Offset of Shock Location in Supercritical Airfoils

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Abstract - *The objective is to review the design parameters, stability and efficiency of an airfoil when the flow approaches transonic Mach number speeds. The formation of a shock wave is discussed which is a type of propagating disturbance and greatly affects the aerodynamic properties such as Lift, Drag, Coefficient of moments and Normal forces at different Mach numbers. Supercritical airfoils are two dimensional turbulent airfoils with good transonic behavior while retaining acceptable low speed characteristics and the designing of such airfoils plays an important role in the overall efficiency of aircraft. In this Paper, comparisons are made between conventional airfoils with supercritical airfoils which show the effects of airfoil profile on drag divergence Mach number and Boundary layer separation and Stall behaviors. And also the advantages of supercritical airfoils have been discussed over the conventional airfoil.*

***Key Words*: Flow over Conventional Airfoil, Supercritical Airfoil, Drag Divergence Mach Number, Leading Edge Thickness, Design Characteristics, Shock Wave, Mach Number, Aerodynamic Characteristics etc.**

1. INTRODUCTION

Aerodynamic characteristics of an airfoil play a crucial role in the designing and performance of an aircraft. The changes in any of these parameters (Mach number, Lift & Drag coefficients, Pressure drag and the strength of the generated shock wave) will result in appreciable loss in stability of the aircraft. Several attempts have been made by researchers to obtain a better airfoil shape to enhance the aerodynamic efficiency. But, there were some early problems, as an airfoil approaches the speed of sound, the velocities on the upper surface become supersonic because of the accelerated flow over the upper surface, and there is a local field of supersonic flow extending vertically from the airfoil and immersed in the general subsonic field. The aircraft loses the stability when the flying speed reaches the speed of sound. This is because of the drag called Wave drag, which is caused by the formation of shock waves around the body, which radiate a considerable amount of energy. These shockwave causes the smooth flow of air hugging the wing's upper surface (the boundary layer) to separate from the wing and create turbulence. Separated boundary layers are like wakes behind a boat -- the air is unsteady and churning, and drag increases. This increases fuel consumption and it can also lead to a decrease in speed and cause vibrations. In rare cases, aircraft have also become uncontrollable due to boundary layer separation.

Although shock waves are typically associated with supersonic flow, they form at a lower speed at areas on the body where local airflow accelerates to sonic speed. The magnitude of the rise in drag is impressive, typically peaking at about four times the normal subsonic drag. The free stream Mach number at which local sonic velocities develop is called critical Mach number. It is always better to increase the critical Mach number so that formation of shockwaves can be delayed. This can be done either by sweeping the wings but high sweep is not recommended in passenger aircrafts as there is loss in lift in subsonic speed and difficulties during constructions.

In order to overcome the situation, many numerical simulations have been carried out for each chosen profile to bring out the best possible stability characteristics so that they can be used in many aerodynamic applications. So it is always desirable for an airfoil to possess best stability characteristics which can further achieve good lifting performance at optimum and extreme flow conditions. Therefore, researchers developed an airfoil which can perform this task without loss in lift and increase in drag. They increased the thickness of the leading edge and made the upper surface flat so that there is no formation of strong shockwaves and curved trailing edge lower surface which increases the pressure at lower surface and accounts for lift. Two of the important technological advancements that arose out of attempts to conquer the sound barrier were the Whitcomb area rule and the Supercritical airfoils. A supercritical airfoil is shaped specifically to make the drag divergence Mach number as high as possible, allowing aircraft to fly with relatively lower drag at high subsonic and low transonic speeds. For a better performance aircraft needs to get the speed closer to Mach 1 without encountering large transonic drag and this can be achieved by delaying drag divergence phenomenon to higher Mach numbers by using the Supercritical airfoils as shown in Fig. 1a.

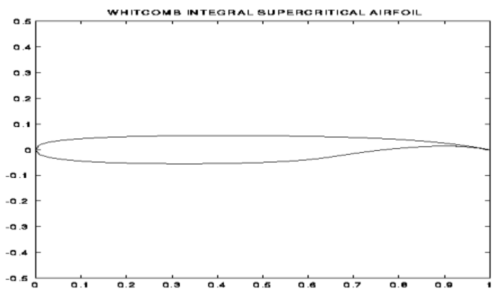

Fig -1a: Whitcomb supercritical airfoil

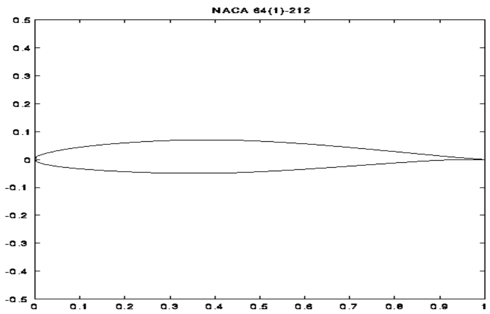

Fig -1b: NACA 64 series airfoil

2. DEVELOPMENT OF SUPERCRITICAL AIRFOIL

Supercritical airfoils are a class of transonic airfoils which operate with subsonic inlet and exit flow velocities and with embedded regions of supersonic flow adjacent to the airfoil surface. The term "supercritical" refers to the presence of velocities in the flow field which are above the "critical" or sonic speed. The supercritical airfoils were designed by NASA engineer Richard Whitcomb, and were first tested on the TF- 8A Crusader. While the design was initially developed as part of the Supersonic Transport (SST) project at NASA, it has since been mainly applied to increase the fuel efficiency of many high subsonic aircraft.

2.1 Slotted Supercritical Airfoil

In the early 1960's, Richard T. Whitcomb of the Langley Research Center proposed an airfoil with a slot between the upper and lower surfaces near the three-quarter chord to energize the boundary layer and delay separation on both surfaces (Fig. 2). It incorporated negative camber ahead of the slot with substantial positive camber rearward of the slot. Wind-tunnel results obtained for two-dimensional models of a 13.5-percent-thick airfoil of the slotted shape and a NACA 64A-series airfoil (Fig. 1b) of the same thickness ratio indicated that the slotted airfoil had a drag-rise Mach number of 0.79 compared with a drag-rise Mach number of 0.67 for the 64A-series airfoil. The drag at a Mach number just less than that of drag rise for the slotted airfoil was almost entirely due to skin friction losses and was approximately 10 percent greater than that for the 64A-series airfoil as shown in Fig. 3

2.2 Integral Supercritical Airfoil

The presence of a slot increased skin friction drag and structural complications. Furthermore, the shape of the lower surface just ahead of the slot itself was extremely critical and required very close dimensional tolerances. Because of these disadvantages an unslotted or integral supercritical airfoil (Fig. 2) was developed in the mid 1960's. Proper shaping of the pressure distributions was utilized to control boundary layer separation rather than a transfer of stream energy from the lower to upper surface through a slot. The maximum thickness-to-chord ratio for the integral Supercritical airfoil was 0.11 rather than 0.135 as used for the slotted airfoil. Theoretical boundary layer calculations indicated that the flow on the lower surface of an integral airfoil with the greater thickness ratio of the slotted airfoil would have separated because of the relatively high adverse pressure gradients at the point of curvature reversal.

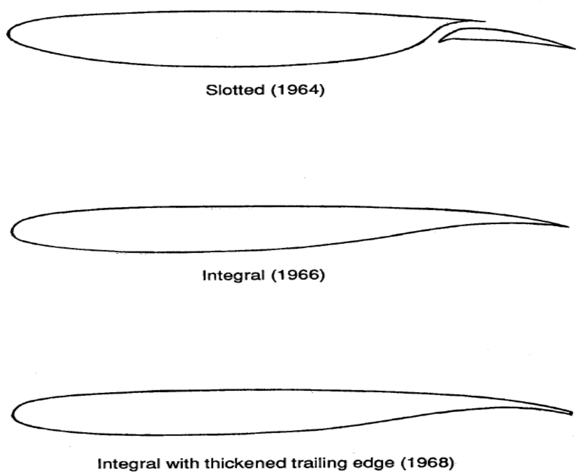

Fig- 2: Advancement in supercritical airfoil shape.

The experimental results shown in Fig. 3 indicated that the MDD for the integral airfoil was slightly higher than that for the slotted airfoil.

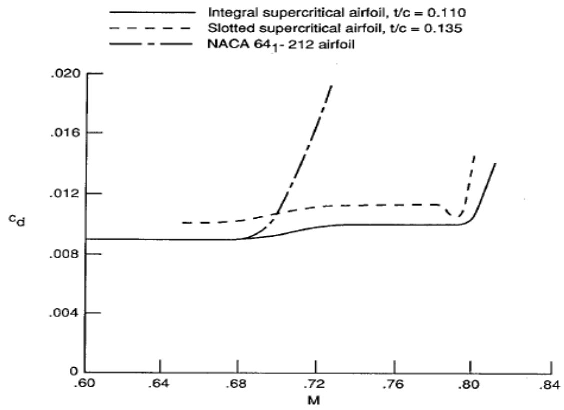

Fig- 3: Variation of drag coefficient with Mach number

3. GENERAL DESIGN PHILOSOPHY

Supercritical airfoils are a class of transonic airfoils which operate with subsonic inlet and exit flow velocities and with embedded regions of supersonic flow adjacent to the airfoil surface. The term "supercritical" refers to the presence of velocities in the flow field which are above the "critical" or sonic speed. The supercritical airfoils were designed by NASA engineer Richard Whitcomb, and were first tested on the TF-8A Crusader. While the design was initially developed as part of the Supersonic Transport (SST) project at NASA, it has since been mainly applied to increase the fuel efficiency of many high subsonic aircraft.

The upper-surface pressure on NASA supercritical airfoils and related velocity distributions are characterized by a shock location significantly aft of the midchord, results a rapid increase in pressure rearward of the midchord to a substantially positive pressure forward of the trailing edge. The elimination of the flow acceleration on the upper surface ahead of the shock wave results primarily from reduced curvature over the midchord region of the supercritical airfoil and provides a reduction of the Mach number ahead of the shock for a given lift coefficient with a resulting decrease of the shock strength as shown in Fig. 4. The strength and extent of the shock at the design condition could be reduced below that of the pressure distribution by shaping the airfoil to provide a gradual deceleration of the supersonic flow from near the leading edge to the shock wave.

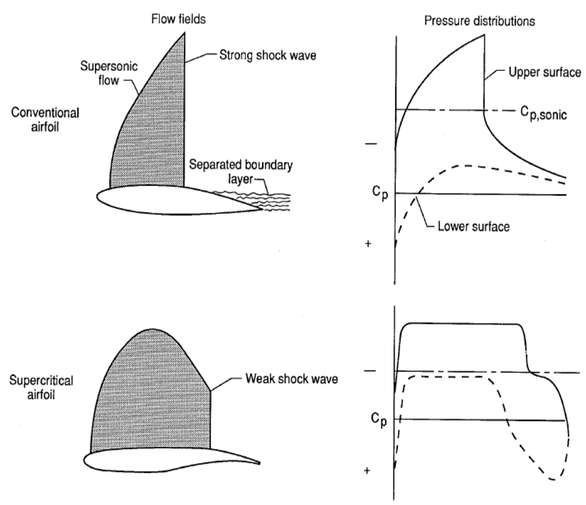

Fig-4: Comparison of transonic flow over a convention NACA 64 airfoil with transonic flow over a supercritical airfoil using CP variation

The airfoil produces expansion waves, or waves that tend to reduce pressure and increase velocity starting near the leading edge. If the flow field were a purely supersonic flow, there would be a continual expansion or acceleration of the flow from leading edge to trailing edge. There is actually an infinite series of expansions that move out of this supersonic field. When the flow is mixed, the expansion waves that emanate from the leading edge are reflected back from the sonic line as compression waves that propagate back through the supersonic field to the airfoil surface. Up to this point of contact, all the expansion waves have been accelerating the flow, but as soon as the compression waves get back to the surface, they start to decelerate the flow. These compression waves are then reflected off the solid airfoil surface as more compression waves. So, there are sets of competing waves working in the flow that are the key to obtaining good transonic characteristics for airfoils and those are need to be balanced.

Two primary factors influence the balancing of these expansion and compression waves: the leading edge and the surface over the midchord regions. First, there need to be strong expansions from the leading-edge region so they can be reflected back as compression waves--thus the large leading radius characteristic of supercritical airfoils. The leading edge of supercritical airfoils should be substantially larger than the conventional previous airfoils and is more than twice that for a 6-series airfoil of the same thickness-to-chord ratio. Second, the curvature over the midchord region must be kept fairly small so that there is not a very large amount of accelerations being emanated that must be overcome by the reflected compression waves--thus the flattened upper-surface characteristic of supercritical airfoils.

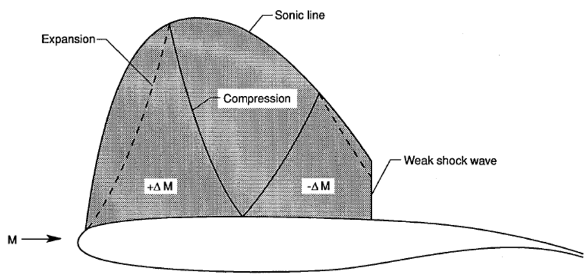

Fig-5: Schematic of the flow field over supercritical airfoil

Finally the critical Mach number (M_{Cr}) and drag divergence Mach number (M_{DD}) is increased by the shape of the supercritical airfoil. The pressure coefficient distribution over the top surface of a supercritical airfoil flying above M_{Cr} but below M_{DD} is sketched in Fig. 5. After a sharp decrease in pressure around the leading edge the pressure remains relatively constant over a substantial portion of the top surface. This is in contrast to the pressure coefficient distribution for a conventional airfoil flying above M_{Cr}.

On a conventional airfoil, the sudden increase in pressure coefficient at mid-chord is due to the shock. At a certain point along the airfoil, a shock is generated, which increases the pressure coefficient to the critical value (C_{pcr}), where the local flow velocity will be Mach 1(Fig. 4). The position of this shockwave is determined by the geometry of the airfoil; a supercritical foil is more efficient because the shockwave is minimized and is created as far aft as possible thus reducing drag. Compared to a typical airfoil section, the supercritical airfoil creates more of its lift at the aft end, due to its more even pressure distribution over the upper surface. Throughout the transonic range, the drag coefficient of the airplane is greater than in the supersonic range because of the erratic shock formation and general flow instabilities. Once a supersonic flow has been established, however, the flow stabilizes and the drag coefficient is reduced as shown in Fig. 6.

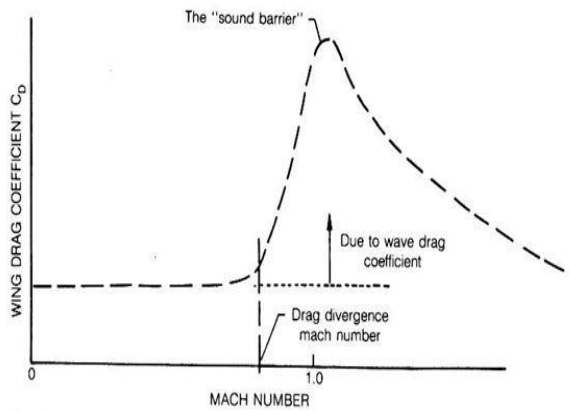

Fig-6: Reduction in drag with Mach number

3.1 Designation for Supercritical Airfoils

The airfoil designation is in the form SC(X)-ABCD, where SC(X) indicates Supercritical (Phase X). The next two digits, AB, designate the airfoil design lift coefficient in tenths (A.B), and the last two digits CD designate the airfoil maximum thickness in percent chord (CD percent) [7].

Examples:

SC (1)-0714: Supercritical (Phase 1)-0.7 design lift coefficient, 14% thick

SC (2)-0714: Supercritical (Phase 2)-0.7 design lift coefficient, 14% thick

SC (3)-0714: Supercritical (Phase 3)-0.7 design lift coefficient, 14% thick

3.2 Design guidelines

1. An off-design criterion is to have a well behaved sonic plateau at a Mach number below the design Mach number.
2. The gradient of the aft pressure recovery should be gradual enough to avoid separation (This may mean a thick trailing edge airfoil, typically 0.7% thick on a 10/11% thick airfoil.)
3. The airfoil has sufficient aft camber so that at design conditions the angle of attack is about zero. This prevents the location of the upper-surface crest (position of zero slopes) from being too far forward with the negative pressure coefficients over the midchord acting over a rearward-facing surface.
4. Gradually decreasing supercritical velocity to obtain a weak shock

4. FEATURES OF SUPERCRITICAL AIRFOIL

4.1 Trailing edge thickness

For an airfoil with a sharp trailing edge, as was the case for early supercritical airfoils, such restrictions resulted in the airfoil being structurally thin over the aft region. In order to investigate more comprehensively the effects of trailing-edge geometry, a refined 10-percent-thick supercritical airfoil was modified to permit variations in trailing-edge thickness from 0 to 1.5 percent of the chord and inclusion of a cavity in the trailing edge (Fig. 2).

The results are (1) increasing trailing-edge thickness yielded reductions in transonic drag levels with no apparent penalty at subcritical Mach numbers upto a trailing Edge thickness of about 0.7 percent, (2) increases in both subsonic and transonic drag levels appeared with increases in trailing-edge thickness beyond approximately 0.7 percent, (3) small drag reductions through the Mach number range resulted when the 1.0-percent-thick trailing edge was modified to include a cavity in the trailing edge and (4) the general design criterion to realize the full aerodynamic advantage of trailing-edge thickness appeared to be such that the pressure coefficient over the upper surface of the airfoil recover to approximately zero at the trailing edge with the trailing-edge thickness equal to or slightly less than the local upper-surface boundary-layer displacement thickness.

4.2 Maximum thickness

In order to provide a source of systematic experimental data for the early supercritical airfoils, the 11-percent-thick airfoil and the 10-percent-thick airfoil were reported to compare the aerodynamic characteristics of two airfoils of different maximum thicknesses. For the thinner airfoil, the onset of trailing-edge separation began at an approximately 0.1 higher normal-force coefficient at the higher test Mach numbers, and the drag divergence Mach number at a normal-force coefficient of 0.7 was 0.01 higher. Both effects were associated with lower induced velocities over the thinner airfoil.

4.3 Aft Upper-Surface Curvature

The rear upper surface of the supercritical airfoil is shaped to accelerate the flow following the shock wave in order to produce a near-sonic plateau at design conditions. At intermediate supercritical conditions between the onset of supersonic flow and the design point, the upper-surface shock wave is forward and the rear upper-surface contour necessary to produce the near-sonic plateau at design conditions causes the flow to expand into a second region of supercritical flow in the vicinity of three-quarter chord.

The modifications over the rear upper surface of supercritical airfoil were made to evaluate the effect of the magnitude of the off-design second velocity peak on the design point. The modification was accomplished by removing material over approximately the rear 60 percent of the upper surface without changing the trailing-edge thickness and resulted in an increase in surface curvature around midchord and a decrease in surface curvature over approximately the rearmost 30 percent of the airfoil. The results indicated that attempts to reduce the magnitude of the second velocity peak at intermediate off-design conditions in that particular manner had an adverse effect on drag at design conditions. The results suggested, however, that in order to avoid drag penalties associated with the development of the second velocity peak into a second shock system on the upper surface at intermediate off-design conditions, the magnitude of the second peak should be less than that of the leading-edge peak.

The broad region of relatively low, nearly uniform, upper-surface curvature on the supercritical airfoil extends from slightly rearward of the leading edge to about 70 or 75 percent chord. the results of extending this region of low curvature nearer to the trailing edge in an attempt to achieve a more rearward location of the upper-surface shock wave without rapid increases in wave losses and associated separation, thus delaying the drag divergence Mach number at a particular normal-force coefficient or delaying the drag break for a particular Mach number to a higher normal-force coefficient. Extending this low curvature region too near the trailing edge, however, forces a region of relatively high curvature in the vicinity of the trailing edge with increased trailing-edge slope. This high curvature would be expected to produce a more adverse pressure gradient at the trailing edge, where the boundary layer is most sensitive, and would result in a greater tendency toward trailing-edge separation. The results indicated that although simply extending the region of low curvature farther than on earlier supercritical airfoils provided a modest improvement in drag divergence Mach number, it had an unacceptably adverse effect on drag at lower Mach numbers.

5. THE KORN EQUATION

Airfoil performance needs to be estimated before the actual airfoil design has been done. To estimate the capability of supercritical airfoils for the purposes of design studies without performing wind tunnel or detailed computational design work, several attempts have been made. The Korn equation was an empirical relation developed by Dave Korn at the NYU Courant Institute in the early 1970s. It appeared that airfoils could be designed for a variety of Mach numbers, thickness to chord ratios, and design lift coefficients. The Korn equation is

$$M_{DD} + \frac{C_L}{10} + \left(\frac{t}{c}\right) = \kappa_A ,$$

Where, κ_A is an airfoil technology factor. The airfoil technology factor has a value of 0.87 for an NACA 6-series airfoil section, and a value of 0.95 for a supercritical section. M_{DD} is the drag divergence Mach number, C_L is the lift coefficient, and t/c is the airfoil thickness to chord ratio. This relation provides a simple means of estimating the possible combination of Mach, lift and thickness that can be obtained using modern airfoil design

6. CONCLUSION

As air moves across the top of a supercritical airfoil it does not speed up nearly as much as over a curved upper surface. This delays the onset of the shock wave and also reduces aerodynamic drag associated with boundary layer separation. At a particular speed for a given airfoil section, the critical Mach number, flow over the upper surface of an airfoil can become locally supersonic, but slows down to match the pressure at the trailing edge of the lower surface without a shock. However, at a certain higher speed, the drag divergence Mach number, a shock is required to recover enough pressure to match the pressures at the trailing edge. This shock causes transonic wave drag, and can induce flow separation behind it; both have negative effects on the airfoils performance.

But Supercritical airfoil has a higher MDD, allowing the aircraft to fly at higher speeds without drag rise and shock waves are generating farther aft than traditional airfoils. Also shock induced boundary layer separation is reduced, this allows for more efficient wing design geometry (e.g., a thicker wing and/or reduced wing sweep, each of which may allow for a lighter wing). The structural design of a thicker wing is more straightforward and actually results in a more lightweight wing. Also, a thicker wing provides more volume for an increased fuel capacity. Clearly, the use of a supercritical airfoil provides a larger design space for transonic airplane.

Lift that is lost with less curvature on the upper surface of the wing is regained by adding more curvature to the upper trailing edge. Now the aircraft can cruise at a higher subsonic speed and easily fly up into the supercritical range. Consequently, aircraft utilizing a supercritical wing have superior take-off and landing performance.

Higher subsonic cruise speeds and less drag translates into airliners and business jets getting to their destinations faster on less fuel, and they can fly farther and that help keep the cost of passenger tickets and air freight down. NASA's test program conducted at the Dryden Flight Research Centre from March 1971 to May 1973 and showed that the supercritical wing installed on an F-8 Crusader test aircraft increased transonic efficiency by as much as 15% and predicted that the net gain for air carriers worldwide would be nearly one-half billion dollars all due to fuel savings of the supercritical airfoil. Before the program ended, the U.S. Air Force teamed with NASA for a joint program to test a SCW designed for highly manoeuvrable military aircraft. An F-111, with a variable-geometry wing, was them testing aircraft and the basic supercritical research took place between 1973 and 1975. Results were extremely successful and showed the test wing generated up to 30% more lift than the conventional F-111 wing and performed as expected at all wing sweep angles.

Several military aircraft in testing and development stages are being built with supercritical wing technology. Among them are the Lockheed-Martin F-22 advanced technology Fighter, and the two aircraft that will be considered for the U.S. military Joint Strike Fighter production contract, the Boeing X-32 and the Lockheed-Martin X-35.

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