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Subsonic impulsively starting flow at a high angle of attack with shock wave and vortex interaction

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Abstract Impulsively starting flow, by a sudden attainment of a large angle of attack, has been well studied for incompressible and supersonic flows, but less studied for subsonic flow. Recently, a preliminary numerical study for subsonic starting flow at a high angle of attack displays an advance of stall around a Mach number of 0.5, when compared to other Mach numbers. To see what happens in this special case, we conduct here in this paper a further study for this case, to display and analyze the full flow structures. We find that for a Mach number around 0.5, a local supersonic flow region repeatedly splits and merges, and a pair of left-going and right-going unsteady shock waves are embedded inside the leading edge vortex once it is sufficiently grown up and detached from the leading edge. The flow evolution during the formation of shock waves is displayed in detail. The reason for the formation of these shock waves is explained here using the Laval nozzle flow theory. The existence of this shock pair inside the vortex, for a Mach number only close to 0.5, may help the growing of the trailing edge vortex responsible for the advance of stall observed previously.

1. Introduction

Starting flow is caused by a sudden change of the angle of attack or forward speed of an airfoil, and is of primary importance in aeroelasticity (which involves step motion[1]), vehicle maneuverability[2,3] (which involves fast movement of command surfaces), and wing-gust interaction[4] (which is equivalent to attain a finite angle of attack).

For a small angle of attack, a linear theory has been developed for incompressible staring flow by Wagner and Walker,[5,6] for supersonic starting flow by Heaslet and Lomax,[7] and for subsonic flow by Lomax et al.[8] A time-dependent analytical lift force coefficient has been obtained for these cases. For the incompressible case, Wagner's solution shows that the initial lift is one half of its steady state value and increases monotonically with time following a curve known as the Wagner function. This force variation is due to a gradual build-up of the boundary vorticity and a free vortex sheet from the trail-

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ing edge. For supersonic flow, the solution of Heaslet and Lomax predicts a force plateau for small time, and this force then increases in time, reaching to the steady state value for large time. This force variation comes from interaction between steady and unsteady Mach waves below and above the airfoil.

For incompressible staring flow at a large angle of attack, vortex spirals form from both the sharp leading edge and the trailing edge, which, by close interaction with the airfoil, cause an initial singularity of lift,[9] and this singularity is then released when the vortex spirals are blown off the airfoil. After a force-increasing stage, stall occurs due to interaction between leading and trailing edge vortices.

An analytical solution has been found by Bai and Wu[10,11] for supersonic and hypersonic starting flows at a large angle of attack. In this case, a steady shock wave and an unsteady shock wave form on the windward side of an airfoil, and their interaction leads to a secondary wave which grows in time. A steady Prandtl-Meyer wave and an unsteady rarefaction wave form on the leeward side of the airfoil, and their interaction also forms a secondary wave growing in time. A further study shows that inside the secondary wave on the leeward side, there is a left-going shock wave.[12]

If we look at the connection between the flow structure and the force behavior for starting flow at a high angle of attack, it may be concluded that for incompressible flow, the force behavior is dominated by vortex flows, while for supersonic flow, this is dominated by compressible flows. However, it is special for subsonic starting flow where both vortices and compressible waves may be important. The subsonic flow problem may be further complicated by interaction between compressible waves and vortices. This interaction may be pronounced at an intermediate Mach number between zero and one.

Indeed, a preliminary study for subsonic starting flow at a large angle of attack[13] shows that stall is advanced at one Mach number, i.e., stall for a large angle of attack occurs at a time earlier than other Mach numbers. It is therefore required to look at what happens at this particular Mach number.

We therefore display in this paper the flow details for subsonic starting flow at that Mach number and at an angle of attack. The particular flow structure will be analyzed. Notably, we will examine whether there are shock waves embedded in the vortex flow structure that may be responsible for the observed lift evolution behavior with advance of stall.

Such a study not only enriches knowledge about the flow structure of subsonic starting flow at a high angle of attack, but also offers a possibility to observe in real applications whether shock waves appear inside a compressible vortex, a phenomenon anticipated using a simple vortex pair model.[14,15] The simple vortex pair model is for steady flow, and here in the present case, the flow is unsteady, so the phenomenon is more complex.

In Section 2, we will demonstrate numerical results of the flow structure. In Section 3, we will perform an analysis of the flow structure observed. Section 4 shows the detailed history of shock formation. Conclusions are provided in Section 5.

2. Numerical results of subsonic starting flow

As usual for study of starting flow, we use the nondimensional time defined by

$$\tau = \frac{V_\infty t}{c_A}$$

This non-dimensional time measures the number of chords traveled at time t by an airfoil of a chord length c_A and travelling at a constant speed V_∞.

Fig. 1 displays the lift force evolutions in time for subsonic starting flow at various Mach numbers and for an angle of attack $\alpha = 20°$. For incompressible flow (zero Mach number), stall occurs after the airfoil travels about 4 chord lengths, i.e., at $\tau \approx 4$. For a Mach number $Ma_\infty = 0.8$, stall occurs at $\tau \approx 3.4$. For a Mach number of 0.5, stall occurs at $\tau \approx 3.0$. Thus, for a Mach number around 0.5, stall occurs earlier than for other Mach numbers, whether they are higher or lower than 0.5. This would mean that something new appears in the flow structure for a Mach number around 0.5.

To see what happens, we display the streamlines, Mach contours, and pressure contours for several typical instants and computed numerically by CFD, for $Ma_\infty = 0.5$ and $\alpha = 20°$.

The flow is computed using a body-fixed frame, in which the airfoil is held fixed. A uniform flow with the given angle of attack is set initially. Once computation is started, the application of a non-penetrating condition along the wall of the airfoil builds vorticity and compressible waves near the wall.

The present study only considers inviscid flow. We thus solve the full set of nonlinear Euler equations in gas dynamics. For numerical simulation, we use the same approach as used before for a similar problem.[10,11] The grid is refined as before to have a grid-converged solution (see Appendix C in Ref. 11 for details). Precisely, we use the well-known Roe scheme based on finite difference approximation and second-order upwinding for the flux. The Fluent code incorporating these CFD approaches is used. This approach has been quantitatively verified using known analytical solutions, including the linear solution of Heaslet-Lomax supersonic starting flow

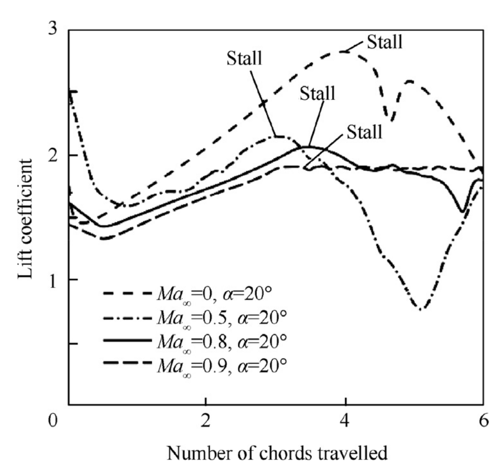

Fig. 1 Lift curves for starting flow of flat plate at several Mach numbers (angle of attack $\alpha = 20°$), showing that stall occurs earlier at a Mach number of 0.5. (The data comes from Ref. 13).

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