FLOW AROUND ELONGATED BODIES: FLOW STRUCTURE AND RESONANCE

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INTRODUCTION

The presence of flow separation from both leading and trailing edges of elongated bluff bodies leads to vortex interactions and resonances not observed in shorter bodies such as circular and square cylinders. In particular, stepwise behaviour in the Strouhal number is observed for long bodies in a number of different situations: natural shedding (Nakamura *et al.*, 1991; Ohya *et al.*, 1992; Ozono *et al.*, 1992; Tan *et al.*, 1998), under transverse forcing (Mills *et al.*, 1995) and with excited duct modes (Stokes & Welsh, 1986).

Presentation will be made of the predicted laminar flow around long plates (up to chord, c, to thickness, t, ratios c/t=16). The two main types of plate considered are rectangular plates and plates with an aerodynamic leading edge. The rectangular plate is a natural extension of the normal flat and square plates. The aerodynamic leading-edge plate is a natural precursor to the rectangular plate because the shedding is only from the trailing edge. The flow around rectangular plates becomes more complicated due to the interaction between the leading- and trailing-edge shedding. Both the natural and forced shedding cases are studied. In the case of forcing, a small sinusoidal cross-flow oscillation added to the free stream. The excitation of a duct acoustic resonance, which takes a similar cross-flow profile to the forced case and is generated when a rectangular plate is place in a duct, is also examined. In addition, the formation of three-dimensional patterns in the boundary layer along the plate and in the trailing-edge wake is predicted. The boundary layer hairpin vortices are compared with the experiments of Sasaki & Kiya (1991); the predicted streamwise modes in the wake are compared with those found in the case of circular cylinders (Williamson, 1988; Thompson *et al.*, 1996).

NUMERICAL METHOD

As in the case of the simulations undertaken by Thompson and Hourigan (1994,1996), who first predicted the wavelengths of both wake modes, A and B, for the circular cylinder and validated against the measurements of Williamson (1988), the spectral element method was used in this study. The spectral-element method is a high-order finite-element approach; for each element, the nodal points are located at the quadrature points of a particular Gaussian quadrature formula. The time stepping method employed was a classical three-step approach described by Karniadakis *et al.* (1991).

RESULTS AND DISCUSSION

Trailing-Edge Shedding Only: Elliptical Leading-Edge Plates

The flow over an elliptical leading-edge plate has been analysed; in particular two-dimensional natural and forced shedding and the wake three-dimensionality. Initially, the flow without external forcing was simulated at different Reynolds numbers and the variation in shedding frequency analysed. The predicted base pressure was used to gauge the response of the system to low amplitude forcing. Further analysis of the flow field found the relative phase of the shedding to the forcing, vortex formation length, trajectory of the vortices and circulation contained within them to enable the forces on the plate to be correlated with the properties of the wake. The three-dimensional simulations show the development of the flow structures similar to those found in the wake of short bluff bodies, such as the circular cylinder; both Modes A and B have been predicted (see Figs. 1a,b). Stability analysis is currently being undertaken of the wake to identify the preferred modes at different Reynolds numbers.

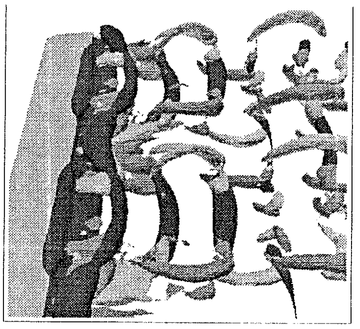

Fig 1a. Mode A in the wake of an elliptical leading-edge plate (flow from left to right).

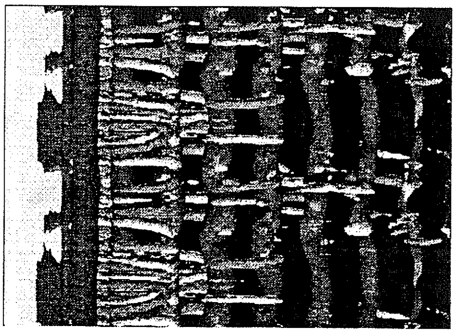

Fig 1b. Mode B in wake of elliptical leading-edge plate (flow from left to right).

Leading-Edge Shedding Only: Splitter Plate

A range of leading-edge shapes with splitter plates has been investigated by Nakamura (1996). The natural shedding was found to change in a stepwise manner with the length of the splitter plate. In this case, it appears that the instability is of the Impinging Shear Layer (ISL) type, as defined by Rockwell & Naudascher (1979). The shear layer separating from the leading-edge is initially elevated above the splitter plate and can extend far downstream to the trailing edge of the splitter plate even for comparatively large chord-to-thickness ratios.

Leading- and Trailing-Edge Shedding: Rectangular Plates

The natural vortex shedding follows a stepwise increase in the Strouhal number with aspect ratio (Fig 2). However, in the case of longer plates, the leading-edge shear layer clearly reattaches well short of the trailing edge and sheds discrete vortex structures into the boundary layer. The global instability is therefore not an ILS type; we propose that it is not strictly of the ILEV type either, as previously postulated by Nakamura *et al.* (1991). Rather, the dominant pressure pulses received and amplified at the leading-edge shear layer are generated by the trailing-edge vortex shedding. The role of the leading-edge vortex shedding is limited to one of interfering with the trailing-edge shedding, sometimes forcing it to adjust its frequency.

Three-dimensional predictions have also been undertaken; for longer plates (c/t=10, 13), the rollers shed from the leading-edge separation bubble are susceptible to a spanwise instability to form hairpin structures (Fig 3). The spanwise and streamwise wavelength of these instabilities is approximately $3t$. This is in agreement with the experiments of Sasaki and Kiya (1991), who observed both wavelengths to be between $3t$ and $4t$. It should be noted that the experiments generally used much longer plates for which the trailing edge shedding becomes less significant. The three-dimensional boundary layer structures interact with the trailing-edge shedding, resulting in a less coherent wake structure. However, the global instability that locks in the leading-edge shedding is still present in the three-dimensional predictions.

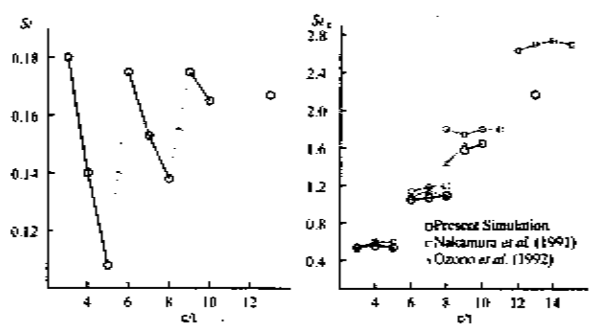

Fig 2. Left: Plot of the Strouhal number (based on plate thickness) versus chord-to-thickness ratio. Right: Comparison of Strouhal number (based on chord) versus c/t for present simulation and the experiments of Nakamura *et al.* (1991) and the simulations of Ozono *et al.* (1992).

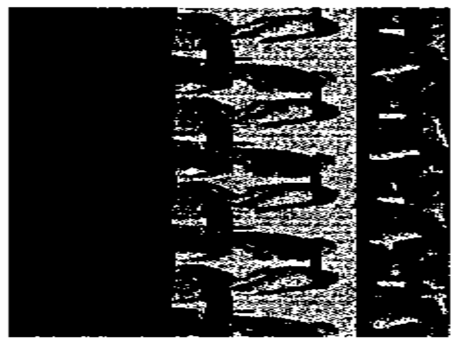

Fig 3. Plan view of prediction of Pattern B on plate with square leading-and trailing-edges; c/t = 10 (flow from left to right).

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