Progress in Analysis and Prediction of Dynamic Stall

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Nomenclature

c	= chord
C_D	= drag coefficient, D/qA
C_L	= lift coefficient, L/qa
C_P	= pressure coefficient, $P\text{-}P_\infty/q$
C_M	= pitching-moment coefficient, M/qA
D	= drag, lb
k	= reduced frequency, $\omega c/2U$
L	= lift, lb
M	= Mach number; pitching moment, ft-lb
P	= pressure, lb/in.^{2}
q	= dynamic pressure, $1/2\rho U^2$
R, Rc, Re, Rn	= Reynolds number
t	= time
U, V	= freestream velocity, ft/s
x	= distance
α	= angle of attack, deg
ζ	= nondimensional chord length, x/c
ζ_{tr}	= transition location
ω	= rotational frequency, rad/s
ρ	= density, lb/ft^3
Λ	= sweep angle, deg

Introduction

DYNAMIC stall is a term often used to describe the complex series of events that result in the dynamic delay of stall, on airfoils and wings experiencing unsteady motion, to angles significantly beyond the static-stall angle. This delay of stall, usually followed by large excursions in lift and pitching moment, has challenged aerodynamicists for many years. The phenomenon appears on helicopter rotor blades, rapidly maneuvering aircraft, wind turbines (used for electric power generation), on jet engine compressor blades and even insect wings. In many cases, dynamic stall becomes the primary limiting factor in the performance of the associated vehicle or structure. Impressive progress has been made, both in analysis and prediction of dynamic-stall effects; in order to give some perspective to the present review of dynamic stall, some history of dynamic-stall research is in order.

The mechanism of dynamic stall was first identified on helicopters. The importance of unsteady aerodynamics was considered by Harris and Pruyn,[1] when helicopter design engineers were unable to predict the performance of high-speed helicopters using conventional aerodynamics. As a result of further analysis, it was observed that the extra lift on the helicopter rotor could be explained if lift on the blade was greater than that predicted by steady flow during the time when the blade was moving opposite to the direction of flight (the retreating-blade condition; see Fig. 1). Concurrently, Ham and Garelick[2] observed that extra lift could be created by rapid pitching of airfoils, and that this extra lift was associated with a vortex formed on the airfoil during the unsteady motion.

The primary characteristics of this three-dimensional, rotor-related phenomenon can be experimentally represented by the shedding of a vortex at the leading edge of two-dimensional airfoils. This was modeled by Ham[3] to reproduce the same form of dynamic overshoot that was observed in helicopter flight tests. Research into this overshoot continued at helicopter companies: Carta[4] was able to identify a pressure field on oscillating, two-dimensional airfoils that was indicative of the passage of a vortex; Liiva and Davenport[5] also observed this vortex passage and the corresponding dynamic pressure distribution. Dynamic stall was then explored by McCroskey and Fisher[6] on a model rotor, and they verified that the dynamic effects were indeed a result of a vortex-dominated flow field that occurred during blade motion into the low-dynamic-pressure environment of the third and fourth quadrants of the helicopter rotor. This model rotor test, and further two-dimensional airfoil wind-tunnel tests, then produced more quantitative information about dynamic stall. Experiments were performed by Martin et al.[7] using flow-visualization techniques to again demonstrate the presence of the vortex. More information is presented in Refs. 8–11, in which various airfoils were studied over wide ranges of mean angles, amplitudes of oscillation, reduced frequencies, Reynolds numbers, and Mach numbers, and a new level of understanding was obtained about dynamic stall. For further review of dynamic-stall research associated with helicopters, see Refs. 12–15.

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Presented as Paper 85-1769 at the AIAA Atmospheric Flight Mechanics Conference, Snowmass, CO, Aug. 19–21, 1985; received Nov. 20, 1986; revision received April 1, 1987.

Interest in improving the maneuverability of fighter aircraft has widened the range of applicability of dynamic stall. Modern fighter aircraft strategy will require dramatic changes in flight dynamics; increased agility requirements will result in significant changes in required performance.[16,17] The effect of unsteady motion on aircraft stall characteristics has been recognized for some time. Harper and Flanigan[18] showed that the lift of an aircraft can be significantly increased if the aircraft is pitched at a rapid rate. However, the level of understanding required to make proper use of this effect has yet to be achieved. Consistent control of unsteady, separated flow will be required if fighter pilots are to make full use of the expanded aerodynamic boundaries that will be made available by unsteady aerodynamics; this emphasizes the need for basic research in three-dimensional dynamic-stall effects, compressibility effects on dynamic stall, and positive control of unsteady separated flow, as well as in other fundamental areas of unsteady aerodynamics.

Most of the aerodynamic research in dynamic stall has been directed toward helicopter or fighter aircraft applications, but there has been a quiet upsurge of research in dynamic stall for application to wind turbines used for electric power generation. Emphasis has been on the design of wind turbines to withstand the rigors of operation in an often severe environment—in areas strongly affected by dynamic stall. Dynamic stall occurs on both horizontal-axis (HAWT) and vertical-axis (VAWT) wind turbines.[19,20] The emphasis in wind turbine research is directed toward limiting the maximum lift to a level that is acceptable, based on fatigue limits. As shown by Veers,[21] an error of 30% in the prediction of dynamic air loads on VAWTs can result in a reduction by a factor of 70 in the expected life span of wind turbines. Since dynamic-stall effects can result in 100% errors in air loads, the improvement in prediction techniques for modeling of unsteady air loads has become an important item in the development of wind-turbine technology.

Dynamic-Stall Events

To set the stage for the discussion, a detailed description of the events associated with dynamic stall is presented. Figure 2 of McCroskey et al.[11] presents C_L, C_M, and C_D through a cycle and shows the character of the instantaneous pressure distributions through the cycle. Figure 3 depicts the development of C_N and C_M versus angle of attack α and the corresponding boundary-layer behavior for a dynamically stalling airfoil; the information is for a NACA 0012 airfoil oscillated in pitch, but the stall development is typical of virtually all airfoils experiencing fully developed dynamic stall.

The vortex-shedding process is the most obvious characteristic of dynamic stall, and much effort has been expended in analyzing this event. However, by the time the vortex is affecting the pressure distribution, dynamic stall, as such, has already begun. To better understand the stall-delay process, the analysis must include conditions significantly before the point at which symptoms appear in the normal force and pitching moment. A chronology of dynamic-stall events should start at point (a) in Fig. 3, where the pitching airfoil passes the static-stall angle without any discernible change in the viscous or inviscid flow around the airfoil. The first indication of disturbance in the viscous flow appears at point (b), when the flow reverses near the surface at the rear of the airfoil. This reversal progresses up the airfoil surface; then, at an angle that depends on many parameters, including airfoil shape, pitch rate, frequency, Reynolds number, and Mach number, as well as three-dimensional effects, the viscous flow no longer remains thin and attached, and a very strong vortical flow develops. This vortex begins near the leading edge of the airfoil point (e) in Fig. 3), enlarges, and then moves down the airfoil, inducing strong pitching-moment effects on the airfoil (points (f) and (i)),

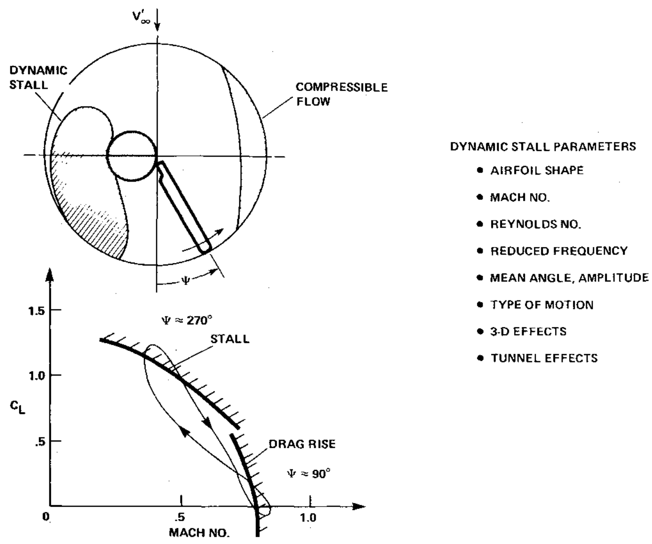

Fig. 1 Helicopter rotor airfoil requirements.

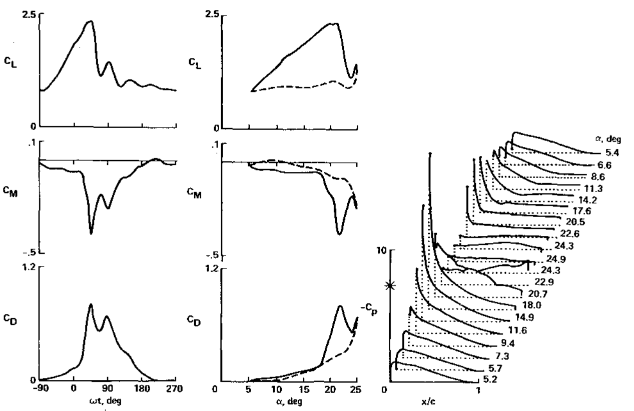

Fig. 2 Lift, pitching moment, and drag versus time in cycle, and angle of incidence; instantaneous pressure distributions for various times through cycle.

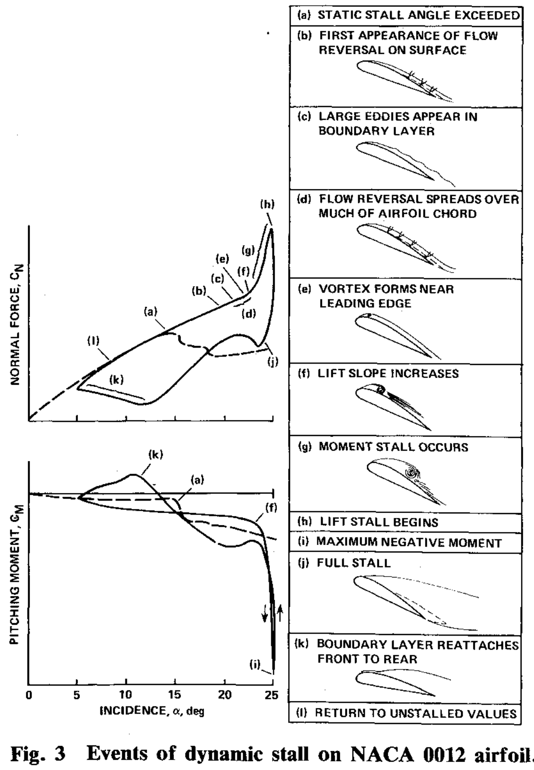

Fig. 3 Events of dynamic stall on NACA 0012 airfoil.

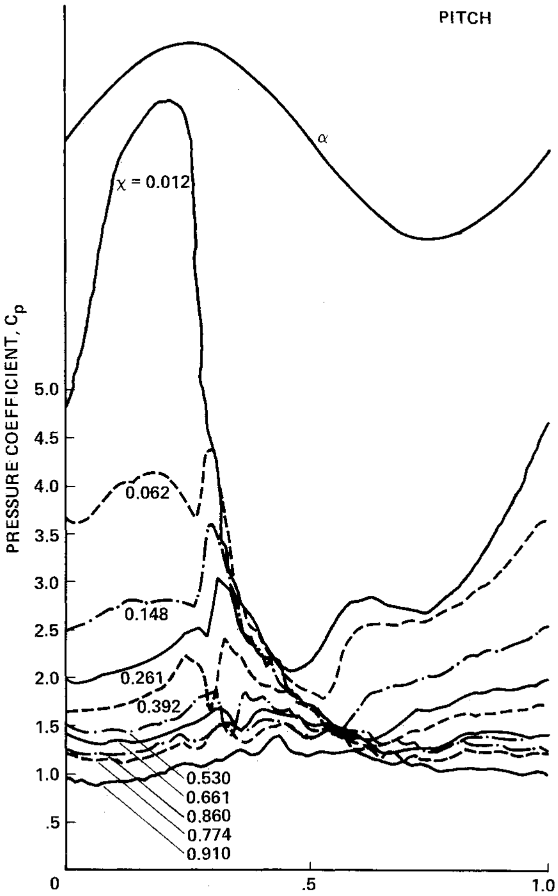

Fig. 4 Pitch-induced instantaneous surface pressures at various chord positions as a function of time in cycle.

producing the phenomenon known as dynamic stall. As the angle of attack decreases (for the pitching case), the vortex moves into the wake, and a fully separated flow develops on the airfoil. Note that the angle of attack has reached its minimum before lift is reestablished on the airfoil.

Dynamic-Stall Motions

Most of the research into the dynamic-stall phenomenon has been performed on airfoils oscillating in pitch. This motion was found to adequately represent the characteristics of dynamic stall on helicopter blades, and until recently, such tests were considered sufficient to illustrate the stall behavior of airfoils. However, different requirements are appearing (e.g., the constant pitch rate of fighter aircraft maneuvering and the complex environment of VAWTs), and more information is needed about the viscous flow encountered during dynamic stall under these conditions. This has led to a more careful investigation of the dynamic-stall process, including evaluation of the type of motion involved. A review of various motion patterns shows some of the sensitivity to history effects in dynamic stall.

In-Plane Oscillation

The effects of variation of freestream velocity on the dynamic stall of airfoils at fixed pitch angle has been explored by a variety of researchers. Saxena et al.[22] explored the effect of oscillation of the freestream velocity on airfoils oscillating in pitch and observed that separation was delayed during the acceleration phase of the freestream oscillation. Krause et al.[23] found that the extent of the separated region is significantly reduced on a fixed-pitch airfoil during acceleration of the freestream flow. Pierce et al.[24] found that

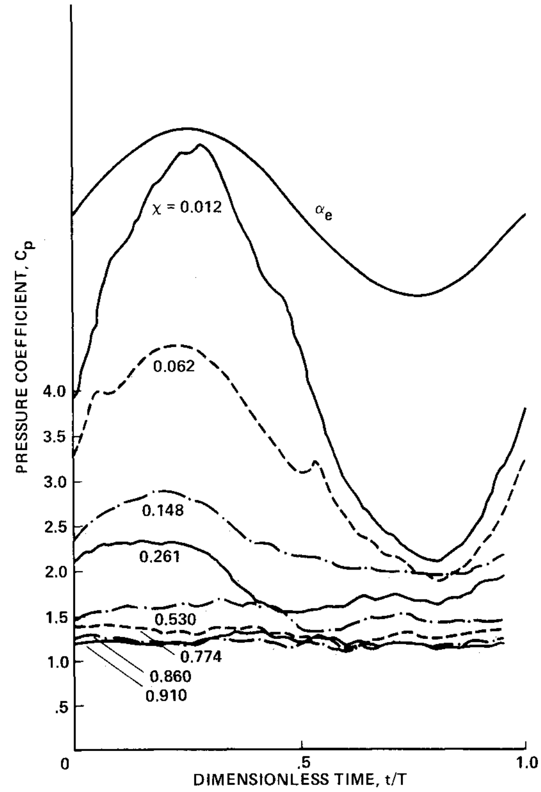

Fig. 5 Plunge-induced instantaneous surface pressure at various chord positions as a function of position in cycle.

oscillation of the freestream has a significant effect on airfoils simultaneously oscillating in pitch.

Pitch-Plunge Equivalence

Conceptually, inviscid flow over airfoils oscillating in pitch can be related, through potential flow theory, to the flow over airfoils in plunging motion. However, the viscous flow in these two conditions can be quite different; the extent of this difference was experimentally explored by Fukushima and Dadone[25] and Carta.[26] The time history of instantaneous pressure measurements at various chordwise locations for an airfoil undergoing pitch oscillation is presented in Fig. 4 (Ref. 26) as a function of time through the cycle, and the corresponding instantaneous measurements for the equivalent plunge condition (equivalent from inviscid considerations; see Ref. 26) are presented in Fig. 5. It can be seen that there are striking differences in the local flow conditions for these two cases; the stall, as evidenced by the abrupt drop in pressure observed at approximately $t/T = 0.25$ time-instant in Fig. 4, is definitely not the same as in the plunge case, Fig. 5. An analysis of the pitch-plunge equivalence was made by Ericsson and Redding.[27] Ericsson[28] suggests that it may not be possible to fully represent the dynamic stall of an oscillating airfoil in wind tunnels because of this influence of unsteady boundary-layer effects. This area deserves further exploration now that analytical techniques have been advanced to a level that will permit analysis of this effect.

Pitch-Axis Location

The effect of pitch-axis change was explored by Helin and Walker,[29] who found that moving the pitch axis rearward did produce some similarity to a higher pitch rate, but that the velocity profiles and vortex dynamics were significantly different.

Dynamic stall contributes to the process of autorotation of free-rotating airfoils as well. Oshima et al.[30] showed by experiment and calculation that autorotation of a rotating elliptic airfoil is caused by the temporary trapping of a vortex on the airfoil, and Aihara et al.,[31] Fremuth et al.,[32] and Billings and Chow[33] studied the effects of transient initial conditions on the resultant aerodynamic flow.

Mean Angle, Amplitude, and Frequency of Motion

Dynamic-stall effects depend significantly on the amplitude of oscillation. Figure 6 from McCroskey et al.[11] presents the C_L, and C_M for three test conditions, each of which has the same mean angle, but different oscillation amplitude. The pitch rate at the mean angle has been maintained as a constant by selecting the appropriate reduced frequency. Note that the dynamic-stall effects persist on the downstroke until the minimum angle is again attained.

The influence of mean-angle variation on the development of dynamic stall is more complex. For mean angles below the static-stall angle, oscillation results in delay of the stall angle past static stall, with no apparent effect on the potential or viscous flow; for mean angles near static stall, viscous effects dominate the developing dynamic stall. Figure 7, from McCroskey et al.,[11] shows the results of oscillation near stall on eight airfoils. Note that some airfoils experience much stronger dynamic-stall effects than others; this effect is sensitive to the type of flow reversal that occurs on the surface of the airfoil. Frequency affects the dynamic stall in a way similar to amplitude. Figure 8 shows the response of a pitching airfoil to changes in reduced frequency; note the similarity, in terms of increasing degree of overshoot, to the variation in amplitude shown in Fig. 6.

Matched Pitch Rate

McCroskey et al.[11] showed that the high-angle part of the oscillating airfoil dynamic-stall cycle depends strongly on the rate of change of angle of attack near the stall angle; the same lift and pitching-moment behavior beyond the static stall angle can be attained by matching the rate of change of α at stall for two cases with different amplitude (see Fig. 9). The characteristics of dynamic stall for constant $\dot{\alpha}$ have been studied for fighter-aircraft maneuverability by several researchers: Francis et al.[34] chose a nondimensional pitch rate for comparing characteristics of airfoils in constant pitch motion; Walker et al.[35] also used this "α^+" to permit comparison of constant pitch-rate experiments. This type of stall behavior also occurs on VAWTs, and similar results were observed by Graham,[36] who has also measured the instantaneous aerodynamic loads on an airfoil in constant $\dot{\alpha}$ mo-

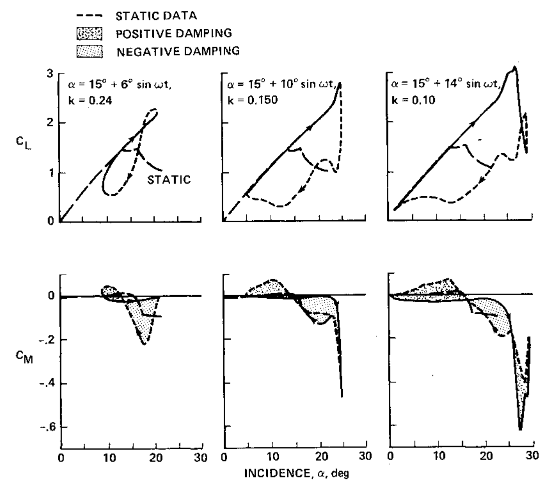

Fig. 6 Effect of amplitude on dynamic stall loads for an airfoil oscillated in pitch.

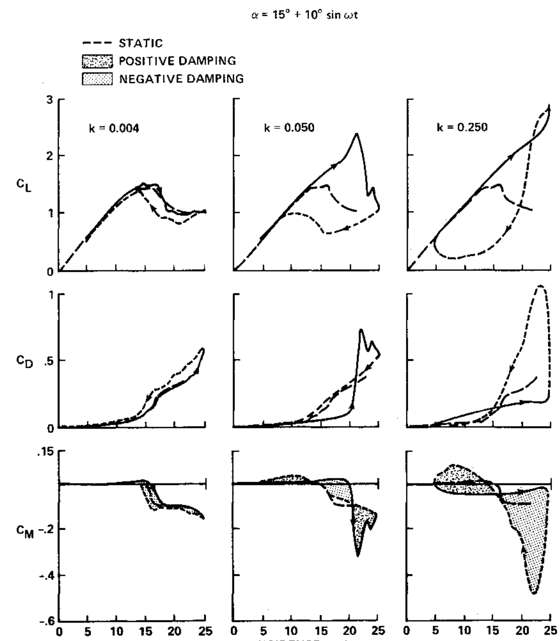

Fig. 8 Effect of reduced frequency on the dynamic stall of an oscillating airfoil.

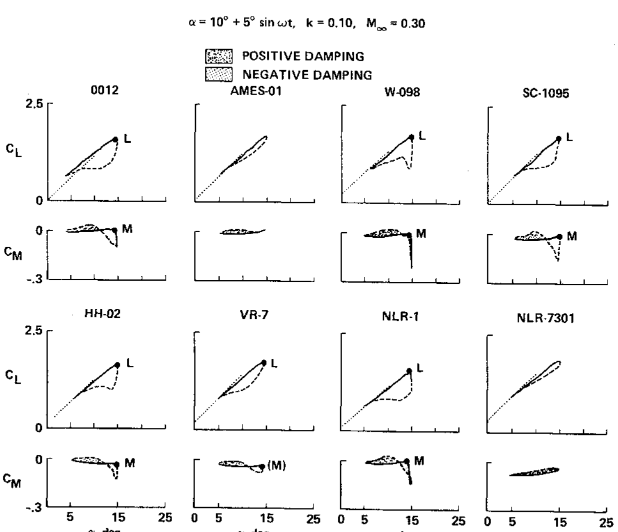

Fig. 7 Dynamic stall behavior of eight airfoils oscillating near the stall angle.

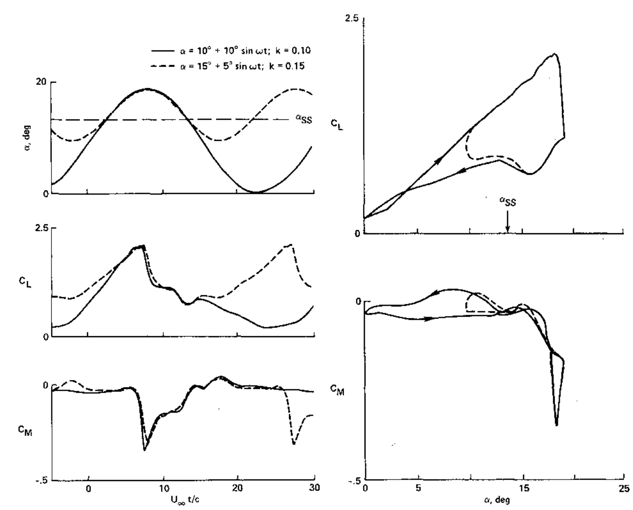

Fig. 9 Lift coefficient versus time in cycle for oscillating airfoil with pitch-rate conditions matched at the static-stall angle.

tion. The corresponding pressure distributions on an operating VAWT blade were reported by Akins et al.[20]

Mach Number Effects

McCroskey et al.[11] have shown that the dynamic-stall behavior of an airfoil is also dependent on Mach number. Figure 10 shows the local Mach number that is reached near the leading edge of oscillating airfoils, indicating that supersonic flow can occur on a variety of airfoils, even for freestream Mach numbers that are comparatively low ($M_\infty < 0.3$). The airfoils included some that stalled because of trailing-edge as well as leading-edge separation at low Mach numbers, but they all stalled from the leading edge at $M = 0.3$. An example is shown in Fig. 11, where the time in the cycle at which flow reversed at specific x/c locations on the airfoil is plotted for various Mach numbers. Note that for lower Mach numbers, the flow reversal first appears at the trailing edge, then moves upstream as the angle of incidence increases. However, at higher Mach numbers, for example, at $M = 0.295$, the flow is reversing at the leading edge as well. Although flow visualization of the leading-edge region was obtained using shadowgraphs, no shock was observed at any part of the cycle. The characteristics of dynamic stall at $M = 0.3$ were also investigated by Katary.[37]

Compressibility can have significant effects on the resultant dynamic-stall pressure distributions. In Fig. 12, instantaneous surface-pressure measurements at various x/c locations are plotted through a cycle of oscillation in pitch (Ref. 38). At $M = 0.3$, there is no change in the signature relative to what is normally present in incompressible flow. However, as the freestream Mach number increases to 0.5, very dramatic changes appear, and at 0.7, no evidence of overshoot remains. St. Hillaire and Carta[39] observed that Mach number effects dominate during the onset of dynamic stall, whereas sweep effects dominate the flow behavior after the stall begins. The character of compressible dynamic stall has also been explored by Lee et al.,[40] who used holographic laser velocimetry to visualize the compressible flow on an oscillating airfoil. However, because of structural limitations, their results do not include the leading edge of the airfoil. Ericsson and Redding[41] discuss some of the factors associated with engineering modeling of the compressible flow effects. A compressible form of the Navier-Stokes equations was solved by Sankar and Tassa,[42] who found that compressibility delays the formation and growth of the dynamic-stall vortex on a two-dimensional NACA 0012 airfoil oscillated in pitch; as a result, lift, drag, and pitching-moment coefficients are increased. This is in contrast to the results of Harper and Flannigan,[18] who determined that the overshoot of $C_{L_{max}}$, which was observed on a wing model oscillating in pitch at low Mach number, gradually disappeared as the Mach number increased until at $M_\infty = 0.6$, no dynamic stall overshoot remained (Fig. 13).

Flight at freestream Mach numbers near sonic values will also be of concern in aircraft maneuvering, since the fighter aircraft of the future will have to be able to perform enhanced maneuvers over the full aircraft speed range; this may result in significant regions of sonic flow on the wings. The effect of oscillation on the flow over airfoils moving at transonic speeds has been investigated by Davis[43] and Beddoes,[44] as well as others.

Reynolds Number Effects

Little has been done to determine the influence of Reynolds number on dynamic stall, since it is difficult to vary the Reynolds number significantly without introducing compressibility effects as well. Since compressibility has such a strong effect on viscous flow behavior during dynamic stall, the accurate determination of a Reynolds number dependence over a wide parametric range has yet to be established. However, the study of freestream turbulence effects has been performed for the design of wind turbines, since the intensity of atmospheric turbulence can reach high levels in the wind boundary layer. Laneville and Vittecoq[45] have determined that freestream turbulence intensity can have a significant effect on the development of the dynamic stall of low Reynolds number airfoils. However, these effects are difficult to separate from effects of freestream turbulence on transition. Unsteadiness can also have a significant effect on transition.[46] Therefore, proper representation of the Reynolds number effect on dynamic stall remains an important, and presently unsolved, question.

Three-Dimensional Effects

Although the essential characteristics of dynamic stall on helicopter rotors can be represented using two-dimensional

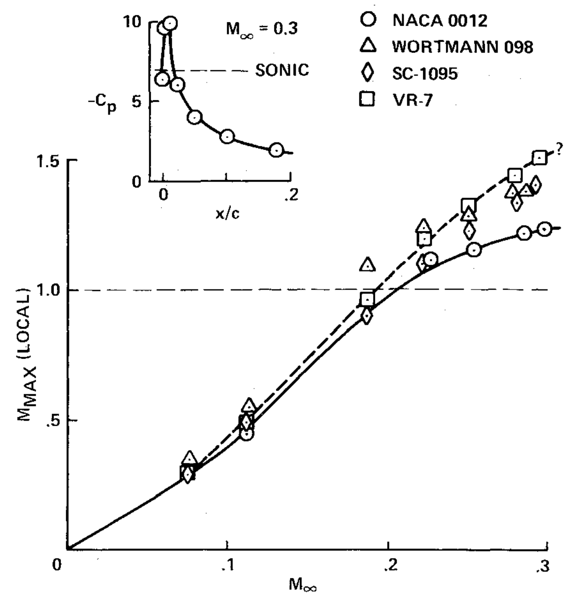

Fig. 10 Local Mach number on leading edge of oscillating airfoil versus freestream Mach number.

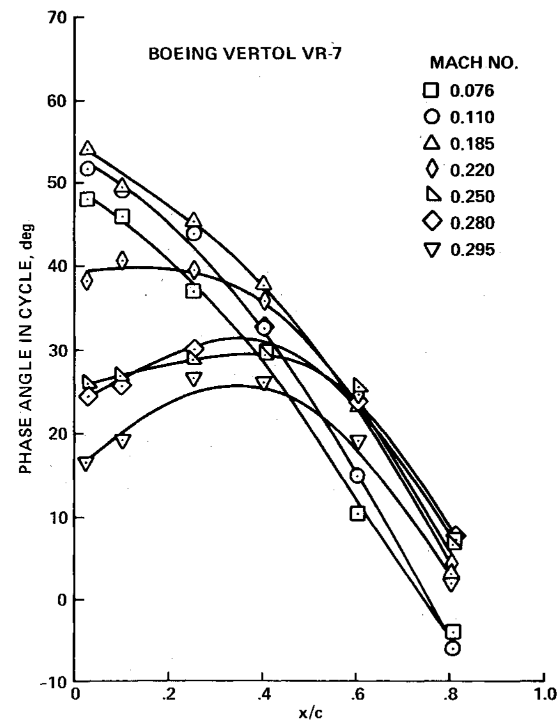

Fig. 11 Location of flow reversal on surface of VR-7 airfoil as a function of angle of attack for various Mach numbers.

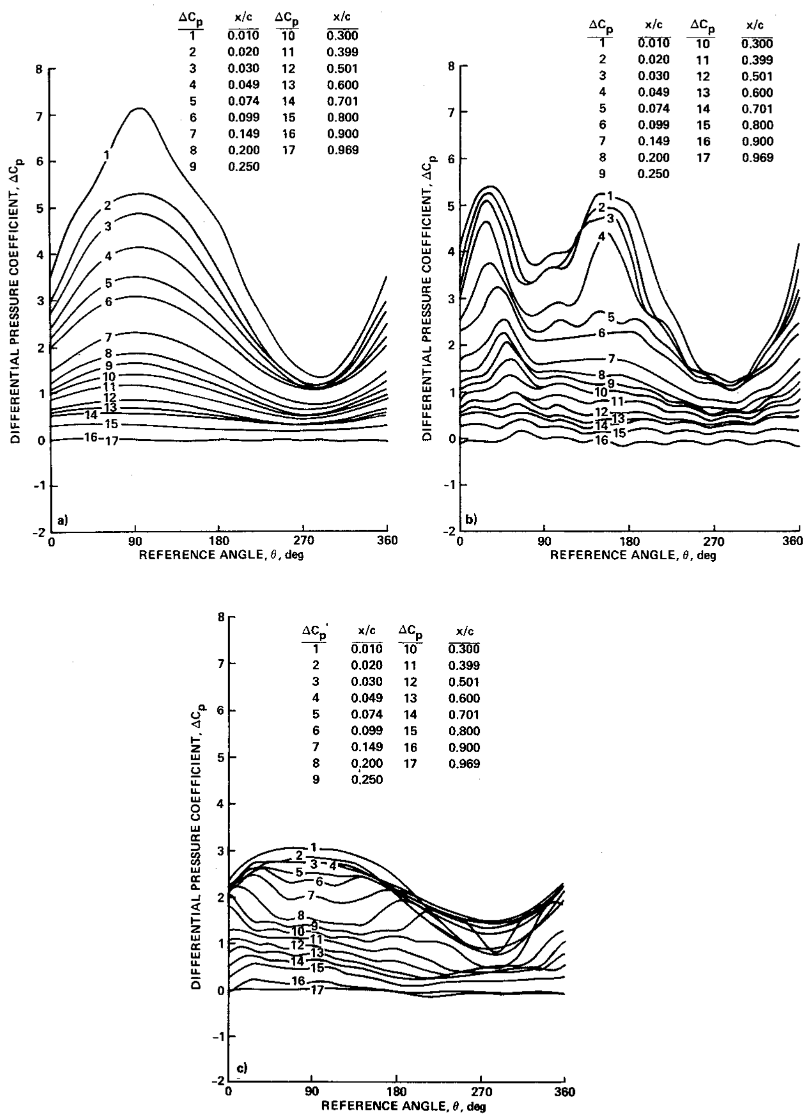

Fig. 12 Time history of differential pressure coefficient for one cycle. a) $M=0.3$; b) $M=0.5$; and c) $M=0.7$.

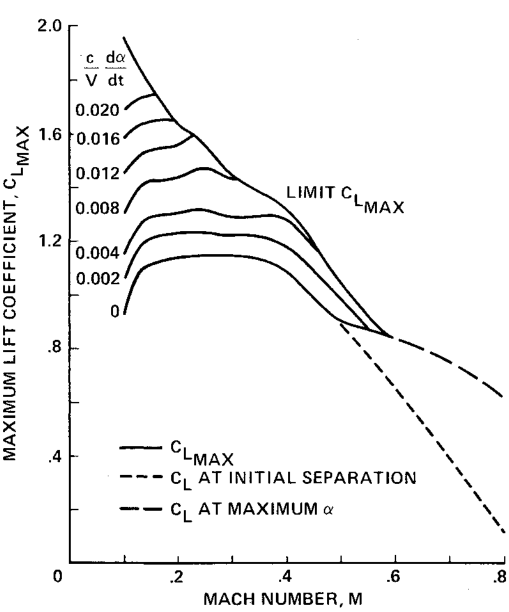

Fig. 13 Maximum pitching rate effect on lift and pitching-moment characteristics of wing model for various Mach numbers.

experiments, the three-dimensional aspects are significant and become even more important as knowledge of the dynamic-stall process is gained and as the analytical models become more accurate. In addition, the effect of three-dimensionality on aircraft dynamic stall is much more significant and must be included at the outset if full representation of dynamic stall on aircraft is to be attained.

Harper and Flanigan[18] obtained load measurements on a three-dimensional wing model, but did not explore the physical mechanism that resulted in the increased load values that were observed. Wagner[47] presents instantaneous pressure distributions for four wing tips oscillated in pitch. The location, size, and character of the tip vortex were found to change significantly, even for small amplitude oscillation. Geissler[48] compared theory and experiment for several blade tips experiencing dynamic stall. The effect of pitch oscillation on a delta wing was studied experimentally by Gad-el-Hak and Ho,[49] who found significant interaction between the vortices shed from the leading edge and those shed during the dynamic stall process.

Under certain circumstances, three-dimensional effects on the dynamic-stall vortex can be limited to regions near the tip of the wing. Flow visualizations obtained by Adler and Luttges[50] for a wing with an aspect ratio of two show flow features similar to two-dimensional stall appearing within a chord length of the tip (see Fig. 14). Carta[51] studied the effect of sweep on an oscillating airfoil and found that sweep

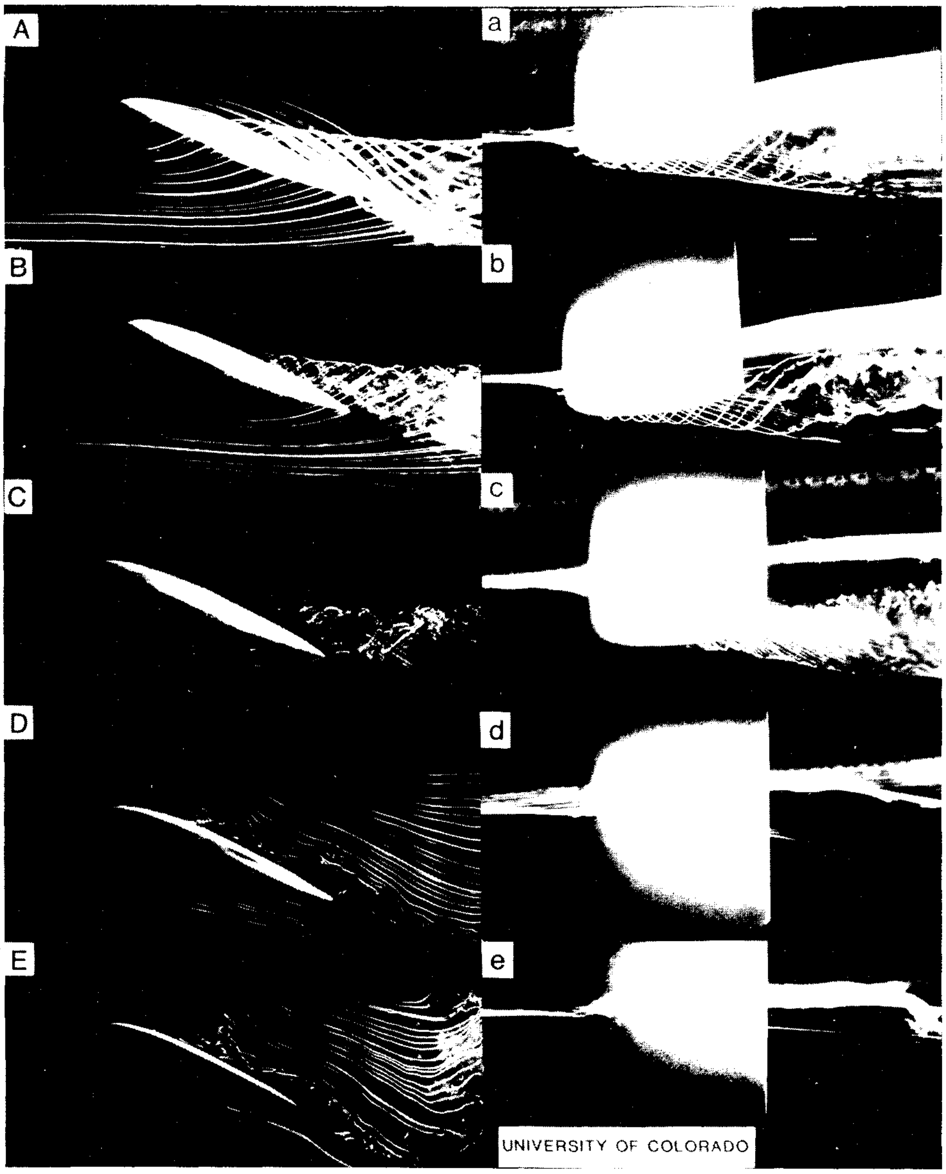

Fig. 14 Visualization of the flow at various distances from the tip of a three-dimensional, constant-chord wing oscillating in pitch.

effects appear near the leading edge, and that there are large phase shifts in the lift results for the swept and unswept wings, but only if dynamic stall has occurred in the cycle.

The preceding is only a partial list of the efforts that have been made to determine the three-dimensional characteristics of dynamic stall, but it is sufficient to given an indication of the types of flow effects that can occur. The influence of three-dimensionality on the dynamic-stall process remains an important area for future research.

Dynamic-Stall Flow Models

Much of the analysis of dynamic stall has resulted from carefully performed physical experiments; only recently has the analytical-computational effort been capable of sufficient accuracy to give equivalent details of the flow. Analysis has progressed using a variety of approaches, each offering new insight into the stall process: linearized potential and discrete vortex inviscid models, unsteady boundary-layer modeling, and Navier-Stokes analyses have been used to investigate the dynamic-stall process. A general review of the computational aspects of using boundary-layer equations to model the viscous flow on oscillating airfoils is presented in Cebeci et al.[52] Mehta[53] developed a Navier-Stokes solver that permitted modeling of the dynamic-stall process at low Reynolds numbers with good correlation with experiment (see Fig. 15).

More recently, work in Navier-Stokes modeling for high Reynolds numbers has resulted in significant progress: Shida and Kuwahara[54] modeled the time-accurate steady stall of a NACA 0012 airfoil, (actually a series of unsteady events) with artificial viscosity that permitted resolution of small scale structure (Fig. 16). Shida et al.[55] modeled the dynamic stall of the NACA 0012 airfoil using a time-accurate, unsteady Navier-Stokes equation solver and computed the flow over the NACA 0012 oscillating in pitch at $M = 0.3$, $Re = 4 \times 10^6$. Geissler[56] modeled the unsteady boundary layer, using a coordinate system tied to the unsteady stagnation point, and found that reasonable representation of the flow-reversal locations can be obtained for airfoils oscillating in pitch.

Carr and Cebeci[46] show that the transition location on an oscillating airfoil is dramatically altered by the dynamic stall process—a review of dynamic-stall experiments indicated that the transition location varied over a range of 30% of chord compared to quasi-steady results. Unless this experimentally determined transition movement was properly

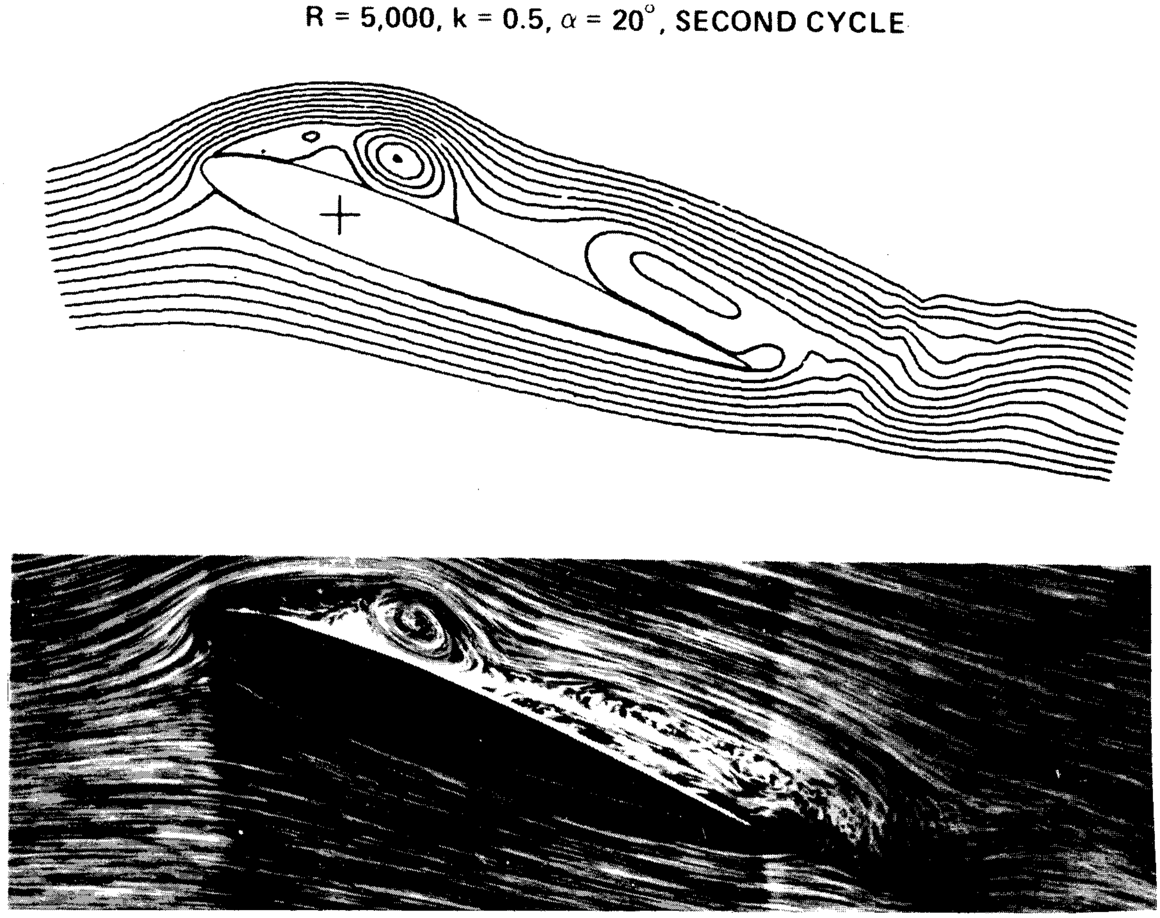

Fig. 15 Comparison of the results of Navier-Stokes computation with visualization of a dynamically stalling airfoil, $Re = 1 \times 10e5$.

represented in the calculations, premature breakdown of the computation occurred. Oshima and Oshima[57] performed combined experimental and numerical studies of an oscillating NACA 0012 airfoil, both in pitch and plunging oscillation. Calculations were made using discrete vortex modeling and compared with experiments made in a water tunnel. Maskew and Dvorak[58] combined an unsteady surface-singularity panel method with an unsteady integral boundary-layer technique to determine the unsteady loads on an oscillating airfoil. Shamroth[59] developed a Navier-Stokes calculation procedure to model instantaneous pressure and velocities and mapped the velocity and vorticity field for an airfoil oscillating in pitch (Fig. 17). McCroskey and Pucci[60] presented a series of dynamic-stall test cases for comparison of experiment and theory.

If further progress is to be made in understanding the overall flowfield associated with dynamic stall, a better understanding of the details of the viscous flow over the airfoil itself will be needed. Several experiments detailing the character of the unsteady viscous flow on oscillating airfoils during the dynamic-stall process are available: Saxena et al.[22] measured the boundary-layer characteristics of an airfoil in an oscillating freestream flow and found that the average normal force can exceed the steady-flow value by 60%; Ho and Chen[61] measured the unsteady wake of a plunging airfoil; DeRuyck and Hirsch[62] obtained the same kind of data for an airfoil oscillating in pitch; and DeRuyck and Hirsch[63] documented the character of the unsteady turbulent boundary layer on an oscillating airfoil. McCroskey et al.[11] documented the flow-reversal character of a variety of airfoils during dynamic stall and observed four distinct types of flow reversal. Covert et al.[64,65] documented the character of the unsteady boundary layer on an airfoil in the presence

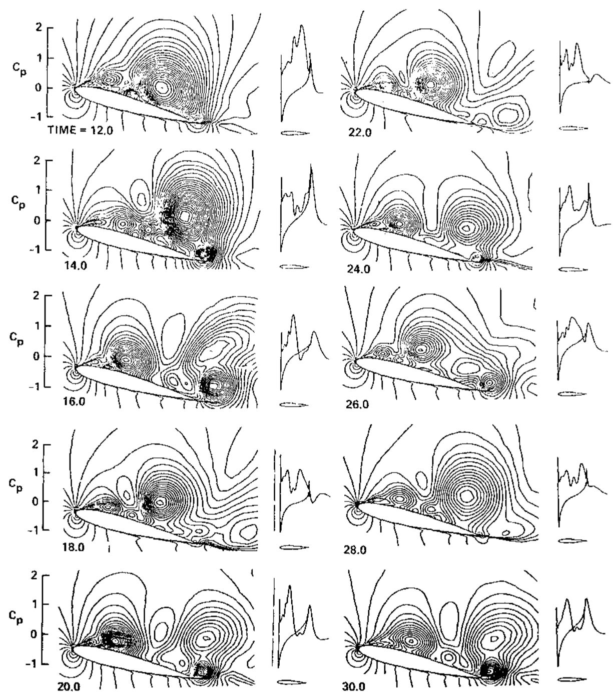

Fig. 16 Time development of density contours and pressure coefficients from Navier-Stokes modeling of an airfoil in steady stall.

of an oscillating elliptic cylinder. Carta[66] found significant differences in the viscous flow near the leading edge of an oscillating airfoil when the results of airfoil tests in two-dimensional configurations were compared with those in a swept three-dimensional flow.

Thus, there is a large data bank that will allow quantitative comparison of numerical and experimental models of dynamic stall, to determine the ability of various models to represent the specific detail of the viscous flow development.

Control of Dynamic Stall

Since the dynamic-stall process produces extraordinary pitching moments, helicopter aerodynamicists have investigated various ways to alleviate or eliminate the vortex usually associated with the dynamic-stall process. McCroskey et al.[11] found that the vortex dominated the poststall flowfield regardless of the choice of airfoil. However, Carr and McAlister[67] found that the dynamic-stall vortex could be eliminated through use of a leading-edge slat, resulting in lift and pitching-moment curves that no longer show the effects of the vortex (Fig. 18). Aerodynamic blowing has been considered for reduction of dynamic-stall effects; McCloud et al.[68] studied blowing on a rotor tested in a large-scale wind tunnel and found significant improvement in performance. McAlister studied tangential blowing for control of the dynamic-stall vortex on an oscillating airfoil and found that significant control could be attained when using blowing coefficients associated with boundary-layer control ($C_\mu = 0.06$), as shown in Fig. 19. Luttges et al.[69] found that pulsed blowing sufficiently redistributed the vorticity on an oscillating airfoil to change the associated potential flowfield. Nagib et al.[70] investigated the effect of forced unsteadiness on separated flows; Reynolds and Carr[71] presented a survey of driven, unsteady separated flows.

Dynamic-Stall Load Models

Helicopter dynamicists have required input information representing the dynamic-stall behavior of helicopter rotor blades. Many models have been developed, each depending on empirical information about the dynamic-stall characteristics. A review of various stall load models is presented in Galbraith.[72] A dynamic-stall model developed by Dat[73] and applied by McAlister et al.[74] is based on experimentally measured coefficients obtained for low-amplitude oscillation over a range of mean angles, including the stall range (see Fig. 20). Gangwani[75] modeled the dynamic-stall process using empirical parameters computed from experiment and represented many parameters of that process, including variation of Mach number, airfoil shape, and aerodynamic sweep; Fig. 21 shows the comparison between model and experiment. Sankar[76] computed the unsteady flowfield using a time-accurate Navier-Stokes solver, with the experimentally determined moment-stall angle as a guide for changing turbulence models.

Conclusions and Observations

There has been dramatic progress in dynamic-stall research during the past 15 years. The level of understanding has advanced from qualitative conjectures concerning the possibility of dynamic delay of stall, to quantitative measurement of the instantaneous character of the viscous flow during the stall process itself, and the development of quantitative empirical models that reflect even small variations of the stall loads during the cycle. There is still much to be learned—little is known of compressibility effects or of the influence of Reynolds number or three-dimensionality on dynamic stall loads, and there is need for an extended effort directed toward measurement of the details of the viscous flow that results in dynamic stall.

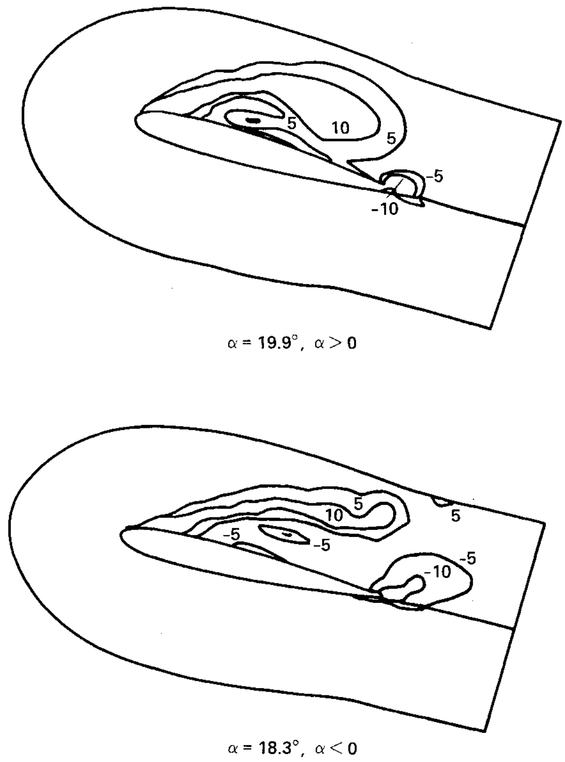

Fig. 17 Vorticity contours on an airfoil oscillating in pitch, based on solution of the Navier-Stokes equations.

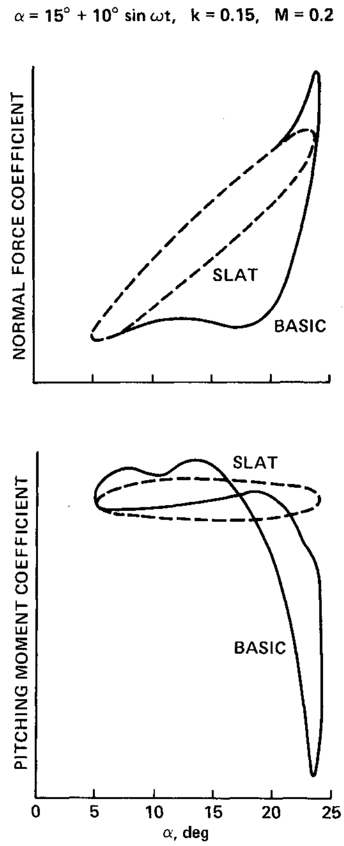

Fig. 18 Lift and pitching-moment coefficients as function of angle of incidence for basic airfoil, and airfoil with leading edge slat.

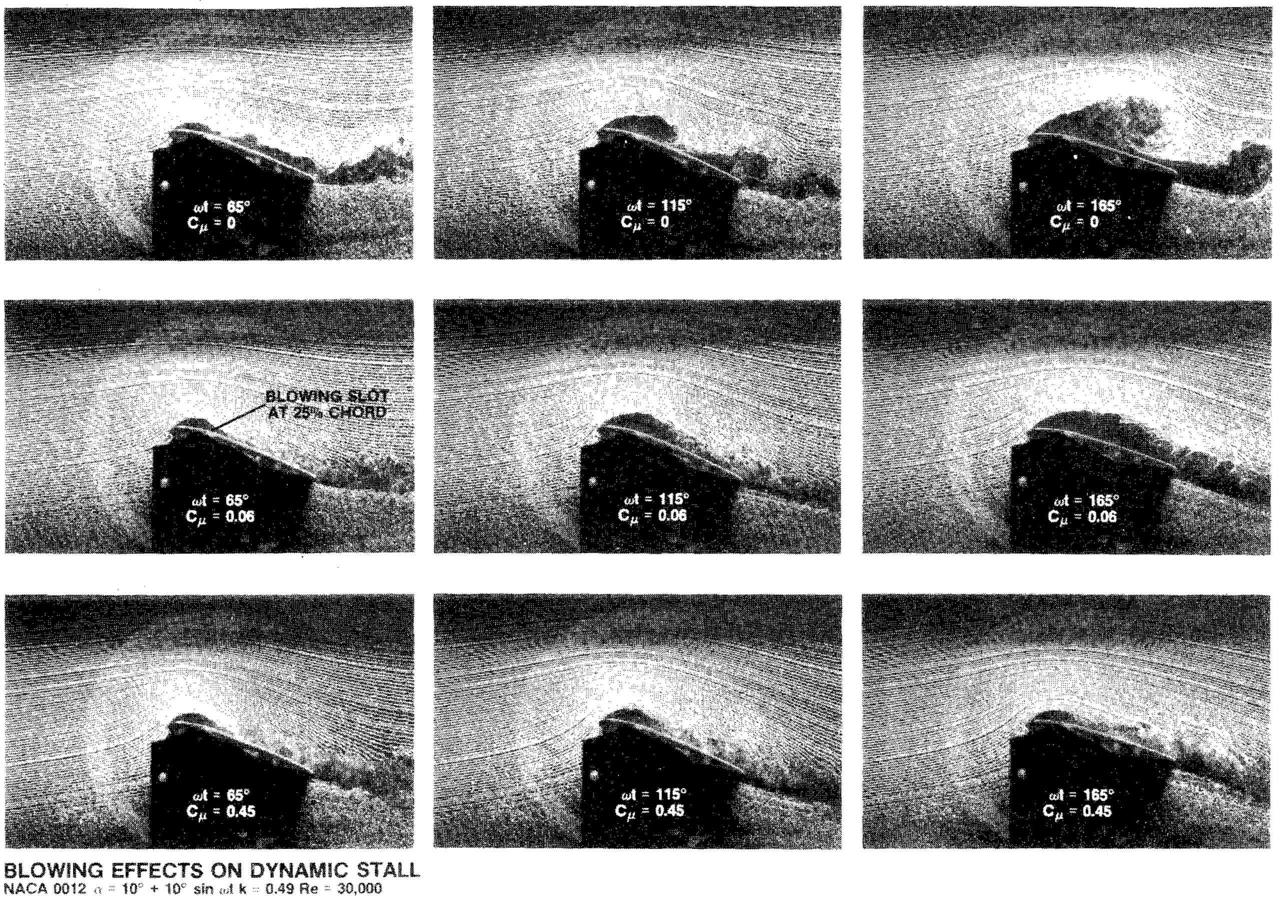

Fig. 19 Effect of tangential blowing on the character of the flow on an oscillating airfoil.

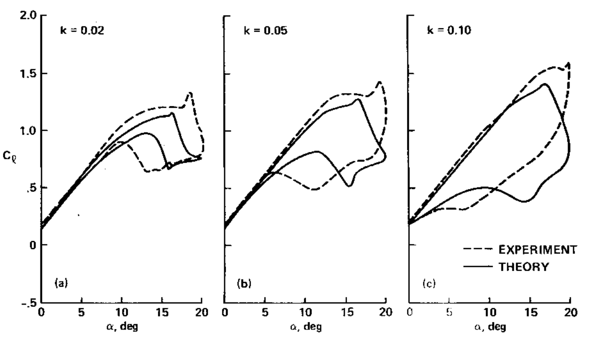

Fig. 20 Comparison of measured and calculated lift using a dynamic stall model for a VR-7 airfoil pitching at $\alpha = 10 + 10$ sin*t*, *Re* = 1.2 × 10*e*,[5].

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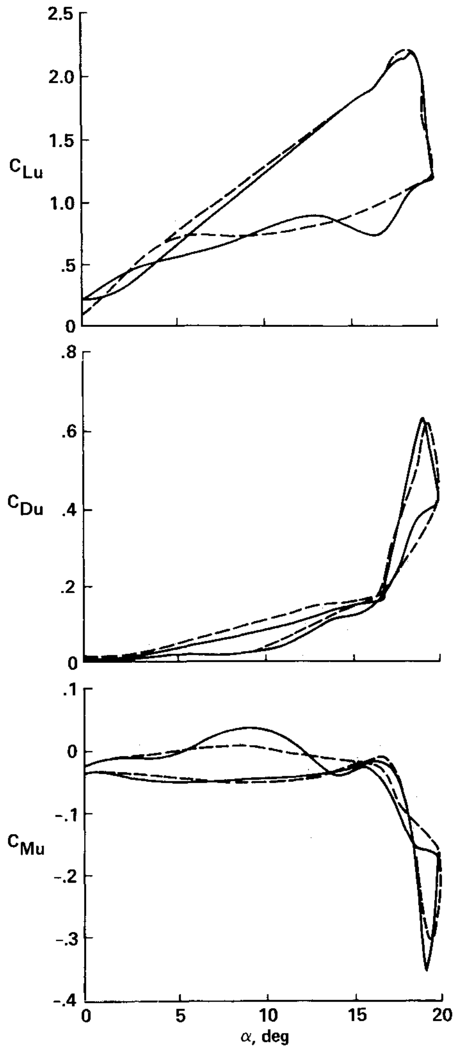

Fig. 21 Comparison of synthesized pitching moment coefficient loops with test data, $M = 0.30$, $Re = 3.8 \times 10e,^6$, $= 0$.

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