Direct Numerical Simulation of Flow Instabilities in Variable Velocity Flows

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by

Sarath K. P.

Department of Aerospace Engineering
Indian Institute of Space Science and Technology
Thiruvananthapuram, India

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Abstract

The origin of turbulence in fluid flow fields has been a significant concern for many years. Flow transition under steady inflow conditions over various geometries has been the subject of extensive experimental, theoretical, and numerical studies. Transitional flows with an unsteady inflow play a vital role in a broad range of applications, including biological fluid transport to space applications, which still went unexplored due to experimental and computational limitations. In such cases, the thickness of the boundary layer formed over the solid surface varies in both space and time, causing a high level of complexity in the path of vortical structures formed from the shear/boundary layer. Also, time and space-dependent shear stress exerted by the fluid, separation, and associated instability phenomena are to be better understood. Recent advances in numerical methods have enabled us to simulate fluid flow under transitional conditions.

This study uses direct numerical simulations (DNS) to investigate the stability of vortical flow structures that form in the transitional boundary layer under an adverse pressure gradient over two different geometries. In the first case, a strong spatial pressure gradient is created using a bell-shaped wall-attached bluff body, while in the second case, a weak spatial pressure gradient is induced using a slowly diverging channel. A transient inflow condition is enforced at the inlet through analytical velocity profiles of a trapezoidal pulse, consisting of the acceleration phase from rest followed by the constant velocity phase and deceleration phase to rest, similar to existing experimental studies [1, 2]. By selecting suitable inflow parameters, we isolate the individual effects of acceleration and deceleration on the vortex evolution. Analytical inflow profiles for such a trapezoidal pulse have been developed using the Laplace transform for a given flow rate [3].

An open-source DNS code (INCOMPACT3D [4]) is used for the flow simulation and is a highly parallelized code that emerged as an efficient way to tackle complex flow simulations. It combines higher-order spatial discretization with spectral methods to simulate incompressible flows over complex bodies enforced through immersed boundary methods (IBM). The use of IBM allows the inclusion of complex geometries in Cartesian mesh without any body-fitting considerations. Both spanwise and streamwise vorticity visualizations depict the vortex growth and disintegration over both top and bottom channel walls. In addition, the spatial and temporal growth of shear layers and three-dimensional instabilities

are investigated in detail for each case using both numerical and theoretical methods. The underlying coherent flow features of the transitional flows and associated time dynamics are extracted using the modal reduction method like dynamic mode decomposition (DMD) and further corroborated with theoretical/numerical growth rate analysis.

In a bluff body wake, the flow development starts with the formation of a primary vortex, followed by a two-dimensional circular array of spanwise vortex tubes by inflectional shear-layer instability. At sufficiently high Reynolds numbers, the shear layer vortices originated from two-dimensional fluctuations deformed by three-dimensional instabilities, giving fragmented streamwise vorticity. In addition, long-wavelength, 'tongue-like structures' and short-wavelength, 'rib-like structures' are evident near the top wall and separation bubble, respectively. The three-dimensional transition phase is further analyzed by the vorticity generation mechanism for streamwise vorticity. Using the DMD algorithm, distinct flow features, such as mode shape, frequency, and growth rate, are identified and compared with significant maxima in the frequency spectrum of vertical velocity and momentum thickness variations.

In a slowly diverging channel with a relatively low spatial pressure gradient combined with a time-varying trapezoidal-shaped inflow boundary condition, the flow transition begins with two-dimensional primary instability characterized by the formation of inflectional velocity profiles, followed by local separation and the emergence of an array of shear layer vortices. We systematically divide simulation cases into three categories based on the onset of secondary instability and the generation of streamwise vorticity. At low and medium Reynolds numbers (type I), the spanwise vortex rolls formed by inflectional instability remain two-dimensional and diffuse at the channel center without exhibiting further instabilities. At high Reynolds numbers and deceleration rates (type II), the rolled shear layer exhibits secondary instability during the zero mean inflow phase, followed by local incipient turbulent structure formation. The streamwise vorticity that develops over the shear layer structures causes oscillations with a spanwise wavelength similar to those associated with the elliptic instability in a counter-rotating vortex pair. Using the Lamb-Oseen approximation of vortices in conjunction with the dynamic mode decomposition algorithm of the three-dimensional flow field, we successfully identified the unstable nature of the elliptical instability evolving over the secondary vortices. The third category (type III) is characterized by periodic unsteady separation, secondary instability, and merging of shear layer vortices, which occurs when Reynolds numbers are high and deceleration rates are low.

In both geometries, flow separation, and vortex formation are caused by highly inflectional streamwise velocity profiles, which are induced in the acceleration phase of a bluff body and during the constant velocity phase of a diverging channel. Shear layer instabilities and sequential roll-ups in a bluff body wake develop from an unstable velocity shear layer induced by early separation and high blockage ratios. Unsteady separation and vortex shedding arise in a diverging channel, offering a low spatial gradient combined with low deceleration rates. The three-dimensional transition is evident only at high inflow velocities for both geometries, whereas low inflow velocities inhibit spanwise oscillation growth, and flow features diffuse during zero-mean inflow. The nature of the vortical structures that develop in the wake of both geometries significantly impacts the onset and development of three-dimensional transition. In the bluff-body wake, the secondary instability initiates with the merging of the co-rotating body vortex structures ejected from the bottom boundary layer due to the shear layer vortex interaction. Such a merging mechanism induces small-wavelength rib-like braid instabilities similar to mode B instabilities in cylinder wake studies. Simultaneously, the counter-rotating vortex pair in the top wall indicates a three-dimensional transition with a relatively higher spatial wavelength. In a diverging channel, the primary vortex that develops from the initial inflectional profile further induces boundary layer vortices, forming a counter-rotating vortex pair susceptible to elliptic instability due to mutual induction and can later lead to three-dimensional disintegration.