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THE KELVIN-HELMHOLTZ INSTABILITY OF THE SEPARATED SHEAR LAYER FROM A CYLINDER

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ABSTRACT

Results are presented from experiments in which the separated shear layer in the near-wake of a circular cylinder was perturbed acoustically. The shear layer instabilities first observed by Bloor (1964) respond most strongly to a particular frequency of perturbation at a set Reynolds number. However, it is shown that the shear layer will respond over a range of frequencies, meaning "unperturbed" experiments must be done carefully in very "clean" flows if the results are to be generally applicable.

The results add weight to the argument that the appropriate length scale in consideration of the shear layer is not the attached boundary layer thickness on the cylinder but the momentum thickness in the shear layer.

INTRODUCTION

The earliest observation of instability waves in the separated shear layer of a circular cylinder appears to be that of Bloor (1964). She detected high frequency oscillations superimposed on top of the Kármán vortex frequency in the hot-wire signal. She hypothesised that these were Tollmein-Schlichting waves from the attached boundary layer on the cylinder and that they were responsible for the transition to turbulence in the wake.

Using boundary layer theory, she deduced a relation between the frequency of these waves and the Reynolds number, Re, such that $f_{SL}/f_K \propto Re^{0.5}$, where f_{SL} is the shear layer instability wave frequency, and f_K is the Kármán vortex frequency.

Wei and Smith (1986) used flow visualisation and hot-wire measurements to arrive at the relationship, $f_{SL}/f_K \propto Re^{0.87}$. They suggested that it was inappropriate to use the boundary layer to scale the frequency of the shear layer instability, and that the appropriate length scale was the momentum thickness of the shear layer in the linear growth region.

Later experiments by Kourta et al. (1987) and Sheridan et al. (1992) appeared to confirm the results of Bloor (1964). Kourta et al. also showed a possible route to turbulence in the wake by revealing the non-linear interaction between the shear layer and Kármán vortices.

With the exception of the study by Sheridan et al., in which the shear layer was acoustically forced, in these studies, and that of Gerrard (1978), the shear layer vortices appeared to develop naturally and to be an intrinsic feature of the near wake of circular cylinders. However, Khor and Sheridan (1994) reported that they could not be detected in the near wake for their experiments at Re up to 13000. Chyu et al. (1995) reported similar findings independently for $Re \leq 5000$.

The experiments described were undertaken to detect the Re at which the instability waves are first found, and to examine possible causes of the discrepancy in frequency dependence on Re found in previous studies.

EXPERIMENTAL APPARATUS

The majority of the experiments for which results are presented were conducted in an open-circuit wind tunnel at C.S.I.R.O. in Highett. The velocity profile across the working section is uniform to within 2.7% outside of the tunnel's boundary layers. Turbulence level was measured at 0.07% at $3ms^{-1}$ when bandpass filtered between 10 Hz and 1400 Hz. The spectrum of the free-stream velocity signal showed no peaks which could be associated with inherent disturbances in the tunnel. The tunnel's working section has a cross-section of 244×244 mm.

Cylinders of diameters 6.29, 9.44 and 12.60 mm were used in the experiments; all cylinders spanned the working section. When a controlled perturbation was applied it was done acoustically using a speaker module placed upstream of the working section.

The velocity was measured using a hot-wire anemometer. The hot-wire signal was acquired with an analogue-digital converter card mounted in a personal computer and was linearised before further processing.

A feature of the experiments is the high spatial resolution of the velocity measurements, this being considered necessary to examine the shear layer instability waves in the detail required. An X-Y computer controlled motorised traversing mechanism was constructed which could move the hot-wire probe in steps of 5 microns with an accuracy of placement of ±0.13 microns.

RESULTS AND DISCUSSION

Presence of Instability

Figure 1 shows spectra of the streamwise velocity fluctuation taken across the shear layer covering the range of frequencies at which the instability waves would be expected to appear. There is no clear spectral spectral peak to indicate the presence of the shear layer instability at this Reynolds number of 3590. This is well above the value at which the instabilities have been found in previous studies. For example, Unal and Rockwell (1988) showed that at certain sections across the shear layer the Kelvin-Helmholtz instabilities gave larger velocity fluctuations than the Kármán vortices at Reynolds numbers as low as 1800. However, there is a broad peak in the spectrum taken on the freestream side of the shear layer ($\frac{y-y_{0.5}}{\theta} = 2$). The peak is centred around a frequency which corresponds to that expected from shear layer instability waves. Norberg (1987) similarly found a broad peak in the spectra at such frequencies, his experiments also being conducted in a very low turbulence wind tunnel. It appears from this that the shear layer responds over a range of frequencies to the effectively random perturbation of free-stream turbulence.

Open-Jet Wind Tunnel Experiments

Clearly a concern in examining instabilities which respond at the frequency at which they are perturbed (characteristic of *convective instabilities*) is the generality of results obtained in a particular experimental facility.

Consequently, a set of experiments were conducted in a low turbulence open jet wind tunnel. While the turbulence level was low, being 0.3%, it was still considerably higher than in the tunnel described above. Figure 2 shows the spectra from an experimental run at $Re = 3360$, the hot wire being placed at $y/D = 0.58$.

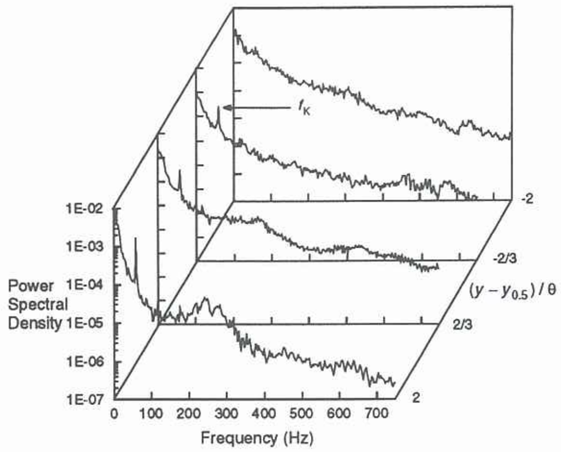

Figure 1: Spectra of streamwise velocity fluctuation taken across the shear layer at $Re = 3590$.

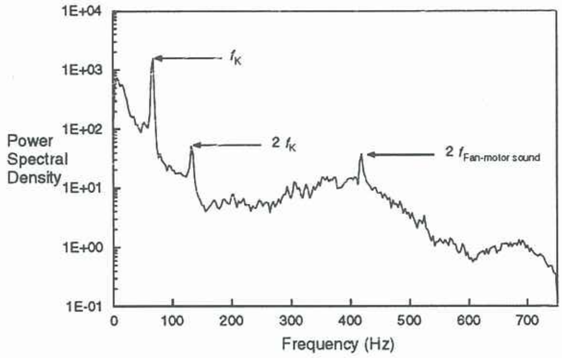

Figure 2: Spectra of streamwise velocity fluctuation taken in the open jet wind tunnel at $y/D = 0.58$ and $Re = 3360$.

The peaks associated with the Kármán vortex and its first harmonic are highlighted but also present is a peak at 418Hz. This was found to be twice the fan motor sound frequency of 209Hz. As the tunnel freestream velocity was increased the frequency of the instability increased linearly; clearly this was caused by the change in frequency of the fan motor noise. Thus, there is an obvious potential for facility-dependence in examining the shear layer.

Response of Shear Layer to Applied Perturbation

To test the dependence of the shear layer on applied perturbation, and in an attempt to resolve the inherent frequency of the shear layer perturbation, an acoustic field was applied to the flow in the open circuit wind tunnel. The shear layer was found to be very sensitive to such perturbations, even when perturbations were as low as $O(10^{-4}U_o)$. Figure 3 shows a spectrum for sound applied at 332 Hz at $Re = 3590$. A peak in the spectrum at this frequency results. This peak is much more pronounced than results from the effect of the acoustic field without flow.

Figure 4 shows the streamwise variation of the maxi-

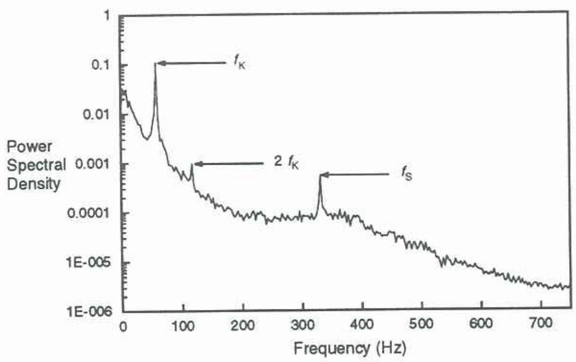

Figure 3: Spectra of streamwise velocity fluctuation with acoustic perturbation at 332 Hz.

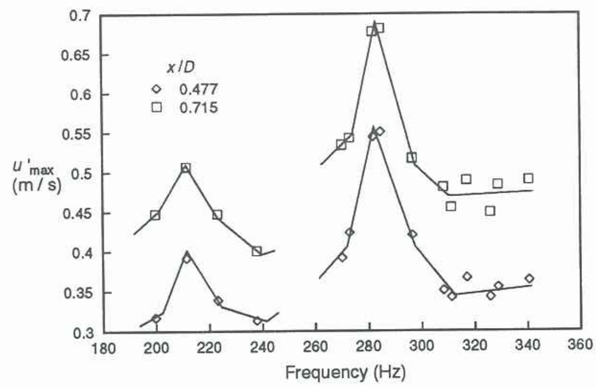

Figure 5: Response of the shear layer at $Re = 2270$ to perturbation at different frequencies.

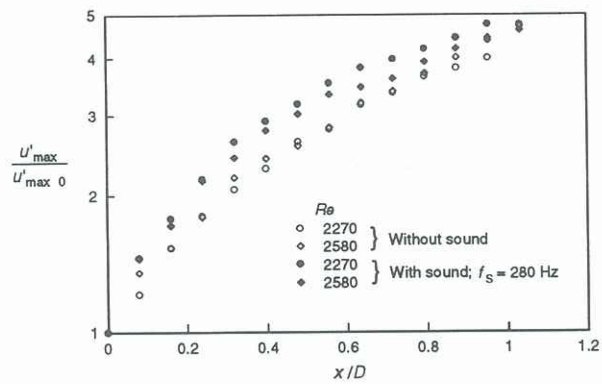

Figure 4: Streamwise growth of shear layer disturbance, showing the effect of perturbing the flow.

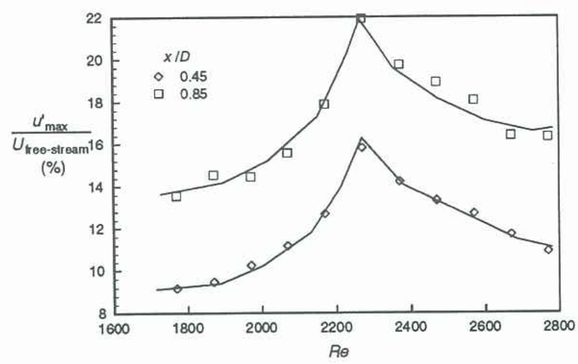

Figure 6: Response of the shear layer at different Re to perturbation at $f = 280Hz$.

mum fluctuating velocity for the unperturbed and perturbed near-wake at two Reynolds numbers, with and without sound. The growth rate of the fluctuation increases for both Re on application of sound of a single frequency. This response depends on the frequency, appearing to behave similarly to a generic free shear layer with a most amplified frequency, f_m, as discussed by Ho and Huerre (1984). It was postulated that the separated shear layer would have a distinct f_m for a particular Re, and that this would correspond to the values of f_{SL} found in previous studies.

To test this, the flow was acoustically perturbed over a range of frequencies centred on f_{SL} for a number of Re. Velocity measurements were taken separately for each frequency and Re. The maximum fluctuating velocity found for each frequency was compared at two streamwise locations and f_m determined.

Representative plots of the shear layer response to perturbation at different frequencies is shown for $Re = 2270$ in Fig.5. The most amplified frequency for this Re is seen to be 280 Hz. A somewhat smaller peak was found at 210 Hz, this being 3/4 of f_m. This is attributable to the nonlinear interactions discussed by Kourta et al. (1987), who showed that such interactions produced responses at $(1 - 1/n)f_{SL}$ frequencies, where $n = 3$ or 4.

To confirm these results, another set of experiments were conducted in which the perturbation frequency was fixed and the Reynolds number varied in a range around that corresponding to this being f_m. This was done for a number of frequencies and Fig. 6 shows a representative result for an applied frequency of 280 Hz. The maximum response occurs at $Re = 2270$, confirming the results shown in Fig. 5.

Both sets of results are plotted against that of other studies in Fig. 7. A regression analysis found the relationship between f_{SL}, f_K and Re to be of the form $f_{SL}/f_K \propto Re^{0.91}$. This is close to the relationship found by Wei and Smith (1986). Bloor (1964) argued that the appropriate exponent should be 0.5 from scaling considerations. However, this assumes that the thickness of the attached boundary layer on the cylinder is the appropriate length with which to scale the shear layer frequency. An alternative, more appropri-

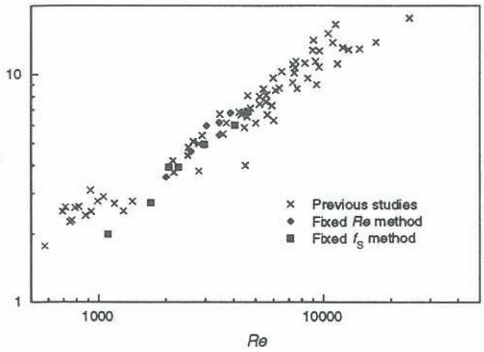

Figure 7: Variation of shear layer(f_{SL}) to Kármán (f_K) instability frequencies with Reynolds number.

ate length scale is the momentum thickness of the shear layer. Consequently, the exponent of 0.5 has no particular significance and this appears confirmed by our results.

Nevertheless, the relationship indicates the intimate connection between the shear layer and Kármán instabilities, as discussed by Unal and Rockwell (1988) and Chyu et al. (1995). This is not unexpected since the vorticity of both is generated in the boundary layer on the cylinder's surface. Even though the separated shear layer has its own characteristics, apparently with a close resemblance to the plane mixing layer, it is also related to the Kármán vortices through their common origin.

To test the receptivity of the shear layer to the applied perturbation, experiments were also undertaken in which it was perturbed with white noise. The shear layer did not select the most amplified frequency as it had when perturbed with a single frequency near its inherent frequency. This was despite the white noise perturbations being applied at higher amplitude than the single tone.

While no exhaustive study has yet been done, these results indicate that the shear layer is selective in how it responds to perturbation. This confirms the results of research into the effect on turbulence intensity and scale on separating shear layers by Saathoff and Melbourne (1989).

CONCLUSIONS

This study shows how the shear layer instabilities in the near wake of a circular cylinder respond to applied perturbations of particular frequencies. For a particular Reynolds number there is an inherent frequency at which response is maximal. This frequency appears to correspond to that found in the "natural" or unperturbed case. However, because the shear layer will respond to a range of frequencies at each Re the determination of this natural case must be done very carefully since there is potential for experimental facility dependence. This is a possible explanation for the variability found in results from previous studies.

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