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Improvement of Transonic Wing Buffet by Geometric Modifications

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Introduction

WING buffet is a result of boundary-layer separation on the wing. Buffeting in transonic flow regime is closely connected with the shock-induced boundary-layer interaction, which can either cause boundary-layer separation beneath the shock leading to a separation bubble, or result in an early rear separation due to the increased susceptibility of the post-shock boundary layer in an adverse pressure gradient.[1] Both types of flow separation cause fluctuations in aerodynamic forces to stimulate the aircraft structure, and thus lead to limitations in the flight envelope of the aircraft.

The buffet boundary is the boundary in the lift (or angle of attack) and freestream Mach number plane separating conditions where the flow is essentially attached and where the flow is totally separated and dominated by shock oscillations and large pressure fluctuations. Most of the earlier studies of buffet were relied on wind-tunnel tests, and the method to determine buffet for airfoil or wing was approached by looking for the first slope decreasing in the C_l-α plot. However, many difficulties to accurately simulate buffeting arise from the experimental side, which include the rigidity of test models, the number of influential parameters being too large, lengthy time, and expensive cost of experiments, etc. A more economical and less time-consuming alternative to the determination of buffet boundaries would be the computational method, which is adopted for the present study.

Theoretically, the buffet onset of a transonic wing can be raised if boundary-layer separation and shock-wave strength are favorably controlled by making appropriate modifications to the wing geometry. Studies of conventional airfoils[2,3] and supercritical airfoils[4] with flaps show that the buffet boundaries can be raised appreciably by applying proper flap settings. More recently, Henne and Gregg[5] examined the geometric properties of a supercitical airfoil and found that a finite trailing-edge thickness can provide increased lift and also improvement in the wing buffet onset characteristics. To gain more insight into the possibilities of using geometric variation as a means for improving transonic buffeting, numerical investigations are carried out to study the performance of a twisted wing and that of a step wing with conventional symmetric airfoil sections.

A numerical tool has been assembled particularly for analyzing the wing buffet phenomenon, which consists of a three-dimensional grid-generation package and an efficient flow solver. The latter is based on an implicit finite difference code for solving the thin-layer compressible Navier–Stokes equations, using the Baldwin–Lomax turbulence model for boundary-layer calculations. A two-factored flux-split scheme is employed, which has the ability to compute subsonic, transonic, and supersonic flows about wings of arbitrary shape with possible weak boundary-layer separation. A detailed description of this numerical scheme is referred to in Pulliam and Steger.[6]

The wing model used for the analysis here is based on the ONERA M6 wing[7] configuration shown in Fig. 1. This untwisted wing of symmetric airfoil sections was developed especially for the experimental support of three-dimensional transonic and subsonic flowfield studies, whose extensive database of surface pressure distribution is available over a range of transonic Mach numbers at angles of attack up to 6 deg.

The computational grids are generated in the C-O topology (C in the streamwise direction and O in the spanwise direction). The total number of grids is 195 × 30 × 49. Either the algebraic or elliptic grid solver may be employed for surface and volume grid generation. Boundary-fitted meshes are generated with adequate spacing in the viscous sublayer to accurately resolve the high Reynolds number turbulent flow. In addition, grid refinements in the shock and wingtip regions are implemented for solving the transonic buffet problem.

Prediction of Light Buffeting

The light buffeting calculation for finite wings (reference to Thomas' idea concluded from the behavior of boundary-layer separation during buffeting) was made by Proksch.[8] The buffeting boundary is determined by taking into account the differential spanwise loading of the wing. For this purpose, a buffeting coefficient C_{bi} is introduced, which is directly related to the rms value of the wing root bending moment

$$C_{bi} = \int_{\eta_R}^{1} \frac{C_s(\eta)}{\bar{C}} (\eta - \eta_R)\, d\eta \tag{1}$$

in which $\bar{C}$ is a reference chord of the wing given by

$$\bar{C} = \frac{2}{3} C_r \left(\frac{1 + \lambda + \lambda^2}{1 + \lambda}\right) \tag{2}$$

where λ is the taper ratio of C_t/C_r, and C_t, C_r are the chords at the tip and root of the wing.

Equation (1) is established by assuming that the fluctuations of the wing root bending moment are proportional to the integral, evaluated along the wingspan, of the product of local lift fluctuations and the distance $(\eta - \eta_R)$ from the wing root. A further assumption is that the local lift oscillations caused by flow separation are proportional to the chord length $C_s(\eta)$ of the separated flow at a station of the wing. It has been shown[9] that a value of C_{bi} from 0.08 to 0.1 will coincide with the measured buffeting boundary. The value $C_{bi} = 0.09$ is used here as the criterion for buffet onset based on the slope method described earlier. In the neighborhood of this value the slope $dC_l/d\alpha$ consistently starts to decrease as shown in our computed results for various wing configurations.

Buffet Improvement

Transonic computations for the baseline M6 wing show that, at buffet onset, some shock-induced separation bubbles

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Aspect ratio	$A = 3.8$
Taper ratio	$\lambda = \frac{C_t}{C_r} = 0.563$
Sweep angle at leading edge	$\Lambda_{0\%} = 30^0$
Sweep angle at $\frac{C}{4}$	$\Lambda_{25\%} = 26.7^0$
Thickness-to-chord ratio	$t_{max} = 0.489$

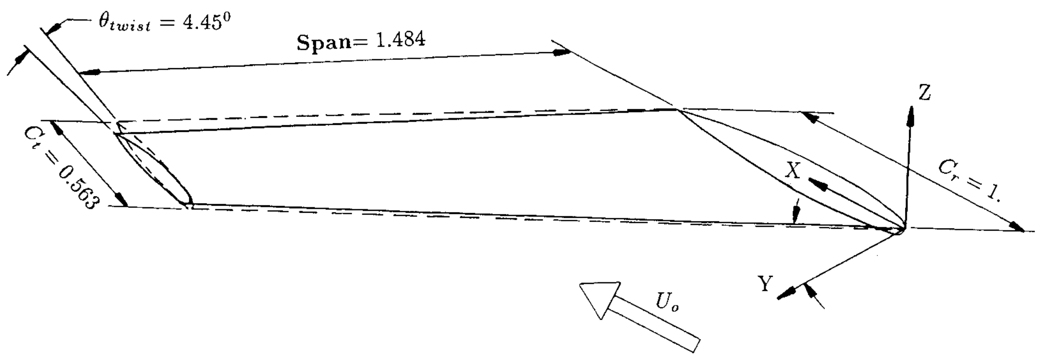

Fig. 1 Perspective view of the baseline M6 wing (solid line) and the twisted M6 wing (dashed line).

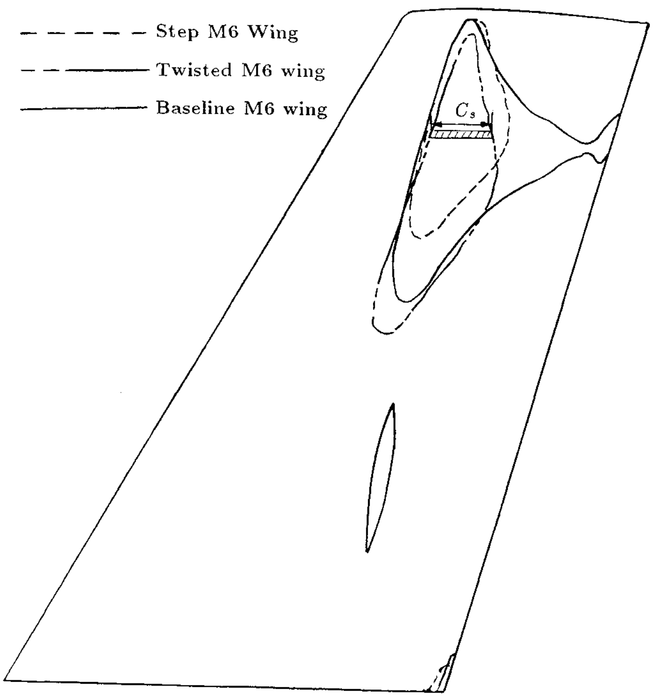

Fig. 2 Comparison of separation region for twisted, step, and M6 wing at $M = 0.84$ and $\alpha = 5.56$ deg.

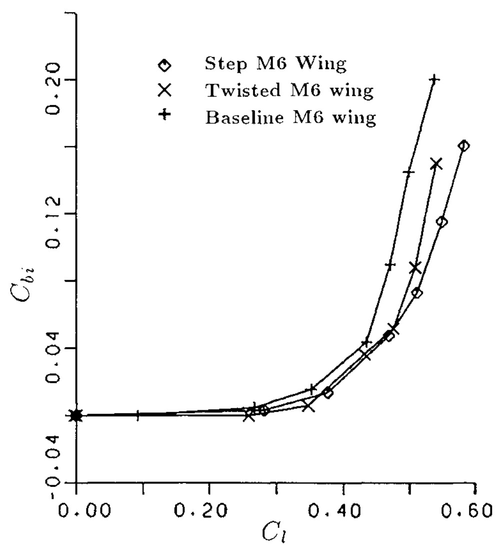

Fig. 3 Effect of twist and step on $C_{bi} - C_l$ behavior at $M = 0.84$.

of significant size appear in the presence of strong shock waves, as described by the solid lines in Fig. 2 for Mach number $M = 0.84$ at an angle of attack of 5.56 deg. A small change of the flow or the geometric may alter the character of the shock-wave/boundary-layer interaction. In order to avoid the separation penalties and raise the buffet boundaries in transonic speed regime, two types of wing design concept are proposed, namely the twisted wing and step wing, whose effects are examined separately.

Twisted Wing

Numerical results for transonic buffet of the M6 wing indicate that the strength of the shock wave in the outboard region of the wing is greater than that in the inboard region, so that separation appears first at outboard of the wing due to the stronger shock-boundary interaction there. While the outboard separation bubble has a stronger influence on raising the buffet boundary, it is speculated that a redistribution of the spanwise loading may result in an improvement on the wing buffet characteristics. The required load modification may be achieved by twisting the wing about an axis so that the sectional geometric angle of attack varies along the span.

For the present numerical study, the conventional M6 wing is modified by giving it a linear twist about the axis through the 25% chord along the wingspan, with a −4.45-deg angle at the tip relative to the root, as shown in Fig. 1. The angle of attack α of the twisted wing is measured from the zero-lift line of the wing.

The buffet onset for the twisted M6 wing is found to occur approximately at $\alpha = 5.9$ deg and $C_l = 0.50$, as compared to $\alpha = 5.6$ deg and $C_l = 0.47$ for the untwisted wing. These buffet conditions are determined in Fig. 3 from the $C_{bi} - C_l$ curves based on the definition that $C_{bi} = 0.09$ for buffet onset. As indicated in this plot, the twisted M6 wing can significantly lower the C_{bi} values in the buffet region. Using $C_l = 0.47$ as an example, at which the baseline M6 wing is already at buffet onset with $C_{bi} = 0.0895$, whereas for the twisted M6 wing the corresponding C_{bi} is only 0.0517, which is 42% lower.

A comparison of spanwise pressure distributions for $M = 0.84$ and $\alpha = 5.6$ deg, when both the twisted wing and the baseline wing are at $C_l = 0.47$, shows modified wing reduces the strength of the outboard shock wave and, as a result, reduces the size of the shock-induced separation bubble in that region. The separated area on the upper surface plotted in Fig. 2 indicates that the twisted wing cannot only reduce the separation size, but also alter the shock wave position and the reattachment line of a bubble. Such a phenomenon would cause boundary-layer separation to occur at a higher lift. Furthermore, the spanwise load distribution for $M = 0.84$ and $\alpha = 5.6$ deg indicates that the twisted wing shifts the load and, therefore, the separation bubble toward the wing root. The reduced distance of the separation bubble from the root would lower the C_{bi} value and raise the buffet onset boundary.

Step Wing

The new airfoil design concept presented by Henne and Gregg[5] using a finite trailing-edge thickness on the supercritical airfoil showed that such a modification can provide an additional lift and raise the buffet boundary. The step trailing-edge concept for supercritical airfoil is now applied to the M6 wing in the hope that this concept can also be used to improve the transonic buffet behavior of wings with symmetric airfoil sections.

The model step wing adopted for numerical study here is obtained by replacing the rear 10% of the baseline M6 wing with a flat step, whose thickness is equal to the local thickness of the original airfoil at 90% chord.

In order to see the effect of the step wing, its flow characteristics are compared with those of the baseline M6 wing flying at the same Mach number of 0.84, and having the same lift $C_L = 0.47$, but at different angles of attack $\alpha = 5.56$ deg (baseline) and $\alpha = 5.06$ deg (step). The step trailing edge modifies the positive aft-camber geometry on the lower surface of the wing and the negative aft-camber geometry on the upper surface of the wing. This modification causes a higher pressure at the lower surface and a lower pressure at the upper surface of the trailing edge, resulting in an increased aft loading of the step wing. For the same lift coefficient, wing loading is redistributed in both chordwise and streamwise directions. The step wing causes a significant reduction in shock-wave strength, which would delay the shock-induced flow separation and thus raise the buffet onset boundary of the step wing. Such an expectation is realized in Fig. 2, which shows a reduced size of the separated region on the step wing as compared with that on the baseline M6 wing at the same Mach number and lift coefficient.

The buffet onset for the step wing at $M = 0.837$ occurs at $\alpha = 5.7$ deg and $C_l = 0.524$, which is determined from Fig. 3 according to Thomas' concept. The increment in buffet lift coefficient for the step wing at $C_{bi} = 0.09$ is approximately 0.053, which is a 10.6% increase compared to the original M6 wing. The relatively large improvement on buffet onset is due to the reduced area of the separated region. The trend of continuing improvement on lift and buffet boundary for the step wing can be expected at higher angles of attack.

In reality, the sharp trailing edge of a conventional wing actually has a finite minimum thickness for structural reasons. Since the trailing edge of finite thickness can support a higher aerodynamic load than that with a sharp edge, the step wing will provide a significant improvement for buzz or flutter of the trailing edge.

Conclusions

With the hope to avoid separation penalties and raise the buffet onset boundary of the transonic wing, the behaviors of twisted wing and step wing have been examined. With a proper twist, the twisted wing can change the spanwise loading to reduce the shock-wave strength, accelerate the upper surface flow, and thin out the boundary layer in the wingtip region so that the size of separation region is reduced. The results also demonstrate that the increase in lift and reduction in drag for the twisted wing are of sufficient magnitudes to be considered for an improved design. On the other hand, the step wing, which has a positive aft-camber geometry on the lower surface and a negative aft-camber geometry on the upper surface of the wing, can significantly increase the aft wing loading, weaken both the shock-wave strength and the upper surface pressure gradient, and thus can provide an improvement on transonic buffeting.

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