INSTABILITIES IN BLUFF PLATE BOUNDARY LAYERS

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Summary A detailed numerical study of the boundary layer flow over a (semi-infinite) square leading-edge plate is presented, examining the instability modes that govern transition from two- to three-dimensional flow. Both Floquet stability analysis and direct 3D simulations reveal a dominant instability mode with a spatial structure consistent with that of an elliptical instability. Together with previous evidence of its role in wake flows, this provides further evidence for the broad significance of the elliptical instability to flow transition.

INTRODUCTION

A complete understanding of turbulent fluid flow has proved elusive, despite its far-reaching importance to a vast array of modern technologies. One avenue towards greater understanding and prediction of turbulent flow is to study its onset – that is, the process of turbulent transition. For flow over an immersed cylindrical body, this process begins with the transition from two- to three-dimensional flow.

This transition is well understood for flows over circular (and square) cylinders, owing to a large volume of numerical and experimental research in this area. Several distinct instability modes have been identified by Williamson [1] and Robichaux *et al* [2], referred to as Mode A, Mode B and Mode S. Each of these instability modes has unique flow field characteristics and varying degrees of dominance with changing Reynolds number. For quite a long time, these instabilities of circular cylinder wake flows were assumed to be somewhat generic for all flow geometries.

However, recent studies have begun to investigate how instability mode characteristics vary for alternative flow geometries. Ryan *et al* [3] performed a numerical study of the wake flow behind an elongated bluff cylinder with an aerodynamic leading edge, revealing that the order of appearance and fundamental characteristics of the instability modes differed significantly from those of the circular cylinder wake. Similarities did, however, emerge between the Mode A instability of a circular cylinder wake and its elongated bluff-body analogue, with both instability modes exhibiting characteristics of the generic elliptical instability mechanism [3,4].

The present study aims to extend these research efforts, by investigating the unique and shared features of instability modes governing three-dimensional transition in the boundary layer flow over a (semi-infinite) square leading-edge bluff plate (Figure 1). The following sections will concisely describe the methodology and major findings of this work.

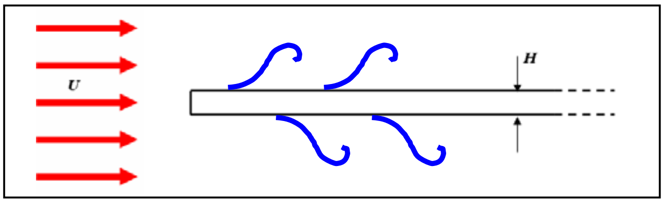

Figure 1 – Bluff plate flow geometry for numerical study.

METHODOLOGY

In the present study we use a high-order spectral-element direct numerical simulation (DNS) code to conduct 2D simulations, Floquet stability analysis [5] and 3D simulations of the boundary layer flow over a bluff plate. Above a certain Reynolds number the flow separates at the sharp leading-edge corners, forming recirculation regions at the start of the boundary layers above/below the top/bottom plate surfaces. During initial 2D simulations it was found that the boundary layer is strongly convectively unstable at moderate Reynolds numbers, with the instability highly receptive to perturbations close to the leading edge. To overcome this difficulty, a low amplitude (0.1%) periodic transverse forcing close to the preferred convective instability frequency was used to convert the convective instability to an absolute instability. (Note that in experimental analogues of this set-up, distinct shedding from the recirculation zone is observed at subcritical Reynolds numbers – presumably caused by background noise and, potentially, fluid-structure coupling [6]). This allowed us to directly examine the nature of the boundary layer instability and draw meaningful conclusions about the underlying physical mechanism.

RESULTS

Two-dimensional base flow simulations and Floquet stability analysis revealed the existence of a dominant instability mode with a spanwise wavelength of 4.6*H* (at Reynolds number 400) and a critical Reynolds number of 383 (presumably variable with forcing amplitude). This is in qualitative agreement with experiments published by Kiya & Sasaki [6]. Furthermore, the perturbation field structure of this instability was found to bear a striking resemblance to that found for the generic elliptical instability, and to the Mode A instability structure of circular cylinder wake flow, which has also been associated with elliptical instability [4]. Such an instability is characterised by pairs of opposing spanwise perturbation vorticity regions confined to the locations of the Karman vortex cores. Qualitative support for this interpretation comes from the alignment of the perturbation vorticity at approximately 45 degrees to the elliptical core axes, and the rapid falloff in the perturbation field outside the cores (see Figure 2 below).

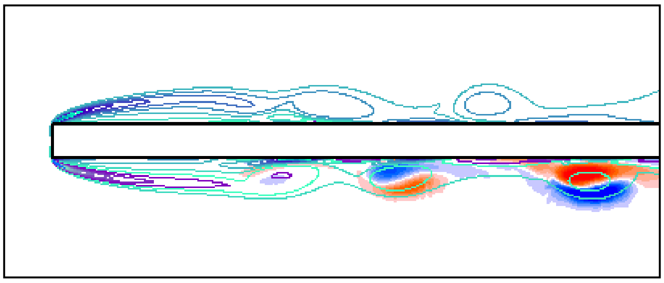

Figure 2 – Spatial structure of dominant instability mode, from Floquet stability analysis. Red and blue indicate +/– spanwise perturbation vorticity, from -0.2 to 0.2; line contours are of spanwise vorticity, indicating positions of von Karman vortices.

No further instability modes have yet been found for this flow. Hence, at this stage, it appears that boundary layer transition for an elongated blunt-edged cylinder is associated with a strong convective instability, resulting in convecting spanwise vortex structures, which in turn are unstable to an elliptic core instability, leading to characteristic three-dimensional vortical hairpin structures.

In order to confirm the findings of our 2D simulations and Floquet stability analysis, fully three-dimensional direct numerical simulations were conducted for an identical boundary layer flow scenario. These simulations successfully confirmed the results of our earlier analysis, producing a dominant instability mode with an identical spanwise wavelength of $4.6H$ at the imposed Reynolds number of 400 (see Figure 3). These three-dimensional simulations were also found to exhibit a staggered arrangement of vortices from one shedding cycle to the next, another characteristic of the downstream Mode A instability structure of a circular cylinder wake.

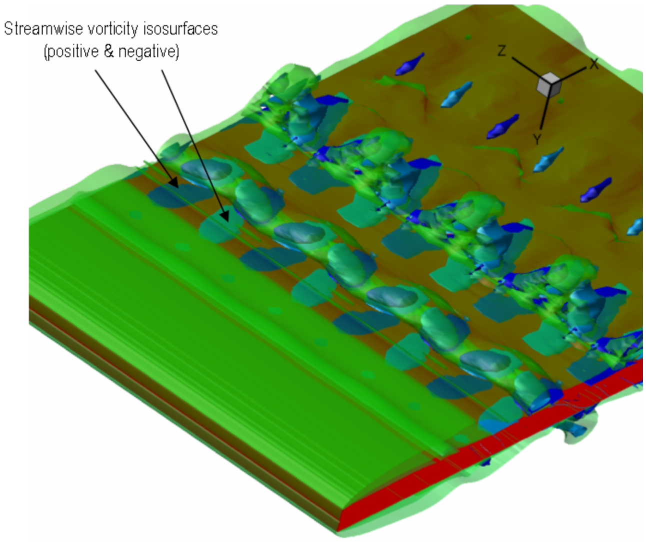

Figure 3 – Visualisation of simulated three-dimensional flow over bluff plate (from lower left to upper right). Green and blue isosurfaces correspond to spanwise and streamwise vorticity respectively; the plate is in red.

In finding such striking similarities between the instabilities governing flows as distinct as a circular cylinder wake and the boundary layer flow over a square leading-edge bluff plate, our findings suggest that the elliptical instability mechanism may be of considerable generic importance to flow transition. Future research will further investigate the relationship between the analytical theory of the elliptical instability mechanism and observed instability mechanisms in transitional flows, aiming to shed new light on the underlying physics of flow transition.

References

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