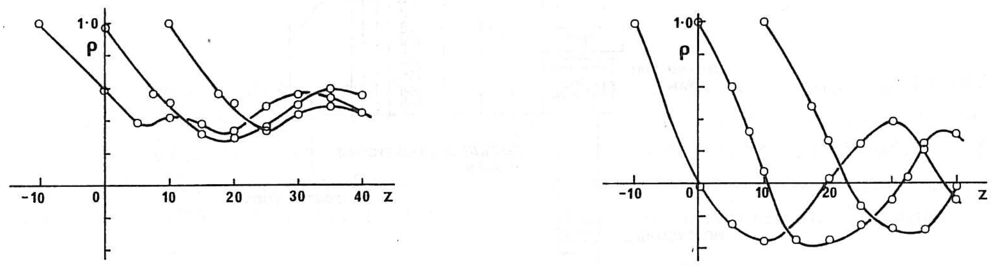


Fig.2 Plate and speakers

The fluctuating velocities were measured using single hot-wire probes which were aligned parallel to the leading edge and at right angles to the flow direction. The fluctuating signals from these probes were band passed, 10-3000Hz, and digitised at 9000Hz concurrently with the data required to determine the mean flow parameters. The data were subsequently processed on a PDP 11/44 mini-computer.

The experimental data presented in this paper were obtained with a mean freestream velocity, upstream infinity, of approximately 8ms^{-1}. The probes were held at a height of 13mm above the plate with one fixed relative to the tunnel outlet and the other fixed relative to the plate/speaker assembly. The applied sound frequency was held at 135Hz and the sound pressure level set to 115dB just above the plate surface at its mid-point.



a) quarter chord b) half chord

Fig.5 Summary of cross-correlation coefficients - phase 0

Careful examination of simultaneous velocity time histories from any two spanwise locations reveals that one signal is either predominantly in-phase or out-of-phase with the other signal, see Fig.6, which shows time histories from two probes with a spanwise separation of 10mm, a zero cross-correlation condition.

A vortex distribution that is consistent with the above data may emerge as follows. An instability wave develops in the spanwise direction of a large-scale vortex structure. This wave 'breaks' the vortex up into a number of hairpin vortices with broad edges distributed in the span-wise direction. The spanwise phase angle of instability waves in subsequent vortices is set by the phase of the preceding vortex. This results in the formation of a train of hairpin vortices regularly spaced chordwise but alternately in anti-phase spanwise. A perturbation to the vortex shedding process may result in another train of hairpin vortices developing with a different spanwise phase. Due to the broad edged geometry of the vortices, time histories in the spanwise direction will therefore be solely in phase or anti-phase for each train. Over an extended period of time, the cross-correlation will have no phase shift and the amplitude will depend on the ratio of in-phase to out-of-phase data.

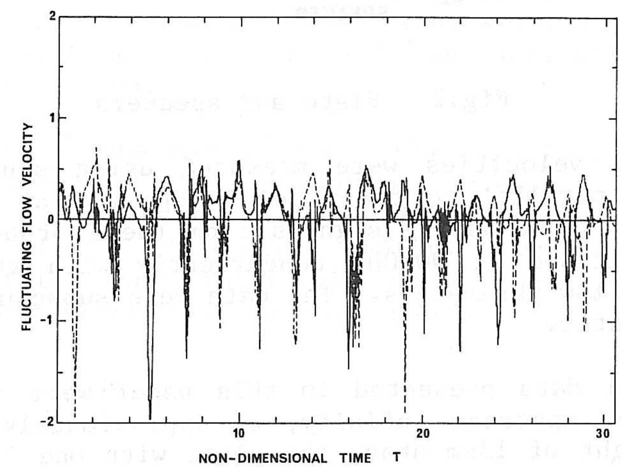


Fig.6 Mid-chord time histories - spanwise separation 10mm

Results and Discussion

The time histories without sound indicate the presence of asynchronous large scale structures, but when a sound field is applied these structures are shed in a regular manner. Above the leading edge the time history reflects the superimposed acoustic velocity, a low amplitude sinusoid at the frequency of the applied sound. Downstream of the point of reattachment a regular pattern occurs at half the sound frequency which is independent of the spanwise position, data recorded at positions to ± 40mm from the centre of the span. The auto-correlation of such data, see Fig.3 taken at mid-chord, shows a strong correlation at half the sound frequency.

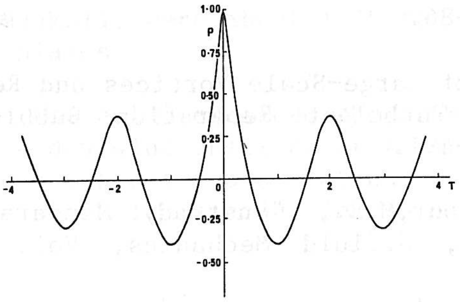
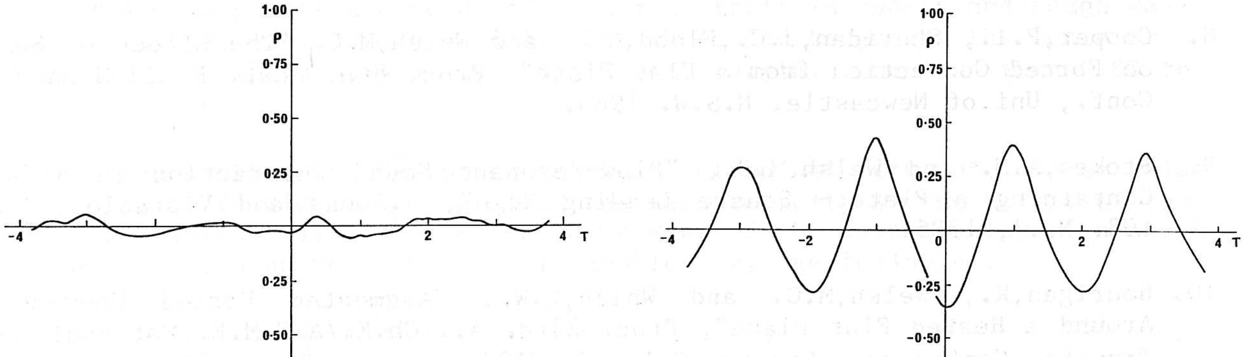


Fig.3 Auto-correlation
Mid-chord
ρ normalised coef.
τ non-dimensional time
(time/acoustic cycle)

Simultaneous recording of signals from two probes located at various positions above the plate have been used for a series of cross-correlations. Fig.4 shows cross-correlations for mid-chord spanwise separations of 10 and 20mm. The cross-correlations for positions 10 to 20mm apart show a change in amplitude from zero at 10mm to a minimum at 20mm, from 20 to 30mm the amplitude increases from the minimum back to zero and from 30 to 40mm the amplitude continues to increase to a new positive maximum at 40mm. There was no suggestion of phase shift.



a) spanwise separation 10mm

b) spanwise separation 20mm

Fig.4 Mid-chord Cross-correlations

At the leading edge the cross-correlation reflects the applied acoustic velocity and there is only a very small change in amplitude as the separation is increased. At the quarter chord position the cross-correlation coeficient changes in amplitude but is never less than zero. Downstream of mid-chord the resulting correlations are the same as at mid-chord. These findings are dependent only on the relative spanwise separation. The relationship between spanwise separation and cross-correlation is summarized in Fig.5.

This work suggests that the coherence of the flow induced by a sound field of medium intensity is restricted by instabilities in the third dimension. The presence of sound at high intensity levels (e.g. duct acoustic resonance [7]) appears, from flow visualisation, to promote a high degree of coherence. It is these levels that may be more appropriate to the use of phase-averaging techniques with LDA equipment.

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