Transonic Characteristics of a Humped Airfoil

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Abstract

A HUMPED airfoil concept to improve the performance of supercritical airfoil at off-design transonic conditions is introduced. Theoretical aspects of the airfoil and recent experimental results from high Reynolds number transonic wind-tunnel tests at NASA Ames Research Center and The Ohio State University (OSU) are presented. Experimental evidence has shown that the humped airfoil generally has more stable aerodynamic characteristics in transonic off-design conditions than the baseline supercritical airfoil.

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The main issues that a new transonic airfoil concept must address are the drag rise associated with off-design conditions, and the resulting transonic buffeting caused by shock wave/boundary-layer interactions at high freestream Mach number or angle of attack. Ways to alleviate these effects are directed toward reducing the level of the interactions such as[1,2] 1) thinning the boundary layer ahead of the shock,[1] and 2) fixing the shock location.[2] The former forces the boundary layer to become supercritical so that communication of positive pressure disturbance from the shock to the upstream is prevented. The latter eliminates the excursion of the shock wave and, consequently, minimizes the magnitude of the shock disturbance.

These considerations lead to a new airfoil concept that should perform reasonably well at off-design transonic conditions if the following features are incorporated: 1) the basics of a supercritical airfoil, i.e., a nearly zero camber and reduced upper surface curvature in the midchord region, high-pressure recovery rear surface, and a cusp at the trailing edge, 2) a compression ramp for decelerating the local flow ahead of the shock, and 3) a sharp corner for fixing the shock location. A new airfoil is, therefore, derived using an existing Korn-Garabedian supercritical airfoil as the baseline airfoil. A small aerodynamic hump was added to the rear upper surface at the shock location of the baseline airfoil. The leading edge is made slightly drooped so that the zero-lift characteristics of the airfoil are unchanged. The new humped airfoil is shown in Fig. 1.

Experimental Investigation

The new airfoil has been experimentally investigated in the transonic wind tunnels at NASA Ames Research Center and OSU. Two airfoil models were constructed for the Ames tests—a humped airfoil and a Korn-Garabedian supercritical airfoil (baseline airfoil). The latter was tested to allow close comparison of the two shapes. The limited test runs conducted at Ames were later supplemented by similar but rather extensive experiments at OSU. Only the humped airfoil was tested at OSU, however.

Both airfoil models had a thickness/chord ratio of 16%. The humped airfoil had the hump located at $x/c = 0.76$, which was determined for the flow conditions at $M_\infty = 0.78$ and $C_L = 0.4$. The large thickness was chosen to explore extremes of transonic flow that is directly influenced by the thickness parameter.

The Ames tests were carried out with a Mach number range of 0.2 to 0.85 and corresponding Reynolds numbers of 1.0 to 4.0×10^6 for a series of angles of attack. Very limited data were obtained for Mach numbers higher than 0.8 and angles of attack beyond 2 deg. The OSU experiments extended the test range of the Mach number and angle of attack of the Ames measurements. The investigations at both facilities were limited to surface pressure measurements for determining the lift and moment coefficients and to the traverse wake survey for obtaining drag values. No schlieren photography for flow visualization was available.

Discussion of Results

The pitching moment coefficients about the leading edge of the two airfoils for a Mach number range of 0.4 to 0.85 at angles of attack of 0 and 2 deg are shown in Fig. 2. Although the variation of the moment coefficients exhibits the same trend for both airfoils, the magnitude of variation is somewhat less for the humped airfoil than for the regular supercritical airfoil. The OSU data follow the Ames trend. The results indicate that the movement of the shock is restricted by the hump, which improves the flow stability at high Mach number conditions. This is supported by the airfoil surface pressure patterns.

Typical drag characteristics are depicted in Fig. 3. Total drag values integrated from the wake rake survey of both experiments are presented. The Ames data indicate that the humped airfoil yields generally higher drag values than the supercritical airfoil throughout the Mach range tested. The difference diminished as the freestream Mach number is increased. The drag coefficient of the OSU tests are generally lower than the Ames data. This is believed to be due to higher test Reynolds numbers. The drag divergence occurs near Mach 0.73 for both airfoils. The level of divergence, however, is more moderate in the case of the humped airfoil than of the supercritical airfoil. This is more evident when the gradients of the drag coefficients at high Mach number range are examined. For Mach 0.772, which is close to the "design" condition of the humped airfoil ($M_\infty = 0.78$), a continuous decelerating flow from supersonic to subsonic is observed. The flow eventually separates after Mach 0.8, and the hump then becomes ineffective.

Experimental results show that the hump breaks the single shock wave into two weak waves over the Mach range tested. Although this generates more lift at lower Mach numbers, a reduction in lift in the high supercritical range is observed. As shown in Fig. 4, the humped airfoil produces less lift at Mach

Presented as Paper 87-1239 at the AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Honolulu, HI, June 8–10, 1987; received Nov. 9, 1987; revision received Dec. 30, 1987. Full paper available from National Technical Information Service, Springfield, VA, 22151, at the standard price (available upon request).

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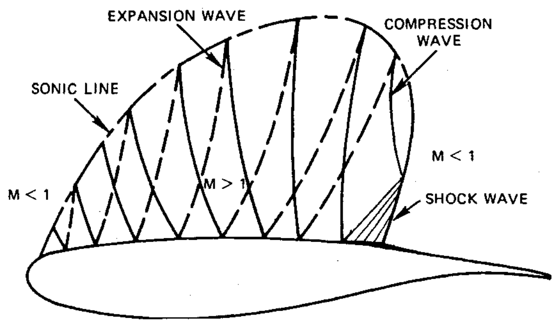

Fig. 1 Humped airfoil.

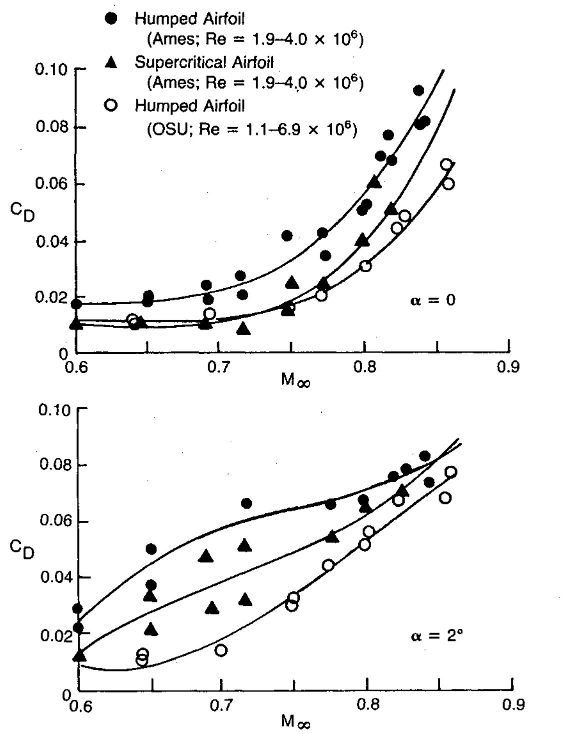

Fig. 2 Pitching moment coefficients about airfoil leading edge.

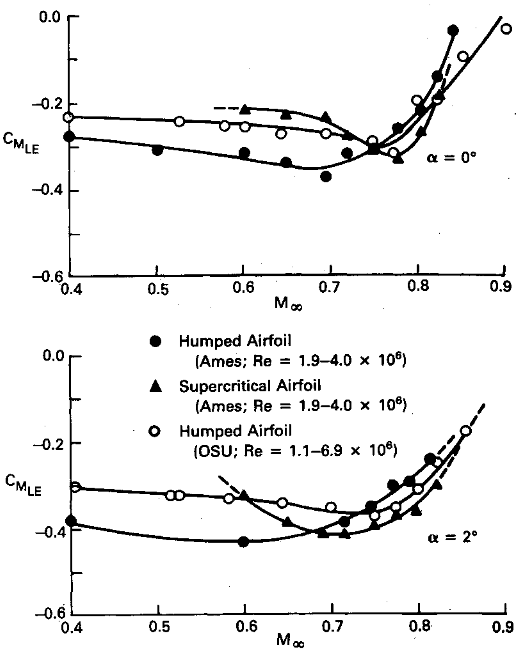

Fig. 3 Airfoil drag characteristics.

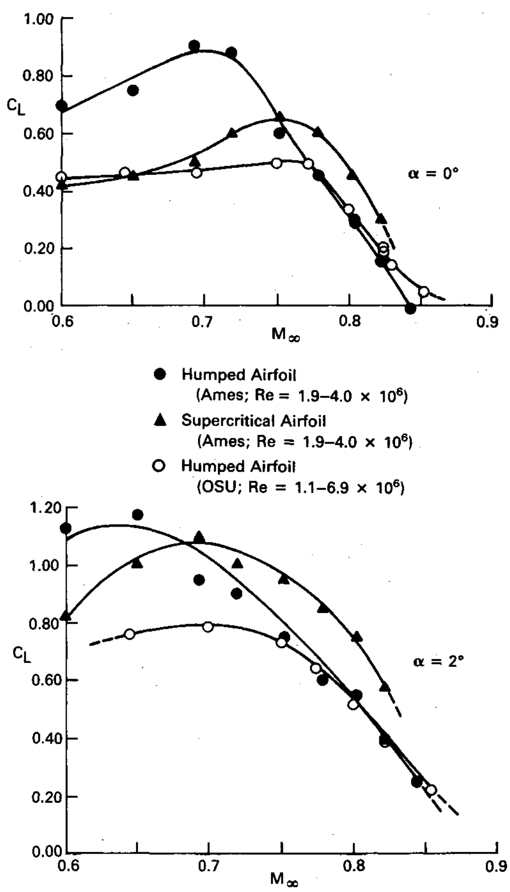

Fig. 4 Airfoil lift characteristics.

0.75 and beyond. The decrease in lift coefficient values at high Mach numbers, however, is compensated for a more stable lift range at high Mach numbers and angles of attack, up to Mach 0.85 and $\alpha = 10$ deg. This is significant for a 16%-thick airfoil where the flow is highly separated, yet no apparent aerodynamic stall occurs.

In summary, the experimental results indicate that the breaking of the shock wave by the hump leads to a concentration of lift near the hump that eventually stabilizes airfoil moments at off-design supercritical conditions. In addition, the lift coefficient of the humped airfoil, although generally reduced, is sufficient and stable for operation at high Mach numbers and angles of attack.

The breaking of the shock implies that the compression in the fore ramp of the hump is rather incomplete and is nonisentropic. This may very well be due to the short compression ramp on the present model (only 3.5% chord). Existing data indicate that generally about 7 to 10% of the chord length is required to decelerate the local supersonic flow isentropically from its peak value to sonic speed. For future hump designs, therefore, the length of the front compression ramp should be approximately 8 to 10% of the chord in length. The height of the hump, which will increase correspondingly, should not exceed the boundary-layer thickness. With the aid of modern computational fluid dynamics, an improved hump design may lead to a new era of supercritical airfoils for transonic maneuver.

References

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[2]Tai, T. C., "Theoretical Aspects of Dromedaryfoil," Rept. DTNSRDC-77/0104, David Taylor Research Center, Bethesda, MD, AD A047 150, Nov. 1977.