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Wake Transition of Oscillating Bluff Bodies

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Introduction

It has long been assumed that even relatively modest transverse oscillation can provide a stabilising effect on the wake on two-dimensional cylindrical bodies, considerably delaying three-dimensional transition. Experiments with an elongated cylinder by Berger (1967) showed that suitable transverse oscillations extended the upper limit of the laminar shedding regime from the non-oscillating limit until Reynolds number $Re = 300 \sim 350$. Koopman (1967) and Griffin (1971) both performed forced oscillation experiments at $Re \leq 300$ based on the assumption that a laminar shedding regime persisted at this Reynolds number. The visualisations of vortex filaments shed from an transversely oscillating cylinder by Koopman (1967) at $Re = 200$ show no spanwise variation. Importantly, it has been established both experimentally and theoretically, that three-dimensional wake transition for a stationary circular cylinder occurs at $Re \simeq 190$ (Williamson, 1996; Barkley & Henderson, 1996).

While the sequence of transitions leading to three-dimensional flow in a bluff body wake depends on body geometry (Ryan *et al.* (2005), Thompson *et al.* (2006)), it appears that the analogues of the circular cylinder modes play a part in transition process. For a circular cylinder Williamson (1996, 1988) produced very clear visualisations of the first two transition modes - mode A and B - and documented their spatio-temporal symmetry. These modes have a spanwise wavelength of about 4 and 1 cylinder diameter, and undergo transition at $Re_c \simeq 190$ and 260, respectively. Barkley & Henderson (1996) theoretically quantified aspects of these modes and observed signs or a further quasi-periodic mode (QP), lying at an intermediate wavelength. Blackburn & Lopez (2003) showed that this mode does not become unstable until much higher Reynolds numbers ($Re \simeq 377$). It has been observed in two-dimensional simulations that moderate amplitude transverse oscillation leads to a unsymmetrical ”P+S” state; i.e., for each shedding cycle the wake consists of a pair of vortices on one side of the centerline and a single vortex on the other side (Leontini *et al.*, 2006; Blackburn & Henderson, 1999). Three-dimensional experiments tend not to show the P+S state, but rather a mean 2P wake state is generally observed (Williamson & Roshko, 1988).

Some of the open questions in this area have been: (1) How much does finite-amplitude transverse oscillation delay the onset of three-dimensional wake transition? (2) Is there a change in the sequence of transitions leading to a fully three-dimensional wake and what effect does this have on the transition to turbulent flow? (3) Why is the P+S mode not observed experimentally, at least for moderate Reynolds numbers, while the 2P mode is? (4) Even post-transition, does oscillation produce a much more coherent (i.e. two-dimensional) wake? This paper will focus on these issues.

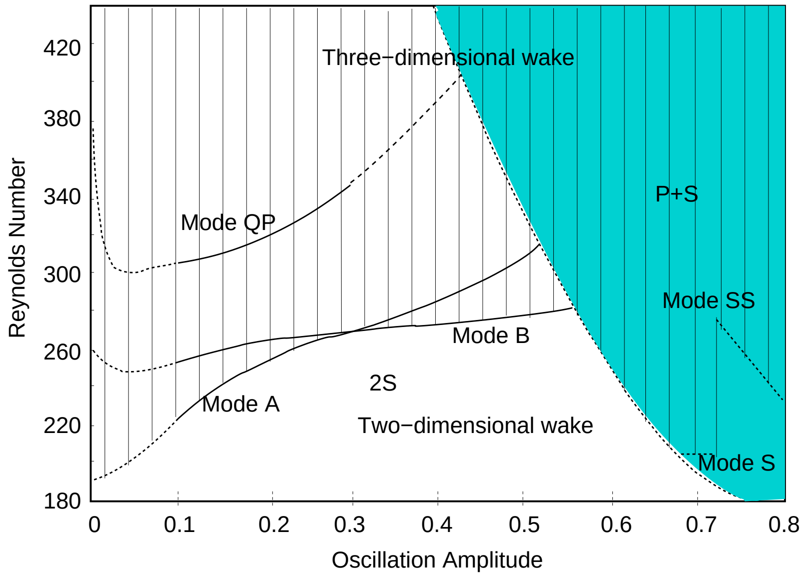

Figure 1: Stability map for the wake state of a transversely oscillating cylinder.

Results

The two-dimensional flow state was determined, using a validated spectral-element flow/stability code (Thompson *et al.*, 1996, 2001), as a function of Reynolds number and oscillation amplitude. The stability map is shown in Figure 1. Over the range of parameters studied, the two-dimensional wake can be in either the 2S state at lower amplitudes, or the P+S state at higher amplitudes. At higher Reynolds numbers, the (two-dimensional) transition from 2S to P+S occurs at lower amplitudes. Both base states become unstable to three-dimensional perturbations as the Reynolds number is increased. There are 4 possible three-dimensional transitions depending on amplitude. For low amplitude oscillation, $|A| < 0.3$, the wake become three-dimensionally unstable through the subcritical mode A transition, as with a stationary cylinder. Between $0.3 < |A| < 0.55$, the first transition is through the supercritical mode B. At slightly higher amplitudes, $0.55 < A < 0.72$, the base flow is the P+S state prior to three-dimensional transition. Indeed for $0.55 < A < 0.67$, the transition is via the 2S to P+S transition, which is immediately unstable three-dimensionally, Here, a subharmonic mode, mode S, is responsible for the initial three-dimensional transition. At higher amplitudes, the transition is through a different subharmonic mode, dubbed mode SS. Notably, for an amplitude of $A = 0.55$, the three-dimensional transition is delayed until $Re \simeq 280$, thus increasing the critical Reynolds number by approximately 90 over the non-oscillating case. A more detailed picture of aspects of wake transition will be presented at the conference.

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