9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE
AUCKLAND, 8-12 DECEMBER 1986

Three Dimensional Separated Flow over the Surface of a Bluff Body

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ABSTRACT

Separated flow around a bluff body gives rise to large vortex structures shed from the separation bubble. Studies of separated flow, including experimental, numerical and flow visualisations have concentrated on the two-dimensional aspect of the flow on planes running parallel to the flow and normal to the plate surface. Early work at the CSIRO has shown that two-dimensional acoustic velocity perturbations can regulate the shedding process. More recent studies now show that such perturbations also influence the formation of spanwise structures. The paper presents results from studies made using constant temperature hot-wire probes in separated flow perturbed by sound. Comparisons of the velocity time histories together with associated auto and cross correlations have led to the development of a three dimensional model of the large scale structures consistent with the measured data.

INTRODUCTION

The flows which follow separation from the square leading edges of thick, flat plates have been the subject of study over a number of years. Plates with chord to thickness ratios up to 4, were studied by Nakaguchi et al (1968) with a view to establishing the aerodynamic drag and vortex shedding characteristics. Parker & Welsh (1983) extended this to include plates with chord to thickness ratios up to 50. Ota & Itasaka (1976) completed a study of the mean flows immediately following separation and downstream to the region where reattachment of the flow occurred.

Kiya et al (1982) undertook a study of the separating and reattaching flows over a blunt flat plate with a square leading edge, they concentrated on the instantaneous flow structures which reveal much greater detail. They also developed and used a "discrete vortex" numerical model to simulate the flow downstream of separation. Hourigan et al (1985) improved the "discrete vortex" model by accounting for the cross-diffusive annihalation of vorticity near the plate's surface by ensuring that the total vorticity shed into the flow was consistent with the surface tangential pressure changes along the surface. This model was able to simulate the instantaneous flow and clearly showed the existence of the "vortex pairing" process occurring near and downstream of the reattachment position. The merging of two structures to form a single structure was referred to by others, e.g. Browand & Troutt (1985), in the two-dimensional mixing layer.

Subsequent studies by Kiya & Sasaki (1985) have shown the limitations of the essentially two dimensional approach adopted in the studies mentioned above. They used a surface pressure transducer in the reattaching zone to detect the presence of large scale vortices and used the pressure signal to conditionally sample the flow parameters. They showed that the flows in the reattaching zone were three dimensional and that the concept of "hair pin" vortices was capable of describing the flows in this region.

The authors of the present paper have adopted an alternative approach. The flows surrounding a plate with a square leading edge were periodically perturbed by superimposing a sound field, which induced velocity perturbations at the sound frequency. Without sound the instabilities in the shear layers are produced, and combine, in an irregular manner. When subjected to a two dimensional sound induced velocity perturbation, the instabilities take on a regular form and the subsequent flow patterns occur at the sound frequency or at a sub-multiple of the sound frequency (Hourigan et al 1985). With regular shedding, techniques such as conditional sampling and averaging at a particular phase angle can be used to obtain a better understanding of the flow processes. It also permits observation of the flow process using stroboscopic light or synchronised flash photography.

The aim of this paper is to present a description of the flow in both the flow direction and across the flow, when sound is applied, consistent with hot wire recordings of the instantaneous flows.

EXPERIMENTAL APPARATUS AND PROCEDURES

These experiments were conducted in the open jet of a small blow down wind tunnel described in (Hourigan et al 1985). The maximum velocity at the tunnel outlet was 15m/s where the profile was uniform within 1%, between the boundary layers, which were approximately 3mm thick. In the open jet working section, the centreline longitudinal turbulence intensity was 0.3% with spectral components less than 100Hz.

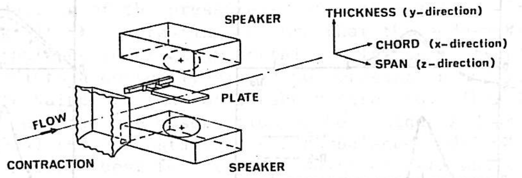

Fig 1: Schematic of the test plate and speakers

The rectangular plate used for these studies was 13mm thick, 135mm span and 130mm chord. The plate was located midway between two 250mm diameter speakers with the mid-chord/mid-span (centre of the plate) on their common axis, Fig.1. The combined plate/speaker assembly was mounted on a machine table that provided precise traversing of the assembly along each of the three major axes. This assembly was located in the open jet with the mid-chord position of the plate nominally 300mm downstream of the tunnel outlet. The speakers were connected in anti-phase to generate the equivalent of an acoustic Parker β-mode around the plate (Parker & Welsh 1983). Endplates fitted at the spanwise extremities ensured a two-dimensional sound field. With a mean flow around the plate the superimposed sound field induced a two-dimensional velocity with the maximum perturbation across the flow near the leading and trailing edges.

Flow velocities above the plate were measured using two single hot-wire probes which were aligned parallel to the leading edge of the plate and at right angles to the mean flow direction. The hot wires and the anemometers were of similar construction, and the slopes of the calibration curves varied by less than 5% at a mean flow velocity of 8m/s. The filters used to condition the signals were matched; linearizers were not used.

The experimental data presented in this paper were measured with a mean freestream velocity of approximately 8m/s. Sound was applied at a frequency of 135Hz and at a sound pressure level of 115dB (re 20μPa) close to the plate surface at mid-chord. The Reynolds number, based on plate thickness (t) and the upstream velocity (U), was approximately 7000, and the acoustic Strouhal number based on t and U was 0.22. One hotwire probe was fixed relative to the tunnel with the other fixed relative to the speaker/plate assembly. The hot wire sensors were located 13mm above the plate which ensured that the probes were never in regions of reversed flow. The fluctuating components of the hot wire signals were obtained by band passing the hot wire signals between 10 and 3000Hz and amplifying by 10. These signals were then digitized concurrently at 9kHz over a period of 1.82s (16384 measurement points per channel at 9kHz). The correlations were determined from the inverse transfer of the mean of 64 FFT's each computed over a period of 0.0284s. Data were recorded at a number of chord positions between the leading and trailing edges and at spanwise positions out to 40mm from the mid-span. Atmospheric pressure, ambient temperature, sound frequency etc. together with the fluctuating velocity data were recorded by a dual microprocessor recording system and stored on a PDP-11/44 computer.

RESULTS

The influence of sound on the measured fluctuating velocities recorded at three different chord positions is demonstrated in Fig.2, without sound, and Fig.3, with sound applied. These short segments are representative of longer data samples, which were found to be independent of the spanwise location of the measurements.

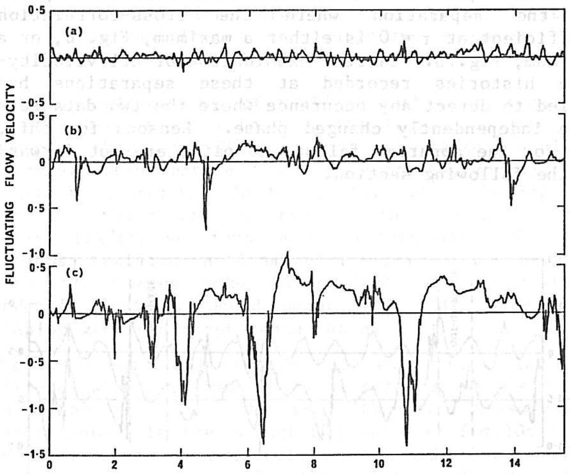

Fig 2: Velocity-time history segment without sound, chord position a) 2.5t, b) 5.0t and c) 7.5t.

Without sound, the mean length of the separation bubble is about 5t. At this position, a typical velocity-time history is shown in Fig.2b. When sound is applied, the separation bubble shortens to about 2.5t and Fig.3b & c are representative of fluctuating velocities downstream of this region. The fluctuating velocity component at positions above the leading edge (not shown) are much smaller than those recorded further down the plate. The visualization photographs, shown in Fig. 4, illustrate the reduced "bubble" length and the general characteristics of the flow with and without sound applied.

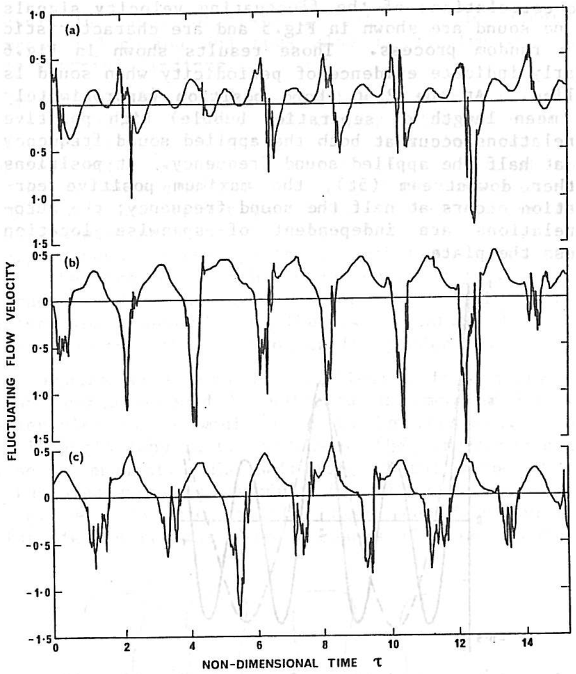

Fig 3: Velocity-time history segment with sound, chord position a) 2.5t, b) 5.0t and c) 7.5t.

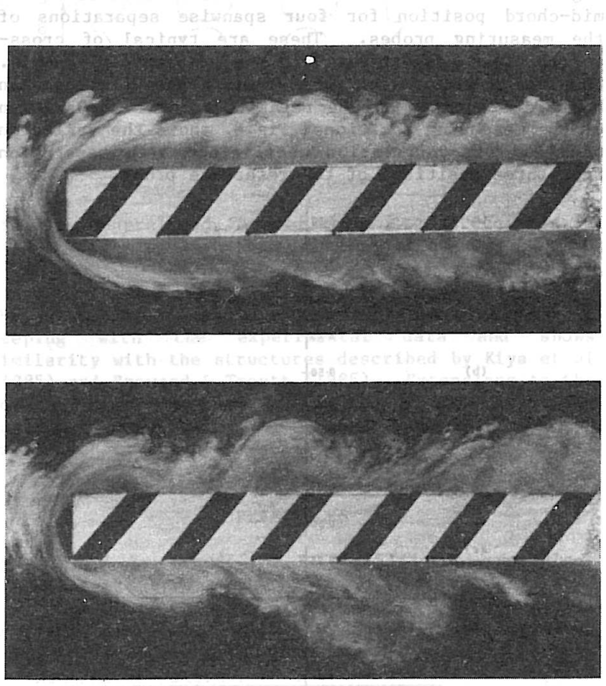

Fig 4: Photographs of turbulent separated flow; top without sound; bottom with sound.

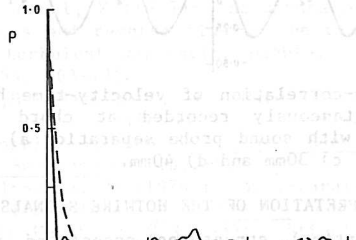

Fig 5: Auto-correlation of a velocity-time history without sound; solid line 2.5t, dashed line 5.0t; ρ normalised correlation coefficient, τ non-dimensional time.

Auto-correlations of the fluctuating velocity signals for no sound are shown in Fig.5 and are characteristic of a random process. Those results shown in Fig.6 clearly indicate evidence of periodicity when sound is applied. At the 2.5t chord position (approximately the mean length of separation bubble) high positive correlations occur at both the applied sound frequency and at half the applied sound frequency. At positions further downstream (5t), the maximum positive correlation occurs at half the sound frequency; the auto-correlations are independent of spanwise location across the plate.

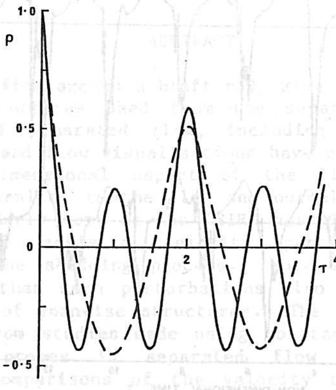

Fig 6: Auto-correlation of a velocity-time history with sound, solid line 2.5t, dashed line 5.0t

Fig.7 shows cross-correlations of data measured at the mid-chord position for four spanwise separations of the measuring probes. These are typical of cross-correlations downstream of the separation bubble. They are not dependent upon absolute spanwise location but are dependent on the relative spanwise separation of the measuring positions. Fig.8. shows the variation of the cross-correlation coefficient with separation from three positions of the reference probe.

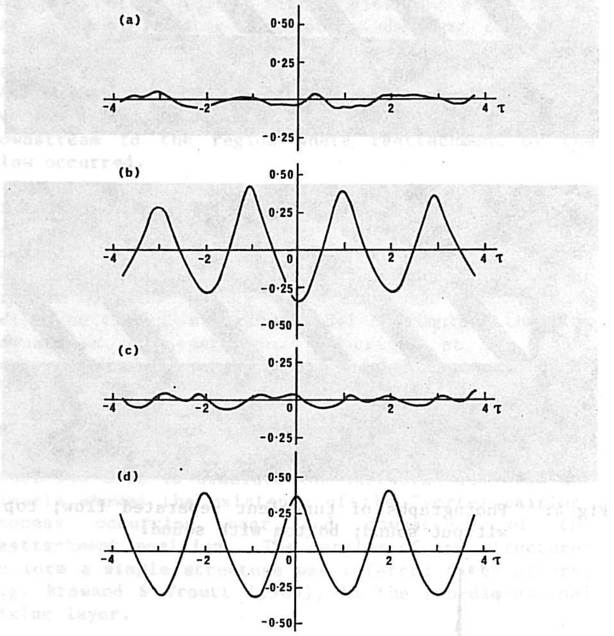

Fig 7: Cross-correlation of velocity-time histories simultaneously recorded at chord position 2.5t with sound probe separation a) 10mm, b) 20mm, c) 30mm and d) 40mm.

INTERPRETATION OF THE HOTWIRE SIGNALS

The large vortical structures associated with the leading edge separation bubble and the subsequent flow reach up to two plate thicknesses above the plate surface and for the data described here, the vortices will pass across the hot wire sensors. The sensors respond to the changing flow velocities associated with the rotational fluid as shown by the traces in Figs.2 & 3.

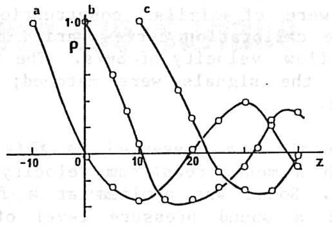

Fig 8: Variation of cross-correlation coefficient with spanwise separation, reference probe positions a, b, & c; chord position 2.5t.

These traces show similar features, that is there are vortical structures in the flow near the plate. The major influence of the sound is that the vortices are shed at a frequency directly related to the applied sound. Particularly noticeable is the increase in amplitude from the end of the separation bubble. Sound reduces the length of the separation bubble and hence the increase occurs closer to the leading edge. When sound is applied, the vortices are seen to pass sensors downstream of reattachment at half the sound frequency which implies that two vortices have merged to become one thus accounting for the increased size. The autocorrelations, shown in Fig.6, confirm the passage of vortices occurs at half the sound frequency over a long time period. Without sound, the vortex structures still combine, but in an irregular manner, leading to a normalised auto-correlation coefficient that quickly decays from unity at $\tau = 0$. With sound, each vortex structure released from the separation bubble forms a pair bond with one of the adjacent vortex structures and these paired structures are detected by the probes. There are occasions when a probe does not detect a pairing and subsequent pairings are detected 180 degrees out-of-phase with the previous pairing. One of the two simultaneously recorded data segments shown in Fig.9 include an occurence of a single structure associated with a change of phase. Initially the developing pair patterns occur in opposite phase, but after the single structure the two traces move in-phase. There are however two important exceptions that occur when the spanwise separation of the two data sets corresponds to the separation where the cross-correlation coefficient at $\tau = 0$ is either a maximum, Fig.7d, or a minimum, Fig.7b. Careful examination of all velocity-time histories recorded at these separations has failed to detect any occurence where the two data sets have independently changed phase. Reasons for this, and for the apparent failure to pair, are put forward in the following section.

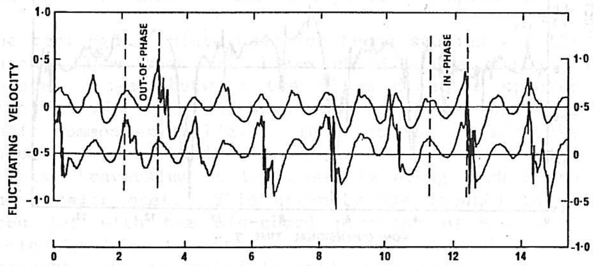

Fig 9: Segments from simultaneous velocity-time histories; chord position 2.5t, with sound.

PROPOSED MODEL OF THE FLOW STRUCTURE

Consider the form of a large scale structure in the spanwise direction. Other work, particularly that using flow visualisation, show how small perturbations to a spanwise vortex tube will induce stretching and result in a series of 'hairpin' or 'horse shoe' vortex structures. The cross-correlations determined from data recorded in the presence of sound indicate a regular pattern in the structure in the spanwise direction and it is possible, using the recorded data and the resulting correlation to deduce the probable form of the large scale structures over the plate.

Vorticity is generated uniformly across the leading edge corner and rolls up to form a spanwise vortex tube. Perturbation of this tube results in a wavy pattern along the length of the tube. Such vortex tubes are continually generated and move progressively down the plate. When sound is applied the resulting velocity perturbations regulate the frequency of shedding from the separation bubble. Our results and the results of numerical studies, see Fig.5 of Welch et al (1986), have shown that, at the sound pressure levels used during these tests, there is a strong tendency for the vortex structure released from the bubble to pair.

Pairing of two adjacent vortex tubes may occur continuously along the length of the two tubes or may occur only over particular spanwise sections of adjacent tubes. For a progressive train of 'wavy' vortex tubes, regular continuous pairing would occur if each newly generated vortex tube followed a similar wave pattern to the tube preceding it, Fig.10a. Regular pairing at particular sections across the span would occur if the vortex tubes form a structure of the type shown in Fig.10b, where each newly generated vortex tube forms a wave pattern 180 degrees out-of-phase in respect to the preceding wave pattern.

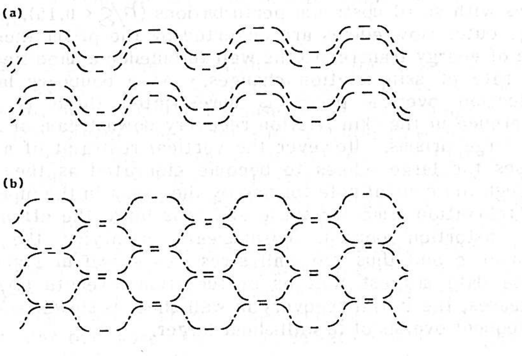

Fig 10: Simplified patterns of vortex tubes resulting in pairing; a) continuous spanwise b) intermittant spanwise.

The physical movement of fluid in both cases requires a stretching process to form the front, but for the pattern shown in Fig.10a there is also required relative motion between successive fronts, moving them together or apart. In the pattern shown in Fig.10b the stretching process results in pairing as new peaks, leading sections, move to form pairs with the troughs, trailing sections, of the preceding wave. If each new vortex tube is randomly displaced then irregular pairing would occur, but this is not in keeping with the experimental data.

The cross-correlations show that the correlation co-efficient is approximately symmetrical about $\tau = 0$ and that the amplitude changes with probe/measurement separation. If the structures were as Fig.10a then the resulting cross-correlation should show a progressive movement of the line of symmetry from $\tau = 0$ as separation between the probes is increased. A structure of the form shown in Fig.10b results in a high cross-correlation coefficient only at the points of pairing. If the waveform is such that pairing forms over a substantial portion of the span, as for the case of a square wave, then the cross-correlations would be either consistently in-phase or out-of- phase depending upon the separation.

Neither of the proposed simple structures are sufficient to explain the results. If however, the square wave structures shown in Fig.10b are subjected to a spanwise shift with time, then the probability of positive or negative correlation would depend upon the relative separation between measuring points and would result in cross-correlations very similar to those shown in Fig.7. Such a square wave pattern would result in auto-correlations that are independent of spanwise location and thus also in keeping with the experimental findings.

A sideway shift with time results in a relative phase shift between fronts. If the spanwise movement is slow, pairing will, for any particular location, procede until successive fronts fail to pair at that location, subsequent pairing will then follow out-of-phase with the former pairings. Time histories from two spanwise positions will depend upon the separation between them. If the spacing is such that it coincides with the wavelength or half-wavelength of the spanwise structure then the resulting change of pairing will occur simultaneously at the two locations, at all other spacings they will occur independently.

The square wave form is idealistic, in reality the sharp corners would be softened or smoothed but the underlying shape would need to be retained. Some small variations in the widths of the structures could also be present. The softening of the shape of the structures may also account for the sometime indistinct velocity profiles that have been found on time histories in regions where a change of phase occurs.

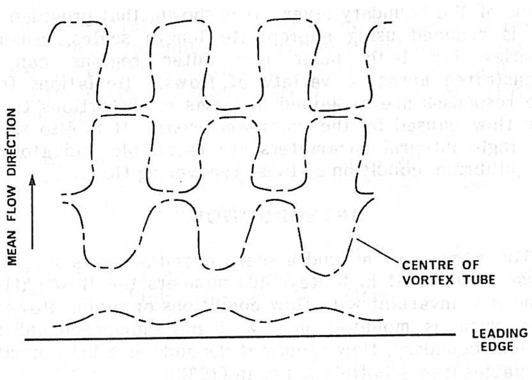

Fig 11: Generalised form of the vortex structures in keeping with the experimental data.

The model described above and shown in Fig.11 is in keeping with the experimental data and shows similarity with the structures described by Kiya et al (1985) and Browand & Troutt (1985). Extensions to the work are to examine the effect of end plates and the particular case where the span is a multiple of the wavelength of the spanwise structures.

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