GLOBAL DYNAMICS OF TRANSITIONAL AND TURBULENT SEPARATION BUBBLES

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ABSTRACT

In this presentation we aim to show the extent to which direct and large-eddy simulations are being used to provide insight into the complex physical mechanisms that dictate the behaviour of separation bubbles. To date most studies have been carried out for bubbles on flat plates, with separation triggered by an imposed adverse pressure gradient and with laminar or turbulent upstream conditions. It is also now feasible to carry out simulations for complete airfoils at low Reynolds numbers, allowing the separation bubbles to evolve in an environment that includes the airfoil trailing edge and allows for the propagation of acoustic disturbances within the computational domain. Transitional or fully turbulent separation bubbles contain a range of physical phenomena that are still not well understood, including laminar-turbulent transition, turbulent separation, boundary layer receptivity to external disturbances, and low-frequency oscillations. In practical applications it is important to understand these phenomena and to develop prediction schemes that reflect the physics of separated flows.

Since the first numerical simulations of laminar separation bubbles on flat plates with vortex shedding [1], numerical studies have illuminated the transition process [2] and have covered the complete transition process including the recovery to turbulent boundary-layer flow after reattachment [3,4]. In these cases transition in the separated shear layer was either forced by upstream disturbances or occurred naturally within the bubble. The latter process of self-sustained transition might be expected to be due to a local absolute instability, but most studies [e.g. 3,5] agree that such instabilities are not present in typical transitional separation bubbles. Here we focus attention on two alternative feedback mechanisms [6,7] that lead to self-sustained transition, i.e. global instabilities that give transition to turbulence even in the absence of upstream disturbances. The first mechanism involves a three-dimensional absolute instability of a time-dependent vortex shedding cycle, in which a vortex stretching instability is convected upstream during part of the cycle leading to strong exponential growth of disturbances. The second mechanism involves acoustic and vorticity modes linked by trailing edge acoustic scattering and boundary-layer receptivity near the airfoil leading edge. This is a weaker mechanism but is argued to be relevant to the origin of the shedding cycle necessary for the first mechanism.

Our recent simulations have been carried out with fully compressible flow codes that resolve acoustic waves. In particular, the presence of a finite sound speed allows one to study separation bubble receptivity numerically [7], since an acoustic wavepacket propagating over an airfoil and the subsequent instability growth in the boundary layer are separated in the time domain. Interesting results are also obtained when the external flow is supersonic [8, 9]. In these cases laminar separation bubbles do not shed vortices in the same way as for subsonic conditions [1,6], providing additional evidence that bubble shedding is the result of a feedback loop requiring downstream disturbances (for example wave reflection from a trailing edge or a numerical outflow boundary condition; or indeed the downstream geometry of a wind tunnel in the physical experiment).

Separation bubbles triggered by an oblique shock wave impinging on a turbulent boundary layer developing under a supersonic freestream exhibit a phenomenon of low frequency unsteadiness that is currently the subject of intensive study. Possible explanations are based on upstream disturbances, feedback loops of various kinds (with acoustic or convective upstream propagation inside the

separated flow region) and stochastic forcing of model equations. Numerical simulations are able to reproduce the low frequency phenomenon even when special care is taken to avoid long ‘superstructures’ in the upstream boundary layer [10]. The increasing availability of accurate numerical databases is enabling simplified modelling approaches to be developed based on underlying physical principles that can be properly validated [11].

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