ARTICLE NO. 80-4034

J80-037

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The Delta Wing in Oscillatory Gusts

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This report describes systematic aerodynamic lift and pitching moment measurements on two sharp edged delta wings of aspect ratio 1 and 2 in oscillatory vertical gusts of varying frequency parameter and gust amplitude. The effects of the nonlinearity associated with the separated flow region are explored and the influence of the potential flow and the vortex induced lift on the measured oscillating forces are discussed with implications that may be of value for developing or validating theoretical models.

Nomenclature

A	= wing aspect ratio
c	= $\frac{1}{2}c_r$, geometric mean wing chord
C_L	= $L/\frac{1}{2}\rho U^2 S$, lift coefficient
ΔC_L	= $\Delta L/\frac{1}{2}\rho U^2 S$, amplitude of lift coefficient in oscillatory flow
C_M	= $M/\frac{1}{2}\rho U^2 Sc$, pitching moment coefficient about a line through the root two-thirds chord point
ΔC_M	= $\Delta M/\frac{1}{2}\rho U^2 Sc$, amplitude of pitching moment coefficient about a line through the root two-thirds chord point
c_r	= wing root chord
L	= lift force
ΔL	= amplitude of lift in oscillatory flow
ΔM	= amplitude of pitching moment about a line through the root two-thirds chord point
S	= wing area in plan
t	= time coordinate
U	= mean freestream velocity
w	= instantaneous vertical (downwash) velocity component of gust
$\bar{w}$	= w/U, instantaneous angle of incident gust
w_g	= amplitude of vertical (downwash) velocity component in oscillatory flow
$\bar{w}_g$	= w_g/U, amplitude of incident gust angle in oscillatory flow
x,y,z	= Cartesian frame of reference wind axes shown in Fig. 4
α	= angle of incidence of test wing—positive nose down about y axis; see Fig. 4
θ_L	= half angle at apex of delta wing planform
ν	= $\omega c/U$, frequency parameter
ν'	= $\omega c/0.61\,U$, "effective" frequency parameter
ρ	= air density
ϕ	= phase difference (in degrees) of lift force or pitching moment relative to gust incidence at wing root two-thirds chord point (phase lead positive)
ω	= radian frequency

I. Introduction

THE separated flow about delta wings of low aspect ratio and with sharp leading edges has been of interest to aerodynamicists for some time now both from the point of view of understanding the fluid mechanics of the complex separation region and of producing quantitative data on the induced aerodynamic forces for aircraft design. Parker[1] presents a comprehensive review of work on delta wings over the last four decades. In particular, the results of various steady flow theories and experimental investigations are brought together and compared. For unsteady flow, most of the research reviewed has been concerned with delta wings undergoing pitching or plunging motions in a steady airstream. It is clear from the review that none of the steady flow theoretical models adequately predicts all aspects of the flow process involved. This is even more pronounced for the unsteady flow regime.

The role of the delta wing in unsteady flow has been put into perspective in a review by Rodden[2] in which the interference effects of the large separated flow vortices typical of delta wings at incidence on local aerodynamic surfaces are emphasized. More recently, the delta winged planform of the space shuttle orbiter has sparked renewed interest in delta wing aerodynamics with work by Ericsson and Reding[3,4] on a mixed theoretical and empirical approach to predicting delta wing characteritics in steady and unsteady flow.

The complexity of the flowfield associated with the separation region and vortex formation on a sharp edged slender wing in subsonic flow makes it extremely difficult to predict aerodynamic forces accurately on purely theoretical grounds, and such a definitive analysis has yet to emerge. As a contribution to an understanding of delta wing aerodynamics, this paper presents some experimental data for lift forces and pitching moments on sharp edged delta wings of aspect ratios 1 and 2 in both steady flow and in oscillatory vertical gusts approaching the stationary wings with a variety of different wing incidences, frequency parameters, and gust intensities. The steady flow data are compared with some theories, and conclusions are drawn as to the nature and behavior of the leading edge vortices in unsteady flow.

II. Experimental Facility

The gust tunnel used in these tests has been described fully by Patel and Hancock.[5] It is based on a conventional wind tunnel with a rigid semi-open working section made up of solid vertical side walls and an essentially open top and bottom. The gust generation device, shown in Fig. 1, consists of flexible extensions to the top and bottom walls at the exit to the contraction. These upper and lower extensions are fixed at their end to a frame which can be moved up and down. Fixed sidewalls extend the contraction exit to the frame. Oscillatory motion of the frame by an electro-hydraulic servo-mechanism perturbs the shear layers above and below the semi-open test section into rolling up and forming discrete vortices in the jet mixing regions, thus inducing a sinusoidal vertical gust in an irrotational flow between the two shear layers. Both the gust frequency (and thus the wavelength) and the gust intensity can be closely controlled between wide limits. A mathematical

Received April 3, 1979; revision received Aug. 13, 1979.

Index categories: Aerodynamics; Nonsteady Aerodynamics.

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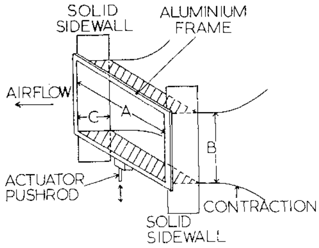

Fig. 1 The flexible nozzle. Shaded areas are flexible walls. $A=0.99$m, $B=0.76$m, and $C=0.38$m.

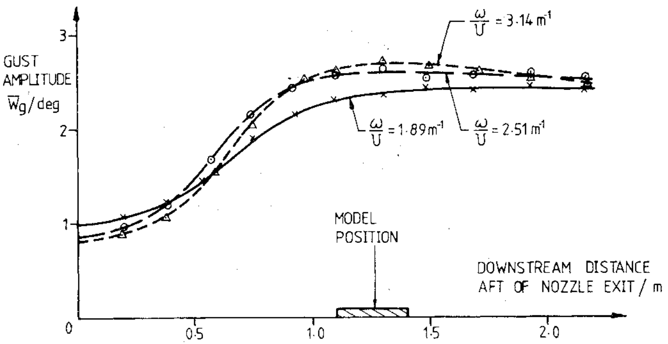

Fig. 2 Freestream gust amplitude variation with distance downstream.

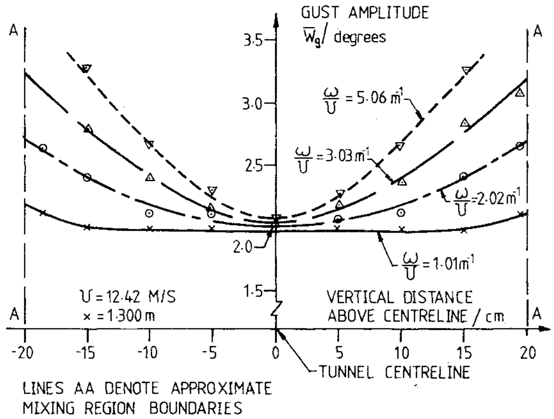

Fig. 3 Freestream gust amplitude variation with vertical distance.

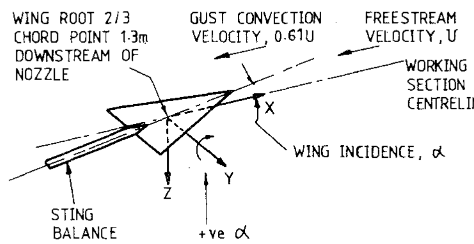

Fig. 4 The wing reference axes system.

description of the oscillatory travelling form of the vertical gust can be written as

$$\bar{w}(x,t) = \bar{w}_g(x)\exp\{i\omega[t+(x/0.61U)]\} \quad (1)$$

where $0.61U$ is the velocity of the travelling wave convecting downstream. This velocity is less than the freestream value U because the rolled up vortices inducing the oscillatory flow are embedded within the mixing region associated with the two shear layers (see Ref. 5). As explained in Sec. IV, the only consequence of this feature is a change in the gust encounter speed for the wings and thus an altered "effective" frequency parameter. For a geometric mean chord of 0.15 m for the two delta wings tested, the gust tunnel is capable of a frequency parameter range of $0.152<\omega c/U<0.764$. The actual frequencies corresponding to these parameters lie in the range from 2 to 12 Hz. A gust amplitude of $\bar{w}_g=0.0314$ or 1.8 deg incidence angle is available for all the frequencies, but for a frequency parameter of around 0.330, gust amplitudes of up to $\bar{w}_g=0.054$ ($=3.1$ deg) can be obtained. This capability has been used to investigate the effects of the nonlinearity with incidence on the delta wing lift in oscillatory flow.

The spatial distribution of gust amplitudes around the test model in oscillatory flow has an impact on the validity of the experimental data. Figure 2 illustrates typical variations of gust amplitude with distance downstream. For a delta wing model of 0.30 m root chord positioned as shown, a region of reasonably constant gust amplitude is available for the wing and its wake. Figure 3 shows the corresponding variations of gust amplitude with vertical distance from the working section centerline. The "hyperbolic cosine" type variation of gust velocity is due to the vortices in the shear layers above and below the working section which induce the gust flow. This feature is not a limitation to the tests described herein since, even for the wings at incidence, a very small height ($\sim\pm3.1$ cm) of the working section about the centerline is utilized and the irrotational flow in the vicinity of this region is reasonably uniform. Furthermore, the oscillatory flow obtained is closely two dimensional in the spanwise direction across the working section flow. Figure 2 shows the streamwise position of the test wings in the horizontal center plane of the working section measuring 0.76 m in height, 0.99 m across, and 2.60 m length. Reference 5 gives more details of the gust tunnel construction and capabilities.

The two delta wings tested, of aspect ratios 1 and 2, were made up from 2.5-mm-thick flat aluminium sheet with symmetric wedge shaped leading edges of 30 deg included angle. Both wings were sized to the same root chord of 0.30 m. Thus, the aspect ratio 2 wing had a leading edge sweep of 63.4 deg and a span of 0.30 m, which is 30% of the working section width. The aspect ratio 1 wing had a leading edge sweep of 75.9 deg with a span of 0.15 m. All aerodynamic coefficients are expressed in terms of the geometric mean chord c, which is a half of the wing root chord. Figure 4 shows the reference axes system. Positive incidence is taken to be "nose down" to insure consistency of positive lift with either wing incidence or downward gust velocity.

Aerodynamic forces on the wings were measured by a cantilever type lift and pitching moment sensing sting balance mounted into the delta wing rear in such a way as to provide a wing-only test configuration with no centerbody at the wing root. The sting balance was designed specifically for unsteady flow measurements and calibrated for both static and dynamic loads (see Ref. 6 for further details).

Measurements in unsteady flow of both upstream gust incidence angle and resultant wing lift force and pitching moments were made by digital signal sampling over successive cycles of gust oscillation. A numerical harmonic analysis of these data was then performed to extract information at the forcing frequency in the incident gust oscillation. The resultant data are presented here as amplitude and phase of $\Delta C_L/\bar{w}_g$ and $\Delta C_m/\bar{w}_g$ against frequency parameter, $\omega c/U$, within an experimental uncertainty of $\pm3\%$ in oscillation amplitude and ±3 deg in phase angle.

III. Test Procedure and Results

Both the steady and oscillatory flow tests were performed for all the wings at two freestream velocities of 12.43 and 20.00 m/s, giving maximum Reynolds numbers of 2.57×10^5 and 4.13×10^5, respectively, based on wing root chord. No provision was made for artificially provoking transition on the wing surfaces. This course of action was supported by preliminary measurements of wing lift with and without transition strips, which showed no measurable differences between the forces for the two flow regimes. However, ex-

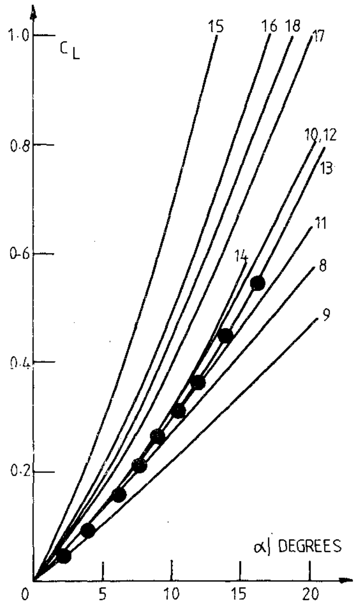

Fig. 5 Steady flow lift curve for wing of aspect ratio 1 (Ref. 1). The points denote experimental data. Solid lines correspond to numbered references.

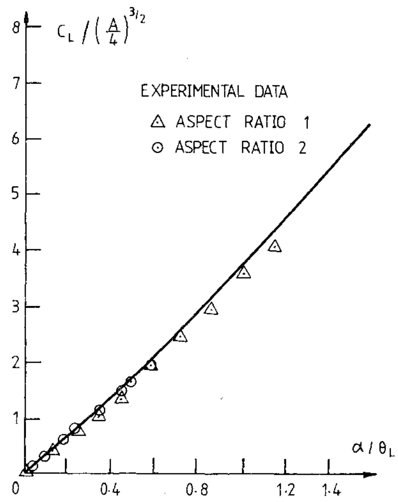

Fig. 6 Universal scaling of delta wing lift (Refs. 3 and 4).

treme care was taken to ensure that the sharp wedge shaped leading edges were accurately machined and symmetrical with respect to the upper and lower wing surfaces. This was felt to be necessary because earlier unpublished work had shown that the presence of asymmetrical leading edges led to significant changes in shed vortex characteristics between positive and negative incidences; in particular measured forces under unsteady flow conditions were difficult to interpret. Sharp symmetrical leading edges have been used in this investigation because it was considered important to produce experimental data capable of direct comparison with current and emerging theoretical models.

The lift and pitching moment against incidence measurements in steady flow for both wings were obtained by conventional techniques. Figures 5 and 6 show the data plotted with corresponding theoretical results. Some values of lift and moment curve slopes at two incidences are listed in Table 1, together with aerodynamic center positions.

Force measurements in oscillatory flow were made relative to the undisturbed freestream gust at the root two-thirds chord point. A yawmeter, sensing instantaneous gust angle, at this point measured the freestream gust relative to conditions at an upstream reference yawmeter in the absence of the test wings. Force measurements were then made for each wing, again relative to the upstream yawmeter output. The resultant phase angle data are therefore relative to the gust oscillations at the wing two thirds chord point.

Two series of tests were performed on both delta wing. The first tests varied the freestream gust amplitude at a constant frequency parameter in order to explore the effect of wing lift curve slope nonlinearity on the unsteady aerodynamic forces. With the wings at 0 deg incidence, the gust amplitude $\bar{w}_g$ was varied from 0.0087 (0.5 deg) up to 0.49 (2.8 deg) at constant frequency parameters of 0.303 and 0.377. The results are tabulated in Table 2. The second series of tests was aimed at determining the variation of aerodynamic force amplitudes with frequency parameter for a constant gust amplitude ($\bar{w}_g = 0.0314$ or 1.8 deg) at two incidences and two freestream velocities. Both delta wings were tested at 0 deg incidence with a second incidence angle chosen such that the leading edge vortices were generating a significant proportion of the total steady lift without vortex bursting occurring until well past the wing trailing edges. The latter was insured by drawing on the experimental results of Wentz and Kohlman[7] on vortex bursting phenomena with delta wings. The wing of aspect ratio 2 was set at 8 deg and that of aspect ratio 1 was set at 12 deg.

The results of the second group of tests are plotted in Figs. 7-12. For the wing of aspect ratio 2, Figs. 7 and 9 show the results of lift and pitching moment, respectively, at incidence angles of 0 and 8 deg in each figure. The data variations with frequency parameter at each incidence are alike in trend but differ substantially in level. Analogous data for the wing of aspect ratio 1 are given in Figs. 8 and 10. It is useful to further plot these data so as to compare the characteristics of the two planforms directly. Figures 11 and 12 display such curves, also plotted in terms of amplitude and phase of lift.

IV. Discussion and Conclusions

The steady flow test results are considered first. Measured lift coefficient against incidence data for the wing of aspect ratio 1 is plotted in Fig. 5, together with curves derived from a variety of calculations based on linear,[8,9] nonlinear,[10-14] and separated flow[15-18] theories. Results from the nonlinear

Table 1 Steady flow measurements and theory

Wing shape and incidence	Lift curve slope, $\partial C_L/\partial\alpha$ Expt.	Theory	Pitching moment curve slope $\partial C_M/\partial\alpha$ Expt.	Theory	Aerodynamic center position x_{ac}/c_r aft of apex Expt.	Theory
AR = 2, $\alpha = 0$ deg	2.20	2.20	−0.35	−0.34	0.563	0.591
AR = 2, $\alpha = 8$ deg	2.62	2.86	−0.52	—	0.561	—
AR = 1, $\alpha = 0$ deg	1.24	1.30	−0.24	−0.13	0.571	0.617
AR = 1, $\alpha = 12$ deg	2.30	2.18	−0.46	—	0.565	—

Table 2 Oscillatory flow measurements; effect of gust amplitude, $\alpha = 0$ deg

			$\Delta C_L / \bar{w}_g$		$\Delta C_M / \bar{w}_g$	
Wing shape	$\nu = \omega c / U$	$\bar{w}_g$, deg	Ampl.	Phase lead	Ampl.	Phase lead
Aspect ratio 2	0.303	0.97	1.76	−18.5	0.48	−151.9
		1.97	1.80	−14.5	0.52	−153.9
		2.80	1.91	−20.2	0.57	−159.3
	0.377	0.97	1.67	−21.0	0.46	−156.8
		1.94	1.70	−15.3	0.53	−163.6
		2.74	1.72	−14.8	0.49	−157.1
Aspect ratio 1	0.303	0.50	1.00	−16.8	0.28	−139.4
		0.97	1.04	−16.1	0.30	−140.4
		1.47	1.05	−16.5	0.28	−133.5
	0.377	1.97	1.03	−16.3	0.30	−135.0
		2.41	1.09	−16.4	0.29	−142.0
		2.80	1.27	−19.8	0.34	−144.5

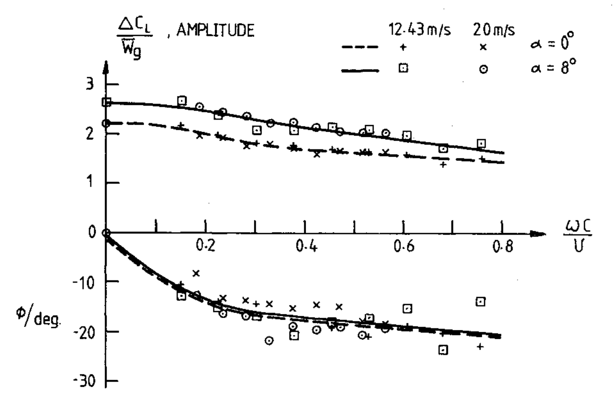

Fig. 7 Oscillatory lift forces on wing of aspect ratio 2.

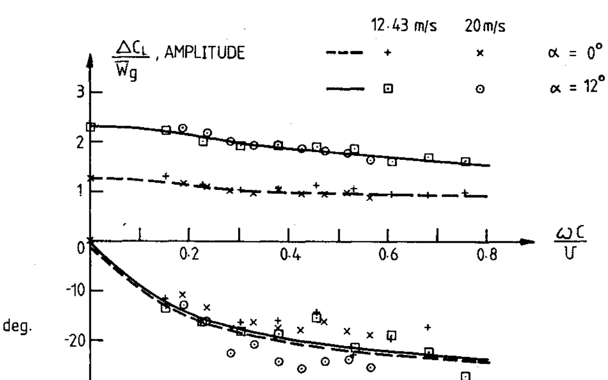

Fig. 8 Oscillatory lift forces on wing of aspect ratio 1.

theories of Polhamus,[10] Garner and Lehrian,[12] and Sacks et al.[13] are in good agreement with these experiments, as well as with other measured data reviewed by Parker.[1] In view of the nature of a delta wing lee-side flow the lack of agreement with the separated flow theories[15-18] is surprising. On the other hand, the calculations of Polhamus[10] based on a simple leading edge suction analogy show consistently good agreement with a selection of measurements.[1,3,4]

Ericsson and Reding[3,4] have extended the method of Polhamus by incorporating the potential flow theory by Jones and empirical data from experiments into producing a universal relationship for delta wing lift. The variation with incidence is plotted in Fig. 6, together with the measurements from these tests. Agreement with the derived relationship is very good for both wings and illustrates the value of the approach adopted by Ericsson and Reding to the aerodynamic design of delta winged aircraft.

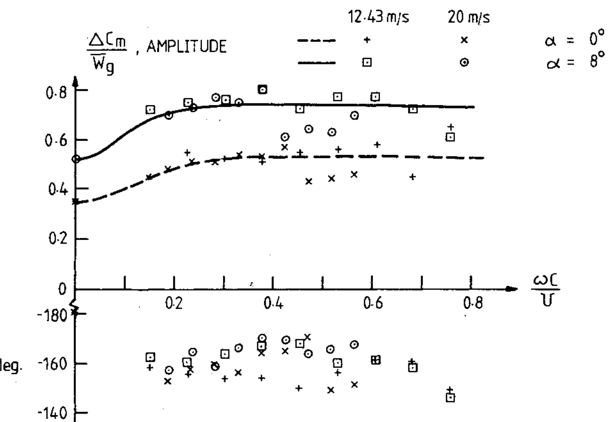

Fig. 9 Oscillatory pitching moments on wing of aspect ratio 2.

Some further comparisons of the test data with theory are presented in Table 1. For 0 deg incidence, lift and pitching moment curve slopes are derived from ESDU Data Sheets Item 70011,[19] which are based on inviscid linearized lifting surface theory. Theoretical results for the delta wing at incidence are obtained from the method of Polhamus.[10] The agreement of test results with both theories is reasonably good.

In the first series of oscillatory flow tests, results in Table 2 show that, for both delta wings, no discernible effect of the lift curve nonlinearity is apparent in the variations of lift and pitching moment coefficient amplitude (per unit gust amplitude) against incident gust amplitude. The variations that do exist are not consistent and are of the same order as the experimental errors. One exception is the measurement at highest incident gust angle (2.80 deg) for the wing of aspect ratio 1. The larger values of lift and pitching moment here can be interpreted as the first indication of the lift curve nonlinearity the effect of which could become more evident with further increases in incident gust amplitude. However, the flow around the delta wings during these small gust incidence changes (<2.8 deg) would be dominated by the potential flow and the absence of significant nonlinear behavior is to be expected.

In the second part of the oscillatory flow tests, Figs. 7 and 8 show the variation of lift force amplitude and phase with frequency parameter at two incidences for the wings of aspect ratios 2 and 1, respectively. For the gust amplitude values of 1.8 deg, the contribution of vortex induced lift at 0 deg wing incidence can be regarded as negligible. The trends of lift amplitude and phase variations are very similar to those obtained in a parallel study[6] for conventional nondelta wings. In particular the trends of lift decay and phase lag build-up

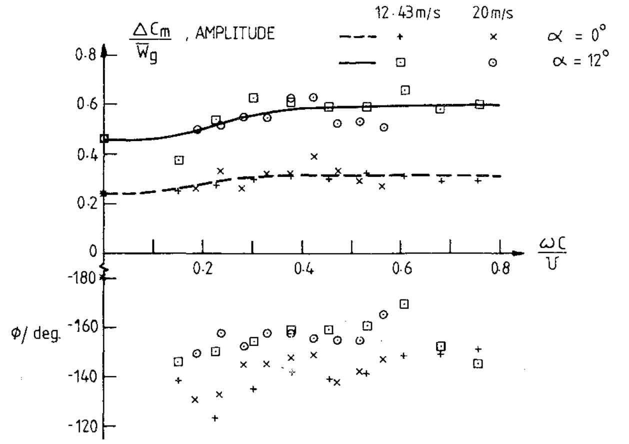

Fig. 10 Oscillatory pitching moments on wing of aspect ratio 1.

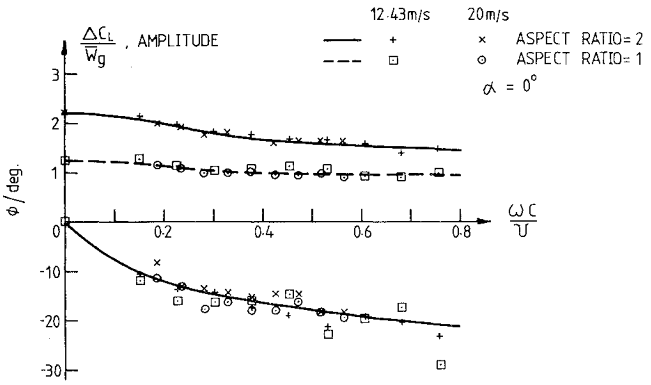

Fig. 11 Oscillatory lift forces at 0 deg incidence.

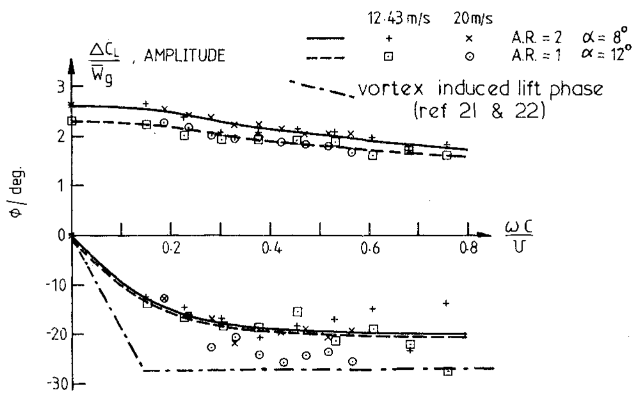

Fig. 12 Oscillatory lift forces at high incidences.

with increasing frequency parameter show strong similarities with the data for attached flows in Ref. 6. However, the corresponding data for higher wing incidences ($\alpha = 8$ deg for aspect ratio 2 and $\alpha = 12$ deg for aspect ratio 1) indicate that the incremental lift amplitudes due to the vortex lift contribution are apparent in amplitude only with no measurable phase changes. In fact, the increases in unsteady lift and moment due to the additional vortex lift contribution can be regarded as being quasistatic in nature. Furthermore, the variation of phase angle with frequency parameter remains virtually the same shape and level for all the tests on both delta wings (see also Figs. 11 and 12).

Figures 9 and 10 display the measured pitching moment data. The vortex-induced contribution is again apparent for amplitude with no detectable phase angle changes. An unusual feature of these curves is the increase in pitching moment amplitude above the quasistatic "zero-frequency" value at nonzero frequency parameters. This increase is probably due to the slender wing amplifying the effect of chordwise unsteady flow structure changes through pitching moment amplitude. The larger scatter in data associated with Figs. 9 and 10 is due to the small absolute values of measured pitching moment. For ease of interpretation, no lines have been drawn through the phase angle data.

Finally, comparative plots of lift force amplitude for the two wings are displayed for 0 deg incidence in Fig. 11 and for nonzero incidence in Fig. 12. The trends in lift amplitude are similar for all cases and once again the variation in phase angle is virtually identical within the limits of measurement error.

The quasistatic nature of the vortex induced lift contribution observed in these experiments is consistent with the work of Dore[20] and Lambourne et al.[21] on sudden plunging motions of delta wings. The vortex formation and inboard movement subsequent to the sudden motion are reported to be complete within a time t given by $Ut/c_r = 1$, which for these experiments would correspond to a time of the order of 0.025 s. Thus, gust oscillations at frequencies of 40 Hz or higher would show up unsteady phase lag effects in the vortex-induced unsteady lift contribution. For frequencies up to 12 Hz in these experiments, the vortex induced lift can be regarded as essentially quasistatic. Using the above criterion, it can further be shown that the upper limit for quasistatic response is approximately $\omega c/U = 2$ in terms of the frequency parameter used in this study. These comments can be further illustrated by following up a reviewer's suggestion. The experimental data on vortex behavior of Lambourne et al.[21] and Maltby et al.[22] can be combined to imply that the phase lag of the vortex induced lift initially varies linearly with frequency parameter and levels out to a constant value at higher frequency parameter. This phase lag variation is shown plotted in Fig. 12. The measured phase lag data are significantly lower than the variation deduced from the leading-edge vortex behavior, emphasizing again that the potential flow maintains a strong influence on the lift force variation with frequency parameter, even at high incidences.

It is appropriate at this stage to note the effect of the oscillatory gust travelling velocity of 0.61 U [see Eq. (1)] on the frequency parameters used in these results. Comparisons with theories based on a gust moving with the freestream velocity can be made by interpreting these expeiments as having a different "effective" gust encounter velocity or gust wavelength. Therefore, although these experiments have been presented with a frequency parameter $\nu = \omega c/U$, for a gust moving with the freestream velocity, the "effective" frequency parameter ν' should be taken as

$$\nu' = \omega c / 0.61U = \nu / 0.61$$

Three major conclusions can be drawn from the unsteady force measurements presented here:

1) The effects of the nonlinear variation of aerodynamic forces with incidence are apparent but local linearization for small amplitudes can be invoked.

2) The behavior of the oscillatory aerodynamic forces at zero and high wing incidences is dominated by potential flow effects and should be predictable by lifting surface theories.

3) The contribution of vortex lift to the oscillatory forces is quasistatic with a constant amplitude increase and no phase change with increasing frequency.

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