Analysis of Current Application of Transonic Flow Aerodynamics

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Abstract. Since man invented flying machines, we have always craved faster, more stable aircraft. In the 1940s, aircraft designers encounter a series of troublesome problems regarding exceeding the speed of sound. Those problems appear because as the aircraft approaches the speed of sound, a large increase in aerodynamic drag takes place and significantly unstabilized the aircraft. The definition of transonic flow is relatively broad, in fact, any fluid approaching the speed of sound can be considered transonic flow. Theoretically, for any point in space, the fluid motion in turbulence satisfies the nonlinear N-S equation, so it is possible to do at least numerical operations with a numerical computer, however, the workload is enormous. After the 1960s, the development of supercomputers made it possible to do numerical calculations in fluid mechanics, which has completely changed the CFD application. Transonic flow, as one of the branches with great practicality and relatively simple arithmetic in CFD, has greatly advanced the development of aircraft.

Keywords: Transonic flow aerodynamics, CFD, N-S equation, Aircraft.

1. Introduction

Since man invented flying machines, we have always craved faster, more stable aircraft. In the 1940s, aircraft designers encounter a series of troublesome problems regarding exceeding the speed of sound [1]. Those problems appear because as the aircraft approaches the speed of sound, a large increase in aerodynamic drag takes place and significantly unstabilized the aircraft. When an object moves at a relatively low speed (smaller than 0.3Ma), the air could be considered incompressible, making the drag force negligible [2]. As the speed increase, the effect of the drag force appears to be gradually stronger and could jeopardize the aircraft. The transonic flow was utilized in this situation to simulate and simplify the Navier-Stokes equation [3].

The definition of transonic flow is relatively broad, in fact, any fluid approaching the speed of sound can be considered transonic flow. To make it precise, and applicable, we mostly consider the body with both subsonic and supersonic regions nearby. Even if the body is operating below the speed of sound, local supersonic regions would appear after the body exceeds the critical number [4-5].

Theoretically, for any point in space, the fluid motion in turbulence satisfies the nonlinear N-S equation, so it is possible to do at least numerical operations with a numerical computer, however, the workload is enormous [6]. After the 1960s, the development of supercomputers made it possible to do numerical calculations in fluid mechanics, which has completely changed the CFD application. Transonic flow, as one of the branches with great practicality and relatively simple arithmetic in CFD, has greatly advanced the development of aircraft.

2. Mathematical model

Navier and Stokes introduced viscosity into the study of fluid mechanics and established the Navier-Stokes system of equations (N-S equations) in 1845 [7]. However, the nonlinear terms of these equations caused great difficulties in solving them, and although simplifying some conditions made the solution possible, they still could not meet the requirements for engineering applications. So inpractice, the first step we make is neglecting viscous stresses, which gave us the Euler equation (reduced momentum) with diagonal stress tensor ($\sigma_{ij} = -p\delta_{ij}$):

$$\frac{Du}{Dt} = -\frac{\nabla p}{\rho} + g \tag{1}$$

Where u is the fluid velocity, ρ is the density, p is the pressure, and g represents body accelerations (per unit mass) acting on the continuum [8].

After neglecting the vorticity and entropy production, we finally get to the small disturbance equation (nonlinear), the TSD (Transonic small disturbance) can be expressed as:

$$\left[\tau - \frac{\partial \varphi}{\partial x}\right]\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} - \frac{\partial^2 \varphi}{\partial x \partial t}\frac{2}{U_\infty} = 0 \tag{2}$$

Small disturbance could be used in Flutter Analysis, simulating the wing's vibration during the flight (which could be very harmful), and enhance the security of the aircraft. It is also widely used to optimized the structure of the aircraft to promote its speed in a safe way. The widely usage of Small Disturbance Approximation symbolize the importance of solving the Navier-Stokes equations and should have a positive influence on the computational fluid dynamics field [9].

3. Application

Limitation on propeller keep most of the airplane out of transonic issue before WW2, however, some fighter might exceed the critical number during a dive, preventing the fighter quickly recover from the dive. Similar problems were magnified after the invention of jet engine. Correspondingly, we can observed CFD and airfoil for experiments that were first researched in the 1930s started to be used on a large scale in the 1940s. Airfoils were carried out in the forties based on Theodorsen's methods and experiments, notifying a start of utilizing CFD in airfoil design. In 1947, von Karman's paper, The Similarity Law of Transonic Flow [2], introduced the transonic flow problem into aircraft design, and his work was followed by a series of experiments and discoveries in 1950. By the 1970s, this was already a well-studied and very productive field, Whitcomb's discovery of the area rule for transonic flow and the development of supercritical winglet was one of the notable examples of how people start to utilize transonic flow to improve aircraft's performance [10].

Figure 1 below shows the typical progression of shock wave as the speed increase. Shock wave appear after critical speed was reached, and became oblique when mach number exceed 1. The shock wave and bow wave after unity are reason of sonic boom, and caused serious safety issues.

After the jet engine started to be widely used, transonic unsteady aerodynamic and aeroelasticity (which was known as CAP-TSD) showed a increasing significance. Considerable amount of researches were carried out to develop a code for calculating transonic unsteady aerodynamics for aeroelastic applications [4].

Designing shock-free transonic configurations is one of the most popular application of transonic flow analysis. Shock wave that occur after the aircraft exceed its critical speed lower the efficiency, and usually come with wave drag and boundary layer separation. A shock-free, irrotational wave might seems promising. However, it was proved that any small change in a shock-free flow would create a shock wave, in other word, shock-free solution is mathmetically isolated. Here, analysis of transonic flow play an important role in designing both airfoils and wings. Richard Whitcomb created airfoils at NASA Langley in the late 1960s that had much improved transonic performance than earlier airfoils [3], which we called supercritical airfoils. Supercritical airfoils are characterized by their flattened upper surface, highly cambered ("downward-curved") aft section, and larger leading-edge radius compared with NACA 6-series laminar airfoil shapes [5]. It was discovered that airfoils could be created with drag rise Mach numbers that were significantly higher than those previously recorded.

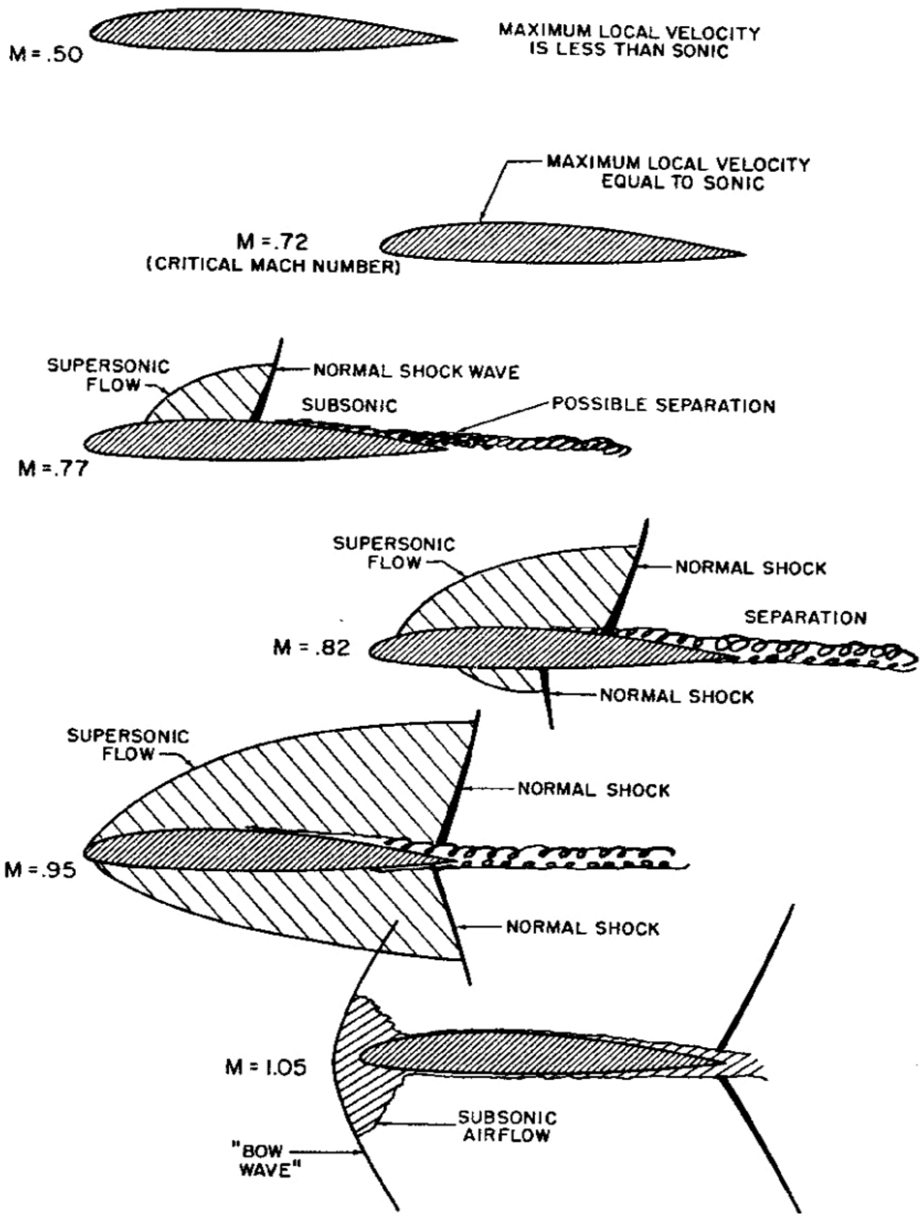
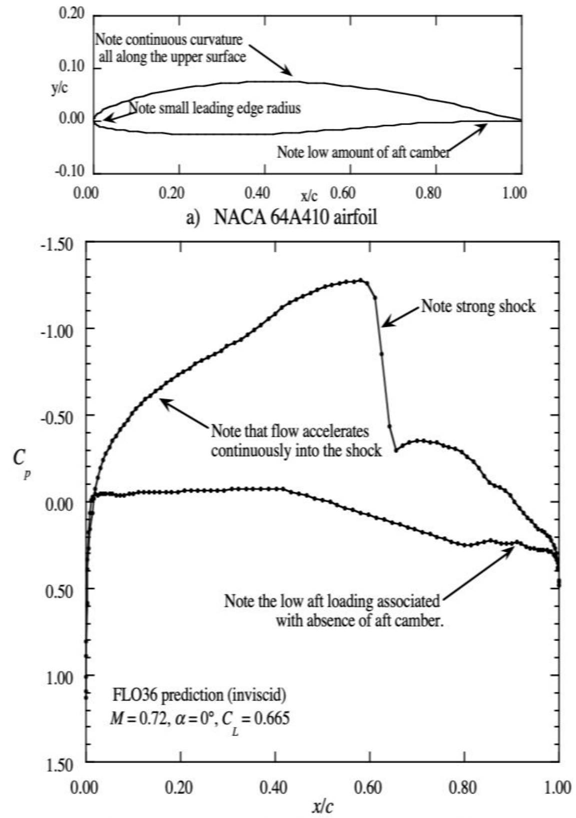


Figure 1. Progression of shock waves with increasing Mach number, as shown in Aerodynamics for Naval Aviators, a classic Navy training manual (not copyrighted)

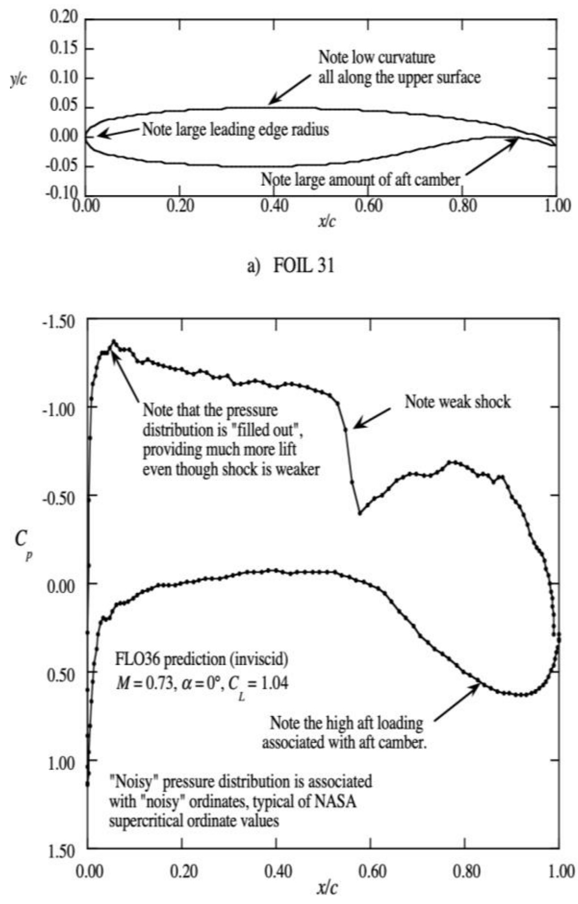
Figure 2 and Figure 3 below show a great improvement of supercritical airfoil in reducing the effect of shock wave compare to the NACA 64A410 airfoil-which was design in 1940s. Those new-designed airfoil oprate much more efficiently had led to significant aerodynamic advances. Various kind of configurations of both civilian and military aircraft were able to improve its efficiency.

Meanwhile, further development was still being made even while researcher are still completing the supercritical airfoils. For instance, the divergent trailing edge airfoil was carried out for achieving lift enhancement without a significant drag penalty [7]. Various attempts were made basis on the transonic flow analysis, and were widely used in aerodynamics field.



b) transonic pressure distribution on the NACA 64A410

Figure 2. NACA 64A 410 airfoil shape and related pressure distribution [2]



b) Transonic pressure distribution on the supercritical airfoil, Foil 31.

Figure 3. FOIL 31 airfoil shape and related pressure distribution [3]

4. Conclusion

As a important branch of CFD, transonic flow aerodynamics, such as SDE, could simplify the condition near unity and enable researchers to study and improved rather complicated configurations. Some monumental design, such as F-16, was based on the CAP-TSD method based on transonic flow aerodynamics. However, solution to more rigorous level-N-S and Euler equation-still need improvement. But it is reasonable to expect more and more complicated usage and increasing efficiency in aerodynamics design under more complicated flow conditions. Also, with the rapid growth of human computer computing power, the future of aerodynamics is certainly something to look forward to.

References

[1] Ulrych J. Analysis of Unsteady Transonic Flow Fields by Means of the Colour Streak Schlieren Method. Acta Polytechnica, 2004, 44(3): 302-308.

[2] Batina J T. Development of unstructured grid methods for steady and unsteady aerodynamic analysis. Congress of the International Council of the Aeronautical Sciences, 1990.

[3] Carr L W, Yu Y H. The use of interferometry in the study of rotorcraft aerodynamics. Optics and Lasers in Engineering, 1992, 17(3-5): 121-146.

[4] Aulchenko S M, Zamuraev V P, Kalinina A P. Criterial analysis of the effect of vibrations of an airfoil surface element on the transonic flow structure. Journal of Applied Mechanics & Technical Physics, 2014, 55(4): 586-592.

[5] Amaral F R, Souza D S, Pagani C C. Experimental study of the effect of a small 2D excrescence placed on the slat cove surface of an airfoil on its acoustic noise. 21st AIAA/CEAS Aeroacoustics Conference, 2015.

[6] Belov V V. Reducing the effect of vibrations on the quality of work of agricultural machinery. Mekhanizatsiya I Elektrifikatsiya Selskogo Khozyaistva, 2000, 78: 30-32.

[7] Daichin B, Zhao L L. PIV measurement of wake flow of an airfoil near free surface and the POD analysis. Journal of Hydrodynamics, 2008, 78(6): 230-239.

[8] Park J, Siegmund T, Mongeau L. Analysis of the flow-induced vibrations of viscoelastically supported rectangular plates. Journal of Sound & Vibration, 2003, 261(2): 225-245.

[9] Manickam T A, Roy S. Aerodynamic Analysis of Active Trailing-Edge Flaps and Passive Surface Roughness on NACA 4412 Airfoil. IOP Conference Series Materials Science and Engineering, 2020, 943: 012036.

[10] Litti Y V. Optimization of Energy Production from Two-Stage Mesophilic–Thermophilic Anaerobic Digestion of Cheese Whey Using a Response Surface Methodology Approach. Energies, 2022, 15(7): 45-49.