140 deg, where the jet noise usually peaks. However, it is important to stress that this can include effects caused by flow and sound interactions.

VI. Conclusions

In this Note we have considered two important improvements that the original MGB code needed for estimating noise generated from high-Reynolds-number turbulent flows. First, we allowed the spatial dependence of the temporal correlation function. Second, we used the Batchelor structure function, which has the appropriate inertial range form. Numerical tests against experimental data and original MGB code calculation demonstrated that significant improvement can be achieved.

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Improved Computational Method for Determining Light Buffet of Flapped Wings

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Introduction

BUFFETING is the response of a transonic aircraft to the fluctuating aerodynamic forces originating from the separated flow regions on its wing. The commonly adopted computational method for predicting light buffet of an aircraft is that developed by Proksch[1] based on the wing area occupied by the separated flow. However, when this method is applied to a flapped wing, unrealistic results might be obtained for large flap-deflection angles.

As an illustrative example shown in Fig. 1, we consider two identical flapped airfoils with different flap-deflection angles δ_a and $\delta_b (> \delta_a)$. The deflection angles are so large that the upper surfaces of both flaps are completely occupied by fully separated flows, whose lengths are equal to the length of the flap. Then, according to Proksch's method, the buffet coefficients for these two airfoils are the same. However, the size of the separation bubble in case b is larger than that in case a, and therefore it is expected to cause a stronger buffeting force on the flap. This simple example indicates that the projected area of the separated flow alone truly cannot represent the buffet intensity of the fluctuating forces originating within the separated flow. The result thus suggests that the vertical dimension of the separation bubble, in addition to its projected area on the wing, is also a characteristic parameter for determining the buffet intensity of wings with strong flow separation.

In this Note, the computational method developed by Proksch[1] for predicting light buffet of a wing is first described, then followed by our proposed method, which takes into account the volume of separated flows. The advantage of using the latter is demonstrated in an example for predicting the light buffet of a model flapped wing utilizing both methods.

All flow computations shown here are carried out using an efficient numerical tool that provides a user-friendly environment for the control of smoothness, clustering, and orthogonality of the grids. The total number of grids is $195 \times 30 \times 49$, with 195 points in the streamwise direction (ξ), 30 points in the spanwise direction (η), and 49 points in the direction normal to the wing surface (ζ). The transonic flow code that solves the thin-layer Navier–Stokes equations using an implicit and approximately factored scheme[2] is based on central differencing in both the η and ζ directions and upwind differencing in the ξ direction. The algebraic turbulent-eddy-viscosity model of Baldwin and Lomax[3] is used to calculate the turbulent shear stress. The code was validated using an unflapped ONERA M6 wing, whose experimental surface-pressure data are available in Ref. 4. Details of the numerical tool and code validation are described in Ref. 5.

Light Buffet Prediction Methods

Method Based on Proksch's Buffeting Coefficient C_{bi}

A numerical procedure for predicting light buffet for finite wings based on the concept of Thomas and Redeker[6] was carried out by

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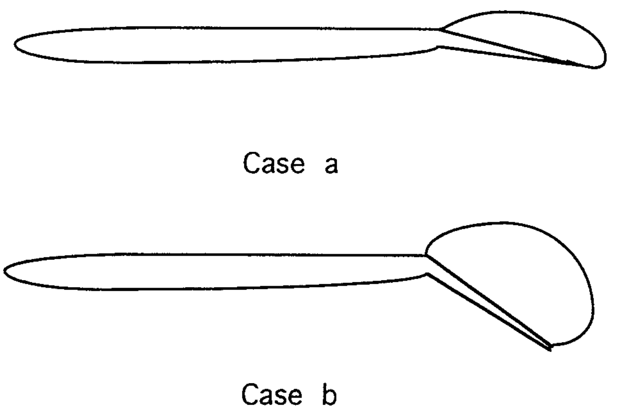

Fig. 1 Separated flow on trailing edge of flapped airfoils.

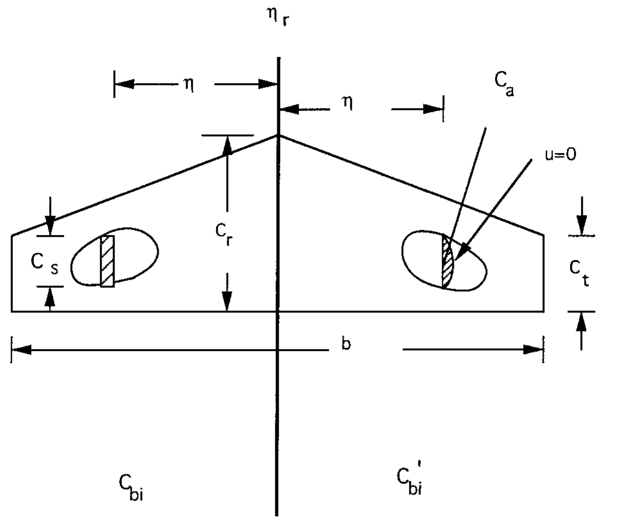

Fig. 2 Definitions for Proksch's buffeting coefficient C_{bi} and modified buffeting coefficient C'_{bi}.

Proksch. Proksch[1] introduced the buffeting coefficient C_{bi} as a predictor of wing light buffet, which is defined on the left of Fig. 2 for an arbitrary wing as

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

where $C_s(\eta)$ is the length of the separated flow at a station η of the wing, which is at a distance $\eta - \eta_r$ from the root, $\bar{c}$ 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 c_t/c_r; c_t and c_r are the chords at the tip and root of the wing, respectively. The distance η_r of the root from the wing centerline is zero for the wing shown in Fig. 2. Proksch's method is based on the assumption that the length of the separated flow at a spanwise wing station can correctly represent the lift fluctuations produced locally by the separation bubble. It will be shown later that unrealistic results could be obtained when Proksch's method is used to compute the buffet behavior of a wing with large flap deflections.

Method Based on the Modified Buffeting Coefficient C'_{bi}

The Proksch's buffeting coefficient is now modified to take into account the volume of the separated bubble. In a numerical solution, it is usually difficult to determine the shape and volume of a separation bubble. However, the surface on which the streamwise velocity component u vanishes within the recirculating bubble can be computed rather easily. Thus, the volume of the region bounded by the $u = 0$ surface and the wing surface (Fig. 3), which is roughly proportional to the volume of the separation bubble, is used here as a representative indicator of the intensity of the fluctuating forces inside the separation bubble. A modified buffet coefficient C'_{bi} is defined accordingly as follows:

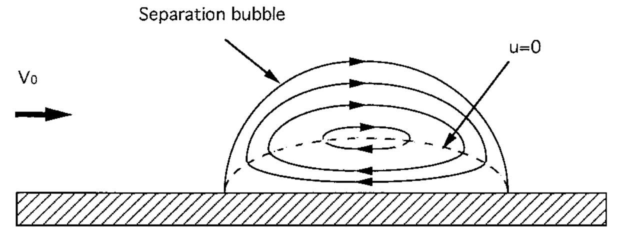

Fig. 3 Separation bubble and u = 0 boundary.

$$C'_{\mathrm{bi}} = \frac{0.1}{c_0 + c_1 M}C_v \tag{3}$$

$$C_v = \int_{\eta_r}^{1} \frac{C_a(\eta)}{\bar{c}^2}(\eta - \eta_r)\,\mathrm{d}\eta \tag{4}$$

where the coefficients c_0 and c_1 are added to accommodate the influence of the Mach number M, $\bar{c}$ is the reference chord defined in Eq. (2), and C_a is the cross-sectional area of the region with $u = 0$ as the outer boundary, which is inside the separation bubble at a spanwise wing section, as sketched on the right half of Fig. 2. Similar to the criterion based on Proksch's buffeting coefficient C_{bi}, the value $C'_{\mathrm{bi}} = 0.1$ is still used to define the light-buffeting boundary. Because of the unavailability of experimental data for flapped finite wings, coefficients c_0 and c_1 are determined using the unflapped ONERA M6 wing. The light buffet boundaries of the unflapped M6 wing are first determined by Proksch's criterion that $C_{\mathrm{bi}} = 0.1$ for a range of transonic Mach numbers, and the corresponding C_v values are evaluated according to Eq. (4) and then plotted as a function of Mach number. For our present case, the values of C_v between $M = 0.60$ and 0.84 are fitted by a straight line, which represents the light-buffet condition of $C'_{\mathrm{bi}} = 0.1$. With the values of c_0 and c_1 determined from this straight line, the light-buffet boundary for the flapped M6 wing is computed by using Eq. (3) with the criterion that $C'_{\mathrm{bi}} = 0.1$.

Computed Results for a Flapped Wing

Because of the lack of experimental data in the literature on the buffet of particular flapped wings for comparison with our numerical results, an ONERA M6 wing with both leading- and trailing-edge flaps is arbitrarily chosen as the model for the present numerical study. As described in Ref. 4, the planform of this trapezoidal wing has an aspect ratio of 3.8 and a taper ratio of 0.56, whose quarter-chord line is swept back through a 26.7 deg angle. The length of the leading-edge flap is $0.15c$ and that of the trailing-edge flap is $0.20c$, where c is the chord of the local wing section.

The use of leading- and trailing-edge flaps has been proven in flight as an effective technique for buffeting reduction. A numerical study of the influence of flap scheduling on aircraft performance at light buffet is carried out here for the ONERA M6 flapped model wing by the use of the modified buffet coefficient C'_{bi}.

As a reference for comparison, the buffet characteristics of the basic unflapped M6 wing are first presented. Light buffeting for this wing is found to occur at angle of attack $\alpha = 7.23$ deg and $C_L = 0.486$ for $M = 0.70$, and at $\alpha = 5.81$ deg and $C_L = 0.492$ for $M = 0.84$. Variations of the lift coefficient at light buffeting ($C_{\mathrm{Ll.b.}}$) with increasing δ_{ef} for different fixed leading-edge flap deflections are plotted in Fig. 4 for both $M = 0.70$ and 0.84. At $M = 0.70$, a 92% increment in $C_{\mathrm{Ll.b.}}$ is obtained by deflecting the leading-edge

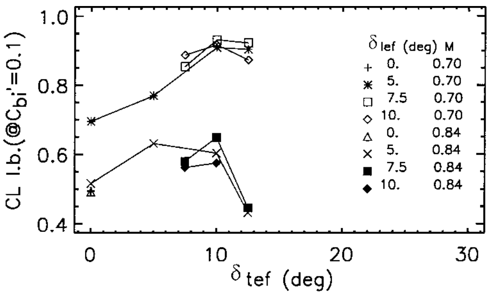

Fig. 4 $C_{Ll.b.}$ vs δ_{tef} for different fixed δ_{lef}, at $M = 0.70$ and 0.84, based on $C'_{bi} = 0.1$.

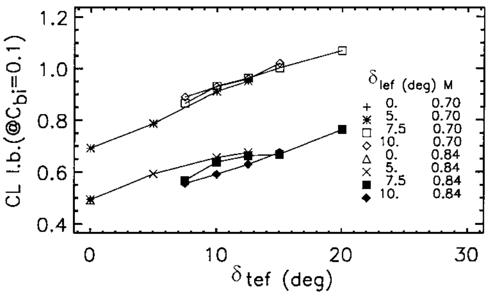

Fig. 5 Results for conditions described in Fig. 4 based on Proksch's light buffet criterion of $C_{bi} = 0.1$.

flap 7.5 deg downward and trailing-edge flap 10 deg downward. At $M = 0.84$, a 32% increment is achieved by the same flap deflection angles. The lift coefficient at light buffeting for the same flap configurations based on Proksch's C_{bi} method is shown in Fig. 5, showing an unrealistic phenomenon of ever-increasing $C_{Ll.b.}$ with increased deflection angle of the trailing-edge flap. Such a result contradicts empirical data for several other aircraft (see Refs. 7–10), whose light-buffet boundaries occur when δ_{tef} is much lower than 20 deg. Even in the absence of published test results for the ONERA M6 wing, we can conclude that the light buffet condition of $\delta_{tef} \sim 20$ deg for this wing is unrealistic, indicating that Proksch's method based on C_{bi} is not suitable for flapped wings.

Conclusions

For analyzing flapped-wing buffet behaviors, Proksch's buffet coefficient C_{bi}, commonly used for numerical prediction of buffet for wings without flap deflections, is modified and named C'_{bi} in this Note to take into account the volume of separated flow regions on the wing. The improvement in buffet analysis by using the modified buffet coefficient has been demonstrated in the numerical example of choosing proper flap scheduling for improving aircraft performance at transonic speeds. It shows that the proposed, modified buffet coefficient is possibly a more appropriate parameter for analyzing the buffet behavior of wings with strong flow separations.

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Revisiting Unresolved Dynamic Stall Phenomena

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Introduction

THE rapid growth of the wind-turbine industry has generated renewed interest in the dynamic stall phenomenon due to the fact that wind-turbine blades operate continuously under stalled flow conditions.[1] In the literature search for Ref. 2, the present author ran across 30-year-old dynamic test results for a NACA-0012 airfoil section, oscillating around 25% chord[3] (Fig. 1), results that deviated dramatically from those expected[4] (Fig. 2). Although the two-dimensional test rig generated a highly three-dimensional flow separation pattern (Fig. 3), the lift measured by the balance at 25% chord should represent the general lift characteristics for two-dimensional unsteady airfoil stall. That is, the attached flow regions near the endplates at $\alpha = 12.3$ deg in Fig. 3a and at $\alpha = 14.6$ deg and 16.6 deg in Fig. 3b would have affected the magnitude of the measured $C_L(\alpha)$ but should not have distorted the general two-dimensional dynamic stall characteristics of the central wing area to make the lift measurements physically misleading. Consequently, the $C_L(\alpha)$ characteristics in Fig. 1 should have a two-dimensional phenomenological explanation. The carefully executed dynamic test, with its thoroughly documented experimental results, vividly illustrates how various flow phenomena could interact to distort the results obtained in subscale dynamic stall tests. The test results also describe full-scale flow interactions that could have significant influence on the unsteady aerodynamics of wind-turbine and helicopter blades.

Accelerated-Flow and Moving-Wall Effects

For the pitching airfoil in Fig. 1, the accelerated-flow effect and the Moving-wall effect act in unison.[5,6] Their combined effect can be represented by the dominating moving-wall effect, illustrated by classic Magnus lift results,[7] in both laminar (Fig. 4a) and turbulent (Fig. 4b) flow separation. The downstream moving-wall effect on the top side delays separation, and the upstream moving-wall effect on the bottom side promotes it. The combined effect is to generate a positive Magnus lift at $U_W / U_\infty < 0.3$ in Fig. 4a and at $U_W / U_\infty < 0.1$ in Fig. 4b. For the pitching airfoil, the corresponding moving-wall effect[6] is generated as shown in Fig. 5. During the upstroke (Fig. 5a), the flow velocity at the leading-edge surface has to be equal to the tangential surface velocity U_W to satisfy the no-slip condition. When the air flow has "rounded the corner" to the upper surface aft of the leading edge, U_W has decreased greatly,

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