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THE INFLUENCE OF SOUND ON THE FLOW OVER A LONG BLUNT PLATE: VORTEX SHEDDING AND BASE PRESSURE COEFFICIENTS

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ABSTRACT

The effect of sound on the vortex shedding and aerodynamic form drag on a long blunt plate is presented. Previous experiments have shown that the time-mean local heat transfer coefficient on such a plate is a function of the leading edge reattachment length and that sound reduces the time-mean reattachment length and decreases the base pressure coefficient. Here, it is shown that for unforced flow, the time-mean reattachment length and the base pressure coefficient are constant over a range of flow velocities. However, holding the time-mean leading edge reattachment length constant by varying the sound pressure level, the base pressure coefficient is observed to be strongly dependent on the flow velocity. Further investigations involving flow visualisation in a water tunnel highlight the different time-dependent flow patterns that are present with and without a transverse perturbation mimicking the sound in the wind tunnel experiments. The vortex shedding at both the leading and trailing edges is found to change dramatically when the flow is forced. In particular, vigorous vortex shedding appears near the trailing edge when a transverse oscillation is applied.

1. INTRODUCTION

The main contribution to the aerodynamic drag on bluff bodies in high Reynolds number flows is often due to the form component. This is especially so if flow separation occurs (see Batchelor (1967), p. 336, for graphic example). In practical situations, the increase in drag when flow separates around a body can offset the improvements in other characteristics such as heat transfer.

The occurrence of flow separation and reattachment results in the formation of large-scale vortex structures which, at other than low Reynolds numbers, are shed. The formation of these vortex structures can lead to reduced surface pressure coefficients beneath the structures. In fact, it has been argued that the dynamics of the vortices that form in the near wake region of a bluff body largely determine the form drag (e.g. Roshko (1955); Bearman (1965)).

Comparing local heat transfer coefficients along the plate when sound was applied, with the results of Ota and Kon (1979) where different leading edge wedge angles were investigated, Cooper *et al.* (1986) showed that the heat transfer characteristics were insensitive to the perturbing mechanism and essentially only a function of the time-mean reattachment length at the leading edge.

Cooper *et al.* (1986) found that for each of three different frequencies (400 Hz, 800 Hz, 1200 Hz), the leading edge reattachment length reduced as the sound pressure level (SPL) increased. This result held for a number of different approaching flow velocities between 10 m s^{-1} and 40 m s^{-1}, with the plate geometry and loud speaker arrangement identical to the present study. At velocities in the lower half of the velocity range, the reattachment length was also a function of the sound frequency. In the study of Cooper *et al.* (1986), the drag coefficient for the plate was generally higher when sound was applied for velocities below 25 m s^{-1} but slightly lower in the upper velocity range. It was not clear from the study what the mechanisms leading to the variation in drag coefficients were.

The studies of Welsh and Gibson (1979), Stokes and Welsh (1986) and Welch (1988) have shown that the vortex shedding from both the leading and trailing edges of long blunt plates (chord-to-thickness ratios of order 10) can be modified by the application of sound. When the Strouhal shedding frequency is close to the applied sound frequency, the vortex shedding frequency can lock with the sound frequency, resulting in a reduced formation region either at the leading edge or trailing edge of the plate, depending on its geometry. These studies have not considered, however, the simultaneous effect of sound at the leading and trailing edge vortex shedding, which is the subject of the current paper.

The aim of the present paper is to determine whether the form drag coefficient of the plate is also a function only of the time-mean leading edge reattachment length, and to investigate the mechanism leading to increased drag when sound is applied.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the working section of the open jet wind tunnel is shown in Fig. 1. The rectangular test plate was 13 mm thick, 135 mm span and 130 mm chord and was mounted in an open jet wind tunnel with endplates. Details of the wind tunnel have been reported by Welsh *et al.* (in press). The velocity profile across the contraction at the outlet of the wind tunnel was uniform to within 1%. The centreline longitudinal turbulence intensity was 0.3%. The free-stream velocity approaching the test plate for each test was maintained constant within ±0.1 m s^{-1}, and the plate was set at zero incidence angle to the flow.

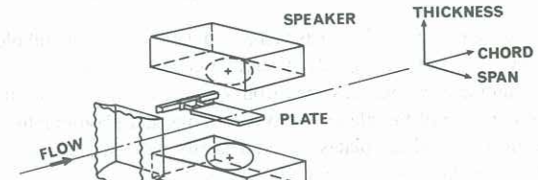

Figure 1 Schematic diagram of the working section of the open jet wind tunnel with loud speaker placement (endplates not shown).

One loudspeaker was mounted above and another below the test plate at a distance of 175 mm from the surface of the plate, such that the centre of the plate was aligned with the centreline of the speakers. To produce an asymmetrical sound pressure field similar to the β-mode for a cascade of plates defined by Parker (1966), the speakers were connected to a stereo audio amplifier in anti-phase and the SPL on the top and the bottom surfaces of the plate was balanced with the aid of a microphone. In Welch (1988) and Hourigan *et al.* (1987), the sound frequency was 135 Hz and the flow velocity was 8.6 m s^{-1}, giving an acoustic Strouhal number St_a (= acoustic frequency x plate thickness/flow velocity) of 0.2 and a Reynolds number Re (= flow velocity x plate thickness/kinematic viscosity) of 7.5 x 10^3 . In the present study, the flow was investigated for a range of flow velocities around these values.

A row of (33) pressure tappings was inserted along the midspan of the plate, with tappings at approximately 1.5 mm from the leading and trailing edge corners of the plate. Five tappings were positioned along both the leading and trailing edges of the plate at midspan. These surface tappings were connected to a Setra low differential pressure transducer via a 'Scanivalve', and the signals were sampled and processed by a PDP11/44 computer, using high-speed data logging software. The pressure transducer had a differential pressure range -105 Pa to 140 Pa and an accuracy to within ±0.5 Pa.

Although the reattachment length of the flow at the leading edge of the plate was not measured directly, it is about 25% larger than a characteristic length of the separation bubble given by the distance from the leading edge corner to the point x_c at which the pressure coefficient C_p (pressure normalised to the dynamic pressure head) has the value $C_p(x_c) = 0.5(C_{p,max} + C_{p,min})$ (Kiya and Sasaki 1983), where *max* and *min* refer to the maximum and minimum C_p along the top surface of the plate. For each case, the form drag C_D, normalised to the dynamic pressure head and the plate thickness *h*, was calculated by integrating the surface pressure coefficients over the front and trailing edges of the plate.

Flow visualisation was conducted in a return circuit water tunnel. Water was pumped into a settling chamber containing filter material and a honeycomb and then passed through a two-dimensional four-to-one contraction before entering the working section. The working section was 770 mm long and was constructed from 25 mm thick acrylic supported in aluminium flanges. The maximum mean flow velocity in the working section was 0.4 m s^{-1}. Two opposite panels in the side walls of the working section were mobile, and could be oscillated in unison, thus superimposing a transverse flow velocity perturbation onto the flow and closely mimicking the effect of sound near the plate in the open jet wind tunnel. The oscillation could be varied from 0 to ±5 mm at frequencies between 0 and 5 Hz. A transverse flow velocity perturbation up to 150 mm s^{-1} could be imposed on the main flow. For this paper, sinusoidally varying transverse wall displacements were applied to the flow of mean velocity 93.6 mm s^{-1} to give a forcing Strouhal number of 0.2, close to the forcing value investigated by Welch (1988).

In the water tunnel, flow was visualised using hydrogen bubbles (Clayton and Massey 1967). A continuous 4 watt laser was used to illuminate the bubbles shed from a thin wire mounted on the leading edge of the plate. Video recordings and photographs of the flow around the plates were taken from above the working section or through the oscillating side walls.

3. RESULTS AND DISCUSSION

The applied acoustic field around the plate is similar to the β-mode for a cascade of plates defined by Parker (1966). This mode can be predicted using the finite element method to solve the Helmholtz equation (Hourigan *et al.* 1987); the predicted local acoustic particle velocity amplitudes and directions are shown in Fig. 2. The acoustic field imposes an identical transverse velocity perturbation at both the leading and trailing edges, which can influence the vortex development in the separating shear layers (e.g. Parker and Welsh 1983).

Over the range of velocities of investigated (5.75 to 11.6 m s^{-1}), the general flow structure as characterised by the pressure measurements does not appear to be sensitive to changes in the flow velocity in the unforced case. The time-mean surface pressure coefficients are shown in Fig. 3 for three different velocities; the profiles are nearly coincident over the entire surface of the plate. In particular, no variation in the pressure coefficients along the trailing edge is observed.

The effect on time-mean surface pressures of holding both the SPL and the sound frequency constant at the reference values of 115 dB and 135 Hz, respectively, whilst varying the flow velocity is shown in Fig. 4. The first segment of each plot of C_p is derived from three data points at the front face of the plate (leading edge), from the stagnation point to the top corner. The last segment represents three data points at the corresponding positions along the trailing edge. The middle set of curves represents C_p along the top surface of the plate. The pressure recovery on the top of the plate occurs further from the leading edge (i.e. the reattachment length increases) as the flow velocity

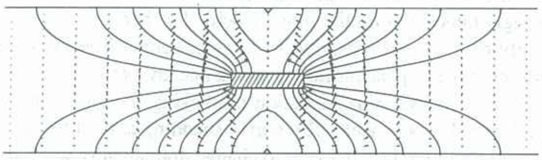

Figure 2 The predicted acoustic particle velocity amplitudes and direction (arrows) and isobars (solid lines) of the Parker β-mode acoustic field.

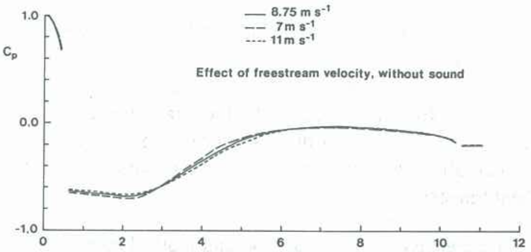

Figure 3 Time-mean pressure coefficient C_p plotted against distance along surface of plate with origin at centre of leading edge for three different flow velocities and no sound applied.

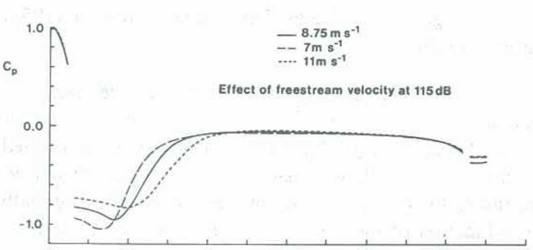

Figure 4 Time-mean pressure coefficient C_p plotted against distance along surface of plate with origin at centre of leading edge for three different flow velocities and sound applied at 115 dB and 135 Hz.

is increased. This result follows from the fact that the relative perturbation velocity due to sound decreases as the flow velocity increases; this is consistent with the observations of Cooper *et al.* (1986).

The effect of increasing the SPL for a given flow velocity is the decrease of the characteristic leading edge bubble length x_c and the increase of the form drag C_D on the plate (Fig. 5). Increasing the SPL appears to force the leading edge separating shear layer to reattach sooner, an effect noted by Welsh and Gibson (1979).

The above results suggest that for different flow velocities, the SPL can be varied to produce time-mean leading edge reattachment lengths identical to the reference case of 115 dB (i.e. x_c = 1.98) and allow a comparison of the effect of sound on the flow at the trailing edge for the different flow velocities. This is demonstrated in Fig. 6 for two different flow velocities (5.75 m s^{-1} and 10.3 m s^{-1}), where the surface pressure profiles at the leading edge and along the top surface of the plate have been made nearly identical by adjusting the SPL. Note, however, that the pressure coefficients (last segment of curves in Fig. 6) are quite different for the two cases.

Comparison of the mean base pressure coefficient $C_{p,B}$ (average surface pressure coefficient over the trailing edge) for different flow velocities with the SPL adjusted to give identical leading edge reattachment lengths is shown in Fig. 7. Also shown is $C_{p,B}$ for the unforced case. The mean base pressure coefficient was found to be a function of the flow velocity, with a local minimum occurring at a velocity of 10.3 m s^{-1} (acoustic Strouhal number 0.17). The form drag coefficient on the plate is C_D = 1.37 when sound was applied at 10.3 m s^{-1} compared with C_D = 1.08 when no perturbation was present. Thus, in the extreme case of 10.3 m s^{-1} and sound applied, C_D is approximately 27% higher than the case with no sound applied.

To understand the influence of sound on the respective leading and trailing edge vortex shedding, tests were conducted in the water tunnel using side wall oscillation of the working section to simulate the transverse velocity perturbation induced by the sound in the wind tunnel experiments. Visualisation of the flow structures formed along the plate with a transverse forcing near the plate matching, in relative terms, that due to the applied sound in the wind tunnel is shown in Fig. 8. The asymmetry of the acoustic field in the thickness direction of the plate leads to the alternate shedding of large-scale vortex structures from the leading edge corners of the plate. These structures reach the trailing edge of the plate alternately, as distinct from the unforced case where vortex shedding is irregular.

Details of the flow near the trailing edge were difficult to capture on photographic film because of illumination and seeding limitations. However, video recordings (to be shown at the conference) of the flow in the water tunnel clearly show that the vortex shedding from the trailing edge was influenced strongly by the transverse perturbation. Without forcing, there was a substantial recirculating region immediately behind the trailing edge; vortex formation in this trailing edge region was not clearly defined. However, with the perturbation applied, vigorous large-scale vortex formation appeared close to the trailing edge with vortex shedding locked in frequency to the perturbation. That is, large-scale vortices were formed in two distinct regions of the plate, these being the leading edge and the trailing edge. The application of sound resulted in modification of the vortex shedding in both regions.

An explanation of the differences in base pressure coefficient on the plate with and without sound is the ability of sound to shorten the vortex formation region at the trailing edge of the plate. The vortex shedding close to the trailing edge is

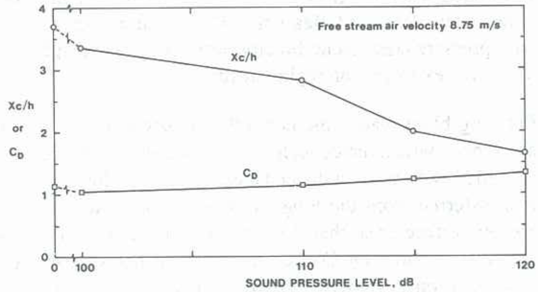

Figure 5 Plots of the characteristic separation bubble length x_c and the form drag C_D as a function of the SPL for sound applied at 135 Hz.

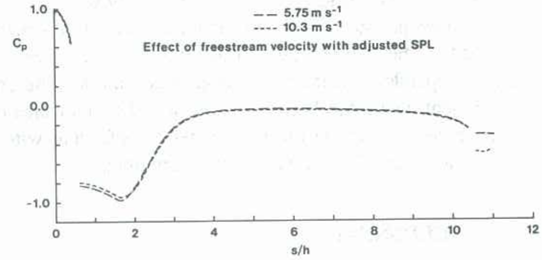

Figure 6 Time-mean pressure coefficient C_p plotted against distance along surface of plate with origin at centre of leading edge for two different flow velocities with SPL adjusted to produce similar reattachment lengths.

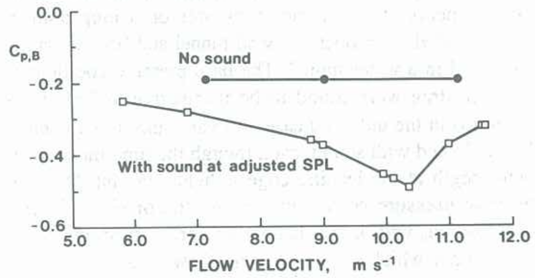

Figure 7 Plot of time-mean base pressure coefficient $C_{p,B}$ as a function of flow velocity with sound applied to maintain a constant reattachment length. For comparison, $C_{p,B}$ for the unforced case is shown.

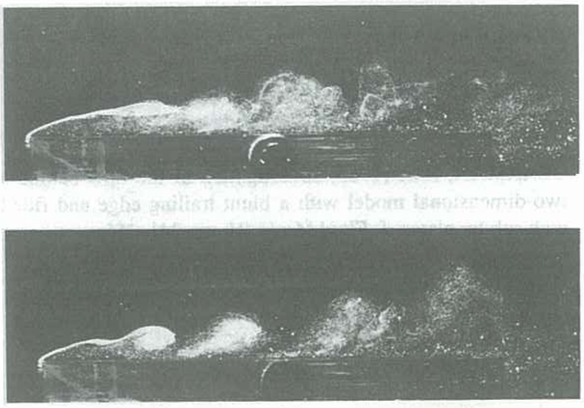

Figure 8 Flow visualisation using hydrogen bubbles in the water tunnel of the vortex structures formed for no applied perturbation (top) and applied transverse perturbation (bottom). Flow is from left to right, hydrogen bubbles are released from square leading edge.

intensified when the flow is forced. This is consistent with the general conclusion of Bearman (1967) that a decrease in the base pressure coefficient directly results from the displacement of the vortex formation region upstream.

For long blunt plates, the possibility arises that the form drag and other characteristics such as the heat transfer coefficient can be varied with some independence. The major fraction of heat is transferred from the long sides of the plate, due simply to greater surface area, than from the leading and trailing edges. Previous research by Cooper *et al.* (1986) has shown that the local heat transfer coefficient on these long sides is a function only of the time-mean reattachment length at the leading edge. The effect of sound is to reduce the leading edge reattachment length and increase the heat transfer rate. However, the form drag is determined by the surface pressures at the leading and trailing edges. The leading edge, where the flow is attached, shows surface pressure coefficients that are relatively insensitive to the SPLs. The trailing edge surface pressure coefficients are strongly dependent on the SPLs, even when the leading edge reattachment length has been held constant. This indicates that it is possible to increase the heat transfer coefficient without incurring a comparable increase in the form drag.

4. CONCLUSIONS

Sound has been found to influence the flow characteristics at both the leading and trailing edges of a long blunt plate. Previous research has demonstrated that the heat transfer coefficient along the long sides of a plate of similar geometry is a function of the leading edge reattachment length. In the present study, measurements of the surface pressures on a long blunt plate were recorded in an open jet wind tunnel and flow visualisation conducted in a water tunnel. The base pressure coefficient and the form drag were found to be insensitive to flow velocity variations in the unforced case, but vary substantially when the flow is forced with sound, even though the time-mean reattachment length at the leading edge is held constant. Decrease in the base pressure cofficient appears to correlate, from flow visualisation, with more distinctive vortex shedding from the trailing edge which occurs when the flow is forced.

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