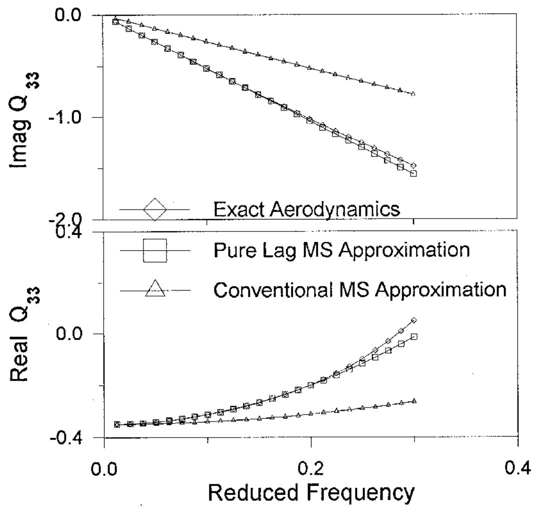

Fig. 2 Variation of three-term reconstruction for element Q_{33} with reduced frequency.

minimum-state approximations provide a much better tradeoff between fit accuracy and state vector dimension than other RFAs.

The nonmonotonic nature rate of fall of fit error with number of *D-E-D* iterations, as reported by Karpel,[2] was also observed in the case of the PLMS approximation. However, the two approximations required a different number of *D-E-D* iterations to arrive at the same level of fit error for the same number of aerodynamic lag poles. This phenomenon necessitates special care in comparing the two approximations. However, the first plateau in the curve of fit error vs number of *D-E-D* iterations was almost always reached before 150 iterations in both approximations.

To bring out the differences in the interpretation of A_0, A_1, and A_2 in the two approximations, the curve fits for both approximations were first carried out using six lag poles each. After computation of the coefficient matrices, the Q_{ij} were reconstructed using only the first three of these matrices, A_0, A_1, and A_2. As a typical illustration, Fig. 2 shows the variation of Q_{33} with reduced frequency $\bar{k}$ using such a reconstruction. It is obvious from Fig. 2 that such a reconstruction using the CMS approximation does not agree with the actual values, even over a limited range of reduced frequency, in contrast to that obtained using the PLMS approximation, which matches well with the frequency domain values. This is because the CMS approximation is consistent only in its totality and has component terms that lack physical consistency. However, in the PLMS approximation, the quasisteady and pure lag terms are decoupled. Similar trends were observed for other elements of the unsteady aerodynamic matrix as well. The pure lag curves in Fig. 2 also allow for the establishment of the domain of validity of the quasisteady approximation for various elements of the unsteady aerodynamic matrix. In particular, the quasisteady approximation is valid for element Q_{33} up to around $\bar{k} = 0.2$. The PLMS approximation thus provides a facility to progressively increase the range of validity of the approximation by the addition of more terms, starting from a one-term approximation. The CMS approximation does not provide this feature.

Conclusions

A PLMS approximation has been developed from the CMS approximation for unsteady aerodynamic loads. The new form of the approximation decouples quasisteady and pure lag terms and allows for direct incorporation of quasisteady wind-tunnel or CFD data into the approximation, in contrast to a more computationally elaborate method through incorporation of constraints, as carried out in the CMS approximation. It is also easier to carry out model order reduction through dynamic residualization in a consistent manner through the use of the PLMS approximation, because of the quasisteady aerodynamic damping matrix being characterized by a single coefficient matrix in the new approximation. Results obtained for the PLMS approximation demonstrate its utility as well as its advantages over the CMS approximation.

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Control of Leading-Edge Vortices with Suction

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Introduction

SEVERAL control techniques have been applied to control leading-edge vortices over delta wings at high angle of attack. The purposes of these control techniques are to influence the strength and structure of the vortices, to generate rolling moment, and to delay vortex breakdown. The application of suction offers advantages over other methods because of its simplicity. The earliest application of suction for vortex control is reported by Werle,[1] who demonstrated a delay of vortex breakdown by applying suction along the vortex axis. Parmenter and Rockwell[2] conducted similar experiments and described the transient response of vortices to suction.

Because the vorticity of the leading-edge vortices originates from the separation point along the leading edge, control of development of the shear layer by blowing/suction has been chosen as a control strategy in several investigations. Wood et al.[3] and Gu et al.[4] applied blowing and suction in the tangential direction along a rounded leading edge. These studies showed that a rounded leading edge can alter the location of separation

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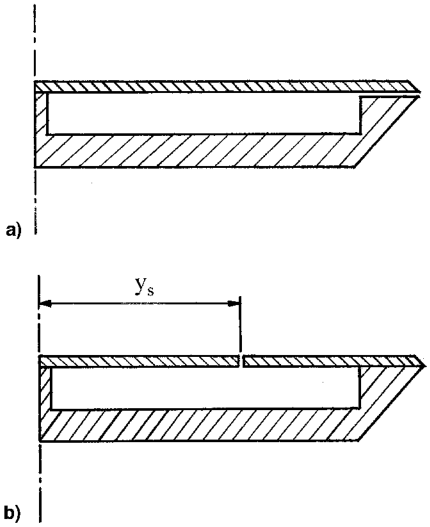

Fig. 1 Schematic of a) leading-edge and b) surface suctions.

from the leading edge by tangential blowing. It has been pointed out that this technique uses the Coanda jet effect to help the shear layer attach to the convex surface. Therefore, the application of this technique requires thick rounded leading edges.

The effect of leading-edge suction on leading-edge vortices over delta wings with sharp leading edges was recently investigated.[5] By using suction near the separation line along the leading edge (Fig. 1), it was shown that the separated shear layer could be effectively manipulated. As a result, the structure of the leading-edge vortex and its location over the wing were modified as well. This can be used to generate rolling moment over a delta wing. At large angle of attack, the delay of vortex breakdown was possible. It was shown that application of the leading-edge suction technique does not require thick rounded leading edges.

The main objective of this work is to explore the feasibility of vortex control by using suction via a slit on the upper surface of a delta wing (Fig. 1). Depending on the location and magnitude of the suction, the location and strength of the leading-edge vortex may be controlled. This can be used to alter the swirl angle and streamwise pressure gradient, which are known to be the main parameters affecting the vortex breakdown. Thus, experiments were conducted to explore the effectiveness of surface suction on vortex breakdown.

Experimental Setup

Flow visualization experiments were carried out in a wind tunnel with a cross-sectional area of 305 by 305 mm. The turbulence intensity in the wind tunnel was 0.25%. Experiments on both the leading-edge suction and surface suction were conducted on two similar model delta wings (Fig. 1) that had a sweep angle of $\Lambda = 65$ deg. The chord length was $c = 122$ mm and the Reynolds number based on the chord length was in the range of $Re = 1.2 \times 10^4$ to 3.5×10^4. The maximum blockage ratio was 3%. The body of the models was made of Plexiglas® and the upper plates were made of stainless steel. The leading edges were beveled at 45 deg on the windward side.

Several upper plates were fabricated to carry out experiments for different locations of suction (Fig. 1). For the leading-edge suction experiments, the height of the suction slot was 1 mm. For the surface suction experiments, the width of the suction slit was also 1 mm. Suction slit (which starts at $x/c = 0.15$ and ends at $x/c = 0.95$) was connected to a large suction reservoir attached to the suction tubing at the trailing edge of the model. The suction flow was generated by a fan located outside the test section. The volume flow rate for suction was measured by a rotameter-type flow meter. The dimensionless suction coefficient is defined as $C\mu = (V_s/U_\infty)^2(A_s/S)$, where V_s is suction velocity at the suction slot, U_∞ is the freestream velocity, A_s is the area of the suction slot, and S is the surface area of the wing. The measurement uncertainty for the suction coefficient is 5%.

Smoke injected near the apex helped to visualize the vortex core and provided information on vortex breakdown location. The flow visualization was videotaped for further analysis. The measurement uncertainty for the time-averaged breakdown location is 2% of the chord length. A single hot-wire probe was used to monitor the velocity fluctuations over the wing. Velocity signals were processed by a two-channel signal analyzer. Further information regarding the experimental setup and instrumentation can be found in Ref. 6.

Results

Figure 2 shows flow visualization photographs for which suction applied at $y_s/s = 0.7$ [where y_s is the location of suction slit (Fig. 1) and s is the local semispan] for a suction coefficient of $C_\mu = 0.72$ and without suction for an angle of attack $\alpha = 25$ deg. It is seen that vortex breakdown location moves downstream with suction. The Reynolds number was $Re = 1.4 \times 10^4$. Note that the vortex axis bends toward the wing surface near the trailing edge when suction was applied. This may be because of a nonuniform surface suction along the slit. At higher speeds, a hot-wire signal was also used to detect vortex breakdown. Figure 3 shows, for $Re = 3.5 \times 10^4$, hot-wire signals for the probe location ($x/c = 0.80$, $y/s = 0.30$, $z/s = 0.22$) with and without suction. The location of the hot-wire probe and the vortex core and shear layer without suction are sketched in the inset of Fig. 3. The location of vortex core and shear layer were taken from laser Doppler velocimetry measurements over a similar model.[6] It is seen that large-scale fluctuations are suppressed with suction because the location of vortex breakdown moves downstream. Note that the results shown in Fig. 3 are only qualitative, because the single hot-wire probe is sensitive to the magnitude of the velocity vector in the three-dimensional flowfield. Nevertheless, it shows the

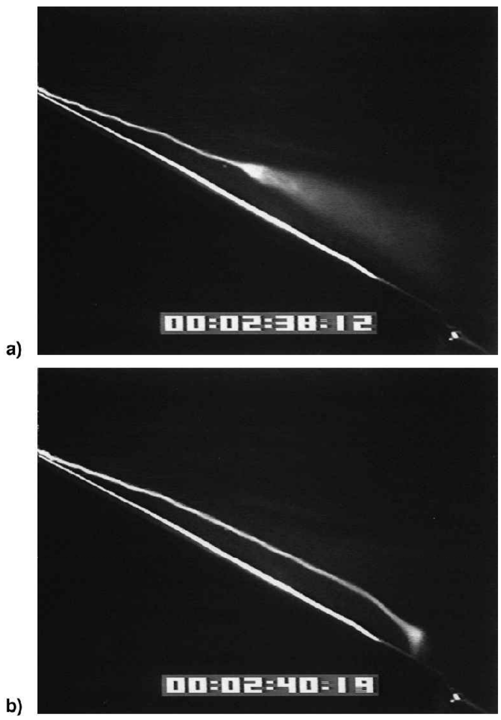

Fig. 2 Flow visualization of vortex breakdown a) without and b) with suction, $y_s/s = 0.7$, $C_\mu = 0.72$, $\alpha = 25$ deg, and $Re = 1.4 \times 10^4$.

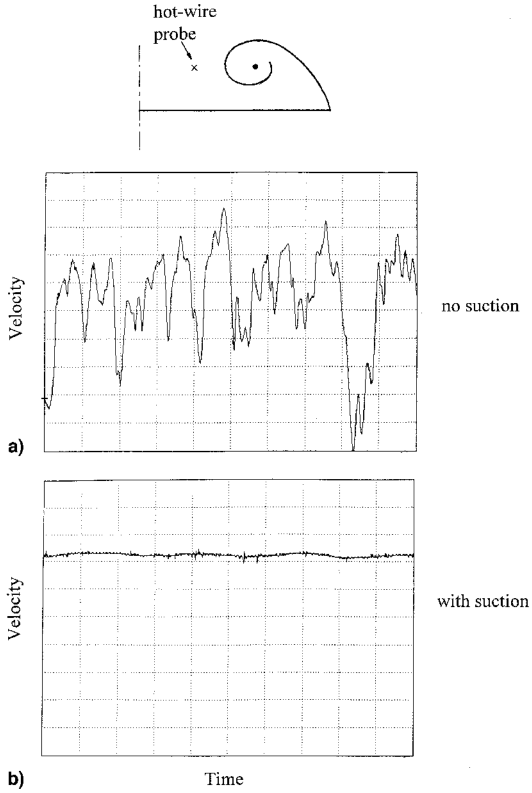

Fig. 3 Hot-wire signals at (x/c = 0.8, y/s = 0.3, and z/s = 0.22) a) without and b) with suction, y_s/s = 0.7, C_μ = 0.72, α = 25 deg, and $Re = 3.5 \times 10^4$.

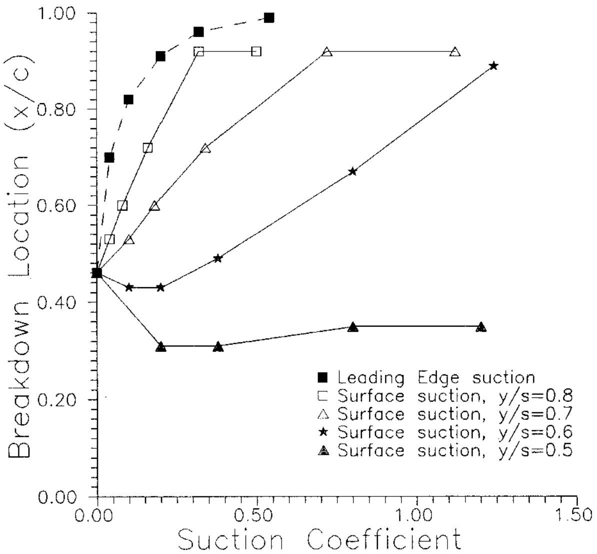

Fig. 4 Variation of breakdown location as a function of suction coefficient.

unsteady nature of flowfield when breakdown exists[7] and an almost steady flow in the absence of breakdown.

The effect of location of suction slit is shown in Fig. 4, together with the results for the leading-edge suction. Note that, in the absence of suction, the spanwise location of vortex axis is $y_v/s \cong 0.60$. For the smallest value of y_s/s tested (y_s/s = 0.5), vortex breakdown location moves upstream when suction is applied. Therefore, the effect of suction on vortex breakdown is negative. For y_s/s = 0.6, there is almost no change for small values of suction coefficient. However, there is an improvement at large values of suction coefficient. It is seen that, as the suction slit gets closer to the leading edge, suction becomes more effective in delaying vortex breakdown (y_s/s = 0.7 and 0.8). Even for small values of suction coefficient, considerable delay of breakdown is achieved. However, surface suction is less effective than leading-edge suction. For very small values of suction coefficient, large improvements can be obtained. On the other hand, both leading-edge suction and surface suction seemed to lose effectiveness when breakdown location reached the trailing-edge region. It is clear that the adverse pressure gradient near the trailing edge is very strong.

Conclusions

The effect of suction on the wing surface on vortex breakdown has been investigated. Suction has been found to be more effective in delaying vortex breakdown for suction slits closer to the leading edge. The exact mechanism of how the surface suction affects vortex breakdown is not clear. However, surface suction is less effective than the leading-edge suction.

Acknowledgment

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Neural Network Parameter Extraction with Application to Flutter Signals

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Introduction

DETERMINATION of the flutter boundary of an aircraft requires accurate measurements of frequencies and damp-

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