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Effects of Time Scales on Lift of Airfoils in an Unsteady Stream

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In unsteady aerodynamics, the reduced frequency has always been considered as the predominant controlling parameter because it relates to the unsteadiness. In this study, we examined the responses of several delta wings of varying aspect ratio and a two-dimensional wing in an unsteady periodic freestream. We found that in certain operating conditions, the lift of the airfoils may or may not be a function of the reduced frequency, depending on whether the leading-edge separation vortex can remain stationary on the wing or not. For delta wings with attached, stationary leading-edge vortices, the lift forces are not a function of the reduced frequency. However, if the leading-edge vortices shed and convect downstream, then the lift force depends on the reduced frequency.

Introduction

DELTA wings behave very differently from two-dimensional (2-D) wings because of a pair of stationary leading-edge separation vortices. A delta wing can provide high lift coefficients at very large angles of attack,[1] even up to 40 deg. The leading-edge vortices can remain stationary on the airfoil because the vorticity originating from the leading edge can be balanced by the vorticity transported along the cores of the separation vortices. With increasing angle of attack or aspect ratio, vortex breakdown occurs on the wing and moves towards the apex. Vortex bursting causes an abrupt change in axial velocity distribution from a jet-like profile to a wake-like one. When the breakdown reaches the apex, the delta wing behaves like a bluff body as vortex shedding occurs. Vortex shedding in the wakes of delta wings at high angles of attack in steady freestream was reported by Redinioitis et al.[2] However, the behavior of leading-edge vortices in unsteady flows is not well understood. Some early experiments focused on a pitching delta wing[3] and a stationary delta wing in a vertical gust.[4] It was observed that the vortices may remain attached to the wing in unsteady flows.[3] An appreciable amount of the lift produced by delta wings is generated by the vortex pair.[5] Since modern aircrafts widely employ delta wing designs, it is very crucial to understand the response of the vortices in an unsteady environment to ensure successful application to highly maneuverable aircraft.

Three delta wings with aspect ratios of $A = 1$, 2, and 4 and a 2-D wing (NACA 0012) are used in the present experiment. In this paper, the behavior of the vortices and the aerodynamic forces of these wings in an unsteady freestream will be discussed with the aid of phase-averaged lift measurements, flow visualization, and velocity measurements. We will concentrate our effort in understanding the effects of the reduced frequency on the lift forces of the wings studied.

Experimental Facility

Experiments were conducted in a vertical unsteady water channel with a cross-sectional area of 45.7 by 45.7 cm in the test section. The flow between the top and bottom reservoirs was driven by gravity, and constant head operation eliminated nonlinear effects due to the pumps. The freestream velocity control was achieved by rotating a gate (which operates like a valve) downstream of the test section. The rotation of the gate was done with a computer controlled stepping motor. The principle and process of controlling the freestream has been explained in detail by Gursul, Lin, and Ho.[6] This channel-gate combination provided a wide range of amplitudes and frequencies of the time-varying freestream with different types of waveforms, including ramp profiles for transient experiments. For a periodic freestream, the velocity can be represented in the form of

$$U/U_\infty = 1 + R\cos\omega t = 1 + R\cos 2\pi t/T \qquad (1)$$

where U_∞ is the average velocity, R is the dimensionless amplitude ($R < 1$) and $\omega = 2\pi/T$ is the radial frequency. The frequency of oscillations was limited by the fact that the freestream uniformity across the test section becomes unacceptable for $\omega \geq 6\ \mathrm{s}^{-1}$. The freestream turbulence level was about 0.5%. The freestream velocity was measured with a two-component laser-Doppler anemometer (LDA) (DANTEC, 55X optical system) operated in forward-scattering mode and equipped with a 100 mW Argon-Ion laser (Ion Laser Technology) and LDA counters (DANTEC 55L96).

The delta wings were made of thin plates with sharp leading edges. The typical thickness-to-chord ratio was approximately 10^{-3}. The NACA 0012 airfoil, which had an aspect ratio of 3.64, was cast from Hysol mixture. The Reynolds number was in the range of 30,000 to 60,000 for all airfoils. The blockage ratio was 0.135 for the 2-D wing at the maximum angle of attack $\alpha = 30$ deg and 0.044 for the delta wings at the maximum angle of attack $\alpha = 40$ deg. No correction was made on lift measurements due to the blockage. A pair of waterproof load cells (Sensotec, model 31) were used to measure the lift force on the airfoils. Lift and velocity signals were digitized by an analog-to-digital converter (RC Electronics, model ISC-67) and processed by an UNIPAQ 386 personal computer. An ensemble-averaging technique was applied to the signals to extract deterministic parts. Typically 50 cycles with 100 points per cycle were averaged.

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The phase-averaged lift force and lift coefficient are defined by

$$L(t) = C_L(t)\tfrac{1}{2}S\rho U(t)^2 \quad (2)$$

where S is the surface area of the wing. To see the effects of unsteadiness, a comparison is made with the quasisteady lift force defined as

$$L_{qs}(t) = C_{L\infty}\tfrac{1}{2}S\rho U(t)^2 \quad (3)$$

where $C_{L\infty}$ is the steady-state lift coefficient. Then, the ratio of the time-averaged values of these forces is considered, i.e., $\overline{L(t)}/\overline{L_{qs}}$.

Flow visualization was carried out by illuminating air bubbles that were entrained into the vortex cores on the delta wings, which provided a way to visualize leading-edge vortices. A tungsten light source made of two 500 W lamps with a slit, as well as a laser sheet scanned by a mirror, were used to illuminate the flowfield. A 35 mm camera (NIKON, model F-3) was used to take still pictures. This camera could be triggered by a pulse at any particular time that was phase-referenced to the instantaneous velocity. The time-dependent flowfield was also videotaped using a CCD camera (ELMO, model SE301) and a VCR (Panasonic S-VHS).

Experimental Results

On a delta wing, vorticity is generated at the leading edge and is convected by the separated flow. If the vorticity generation is balanced by the convection, the separation vortex will be stationary. Otherwise, the vortex will move downstream. While the vortex remains at the leading edge, it forms a convex streamline and thereby high suction, which produces a high lift force. However, this additional force diminishes if the vortex convects away. Therefore, the lift force contributed by the unsteady effect is directly affected by whether the vortices remain stationary near the leading-edge area.

When vortex shedding from the leading edge takes place, the convection speed is a fraction of the average freestream velocity U_∞. The time scale c/U_∞, where c is the chord length, can be considered as a measure of the time needed for a vortex to pass the airfoil. In an unsteady freestream, the reduced frequency $k = \omega c/2U_\infty$ can be interpreted as the ratio of two time scales: an intrinsic vortex convection time scale c/U_∞ and an external perturbation time scale $T = 2\pi/\omega$. The reduced frequency is always considered as an important parameter in unsteady aerodynamic studies.

The time-averaged lift force normalized by the time-averaged quasisteady lift force $\overline{L(t)}/\overline{L_{qs}}$ is shown as a function of

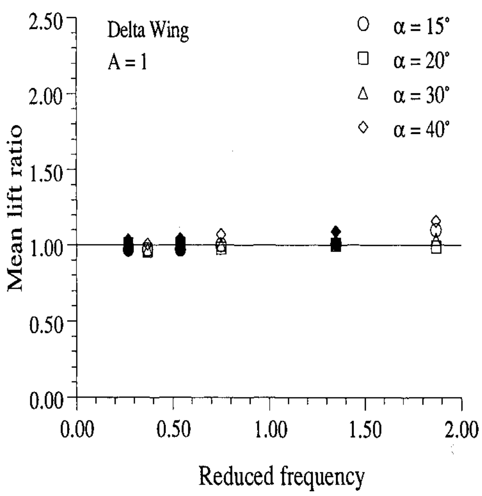


Fig. 1 Variation of time-averaged lift force normalized by time-averaged quasisteady lift force for aspect ratio $A = 1$ delta wing; $R = 0.42$ for solid symbols and $R = 0.59$ for open symbols.

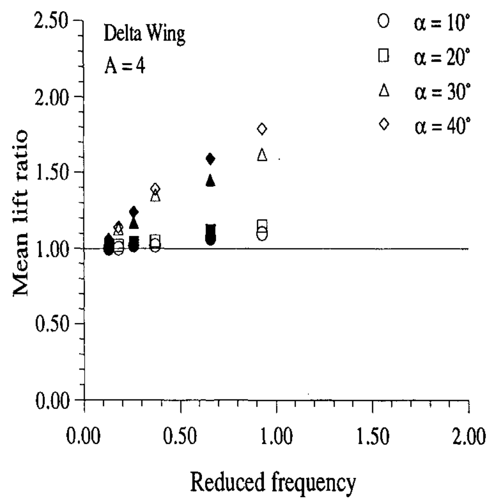


Fig. 3 Variation of time-averaged lift force normalized by time-averaged quasisteady lift force for aspect ratio $A = 4$ delta wing; $R = 0.42$ for solid symbols and $R = 0.59$ for open symbols.

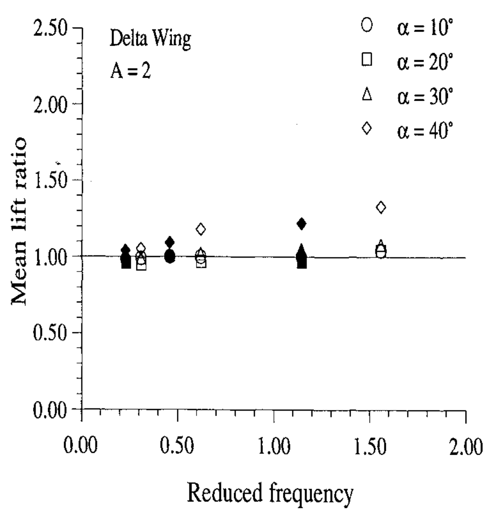


Fig. 2 Variation of time-averaged lift force normalized by time-averaged quasisteady lift force for aspect ratio $A = 2$ delta wing; $R = 0.42$ for solid symbols and $R = 0.59$ for open symbols.

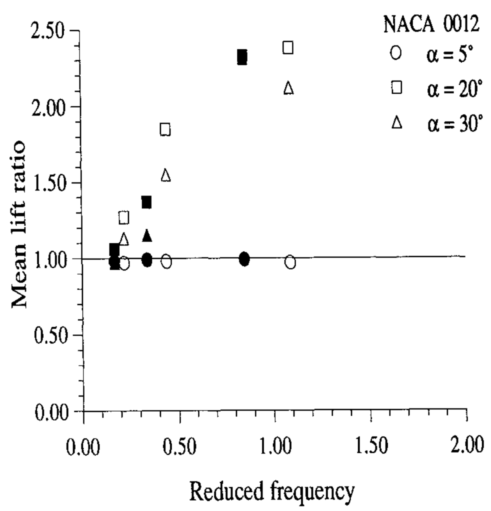
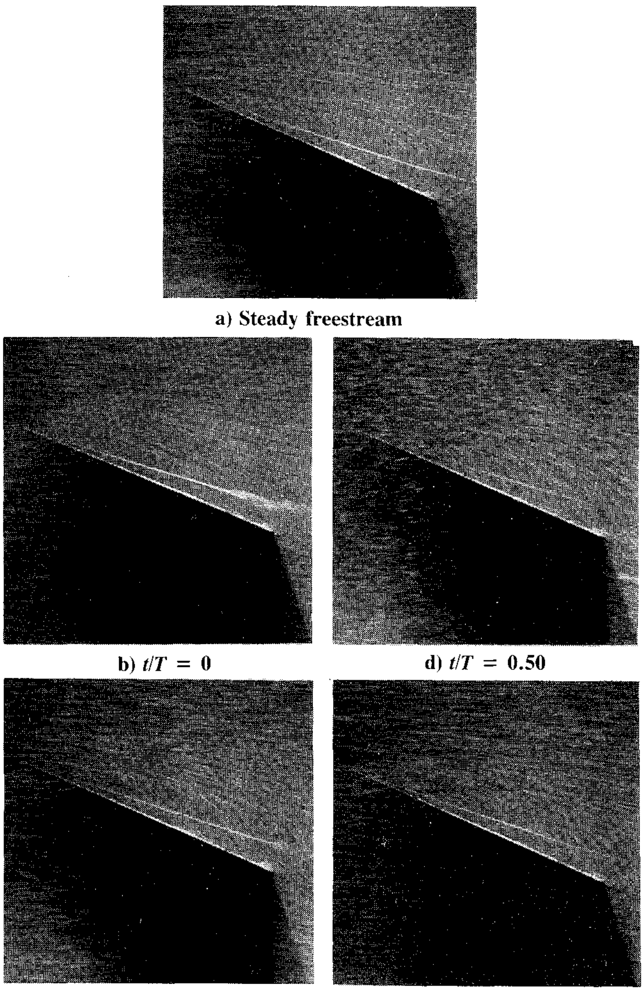


Fig. 4 Variation of time-averaged lift force normalized by time-averaged quasisteady lift force for 2-D wing; $R = 0.42$ for solid symbols and $R = 0.59$ for open symbols.

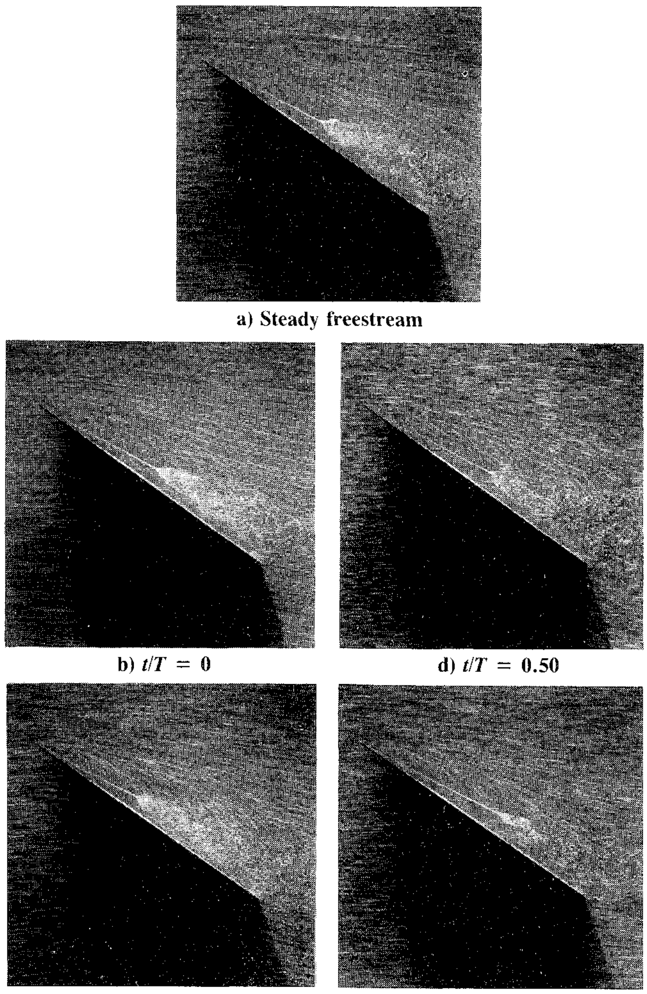


a) Steady freestream

b) $t/T = 0$ d) $t/T = 0.50$

c) $t/T = 0.25$ e) $t/T = 0.75$

Fig. 5 Flow visualization for $A = 1$ delta wing at $\alpha = 25$ deg at different phases of the cycle ($R = 0.42$, $k = 0.93$).



a) Steady freestream

b) $t/T = 0$ d) $t/T = 0.50$

c) $t/T = 0.25$ e) $t/T = 0.75$

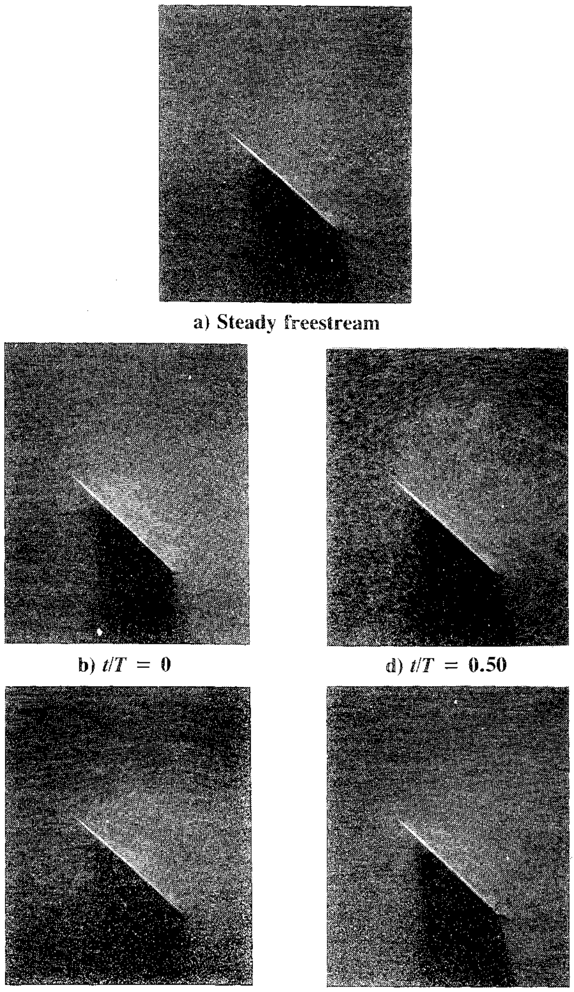
Fig. 6 Flow visualization for $A = 1$ delta wing at $\alpha = 40$ deg at different phases of the cycle ($R = 0.42$, $k = 0.93$).

the reduced frequency in Figs. 1–4 for all wings tested. The solid and open symbols denote different amplitudes of oscillations ($R \approx 0.42$ and $R \approx 0.59$, respectively). Note that for the smallest aspect ratio delta wing (Fig. 1, $A = 1$), the time-averaged lift force is not a function of the reduced frequency for a large range of angles of attack ($\alpha = 15$ deg to 40 deg). Flow visualization for this delta wing at $\alpha = 25$ deg (at a relatively high reduced frequency $k = 0.93$) shows that the vortex core remains attached to the wing and remains essentially in the same position with respect to the wing during the whole cycle (Fig. 5). In other words, the geometry of the core does not change. Since the vortices remain attached, there is no intrinsic time scale. Therefore, the reduced frequency is not a controlling parameter.

Further flow visualization showed that the breakdown is observed around the trailing edge during a portion of the cycle for high reduced frequencies. However, as seen in Fig. 1, the time-averaged lift force does not change with the reduced frequency. This lack of change implies that the observed changes in the breakdown position near the trailing edge do not affect the lift force. This result is not surprising because the Kutta condition requires vanishing pressure difference between the upper and lower surfaces near the trailing edge. Therefore, the lift produced in this region is very small, and hence the vortex breakdown around this region does not alter the C_L significantly. This result has been demonstrated by pressure measurements in the steady case by Lambourne and Bryer.[7] At the largest angle of attack ($\alpha = 40$ deg), a departure in the time-averaged lift force seems to begin. The vortex breakdown position is approximately at midchord for this angle of attack. In Fig. 6, flow visualization of the same wing ($A = 1$) at $\alpha = 40$ deg is shown at the same reduced frequency as in Fig. 5 ($k = 0.93$). It shows that the position of breakdown does not appear to be affected by unsteadiness in the freestream. In general, the breakdown position is not sensitive to the unsteadiness, except when it is near the trailing edge.

Unlike the $A = 1$ delta wing, the time-averaged lift force is a strong function of the reduced frequency for the 2-D wing in the poststall region (Fig. 4). The vorticity generated at the leading edge will form a vortex, which cannot remain stationary on a 2-D wing and will shed downstream. Therefore, the intrinsic vortex convection time scale always exists and the reduced frequency is a meaningful parameter. However, when the flow is attached, as for small angle of attack ($\alpha = 5$ deg), there is no convected vortex. Consequently, the lift is not a function of the reduced frequency.

The response of delta wings at aspect ratios higher than one has a transitional behavior between the 2-D wing and the delta wing with $A = 1$. When the aspect ratio is increased, the mean velocity component in the leading-edge direction decreases. Hence, the ability of convecting vorticity along the core of the leading-edge vortex is reduced. This situation worsens when the angle of attack is increased. Eventually, the leading-edge vortices start shedding. In these cases, the intrinsic convection time scale appears on the delta wing. Thus, the lift force depends on the reduced frequency, which is analogous to the 2-D wing case (Figs. 2 and 3). In Fig. 7, flow visualization for the $A = 4$ delta wing at $\alpha = 40$ deg is shown at different phases of the cycle. There are strong similarities to the flow around a 2-D wing in the poststall region.[8]



a) Steady freestream

b) $t/T = 0$ d) $t/T = 0.50$

c) $t/T = 0.25$ e) $t/T = 0.75$

Fig. 7 Flow visualization for $A = 4$ delta wing at $\alpha = 40$ deg at different phases of the cycle ($R = 0.70$, $k = 0.93$).

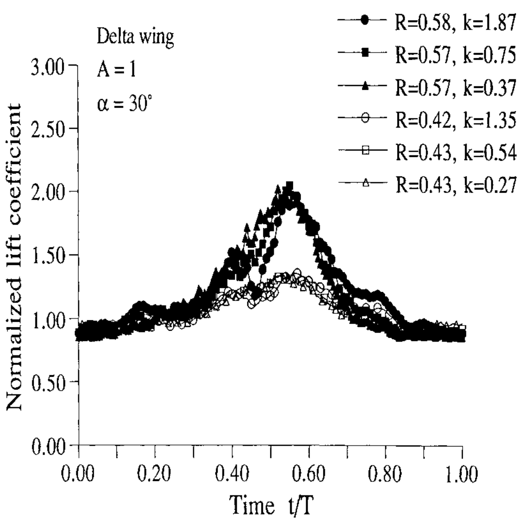


Fig. 8 **Variation of phase-averaged lift coefficient normalized by the steady-state one, $C_L/C_{L\infty}$, for aspect ratio $A = 1$ delta wing, $\alpha = 30$ deg.**

So far the discussion was based on the time-averaged lift force. Yet, the same conclusions can be arrived at by studying the phase-averaged lift coefficient. The phase-averaged lift coefficients in general have a bell-shaped profile during one cycle variation of the freestream velocity. It is observed that when the leading-edge vortices are attached ($A = 1$, 2 at $\alpha = 30$ deg), the phase-averaged lift coefficient is not a func-

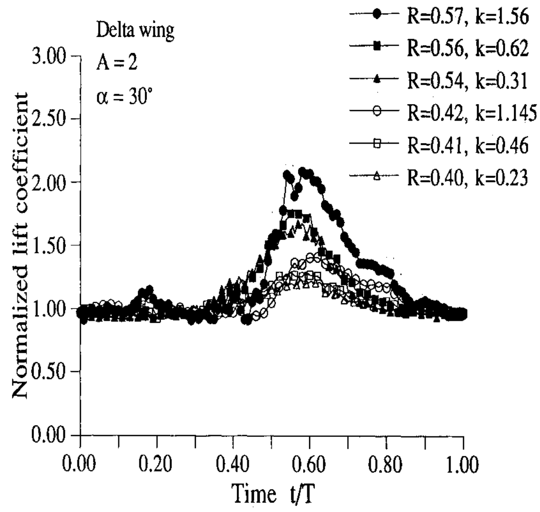


Fig. 9 **Variation of phase-averaged lift coefficient normalized by the steady-state one, $C_L/C_{L\infty}$, for aspect ratio $A = 2$ delta wing, $\alpha = 30$ deg.**

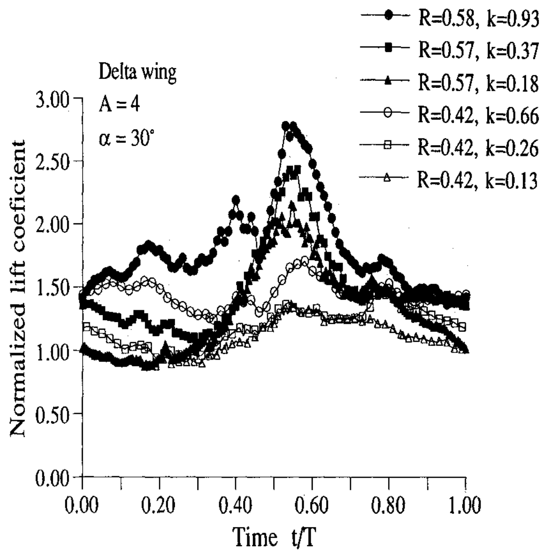


Fig. 10 **Variation of phase-averaged lift coefficient normalized by the steady-state one, $C_L/C_{L\infty}$, for aspect ratio $A = 4$ delta wing, $\alpha = 30$ deg.**

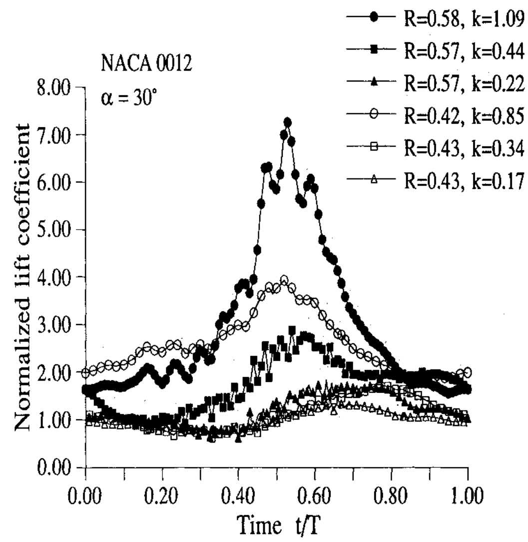


Fig. 11 **Variation of phase-averaged lift coefficient normalized by the steady-state one, $C_L/C_{L\infty}$, for 2-D wing, $\alpha = 30$ deg.**

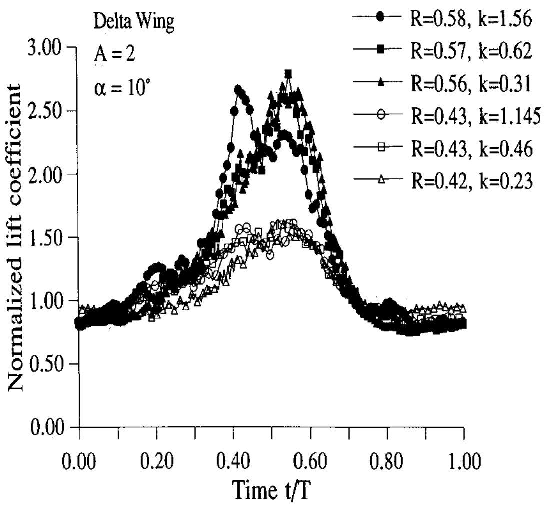


Fig. 12 Variation of phase-averaged lift coefficient normalized by the steady-state one, $C_L/C_{L\infty}$, for aspect ratio $A = 2$ delta wing, $\alpha = 10$ deg.

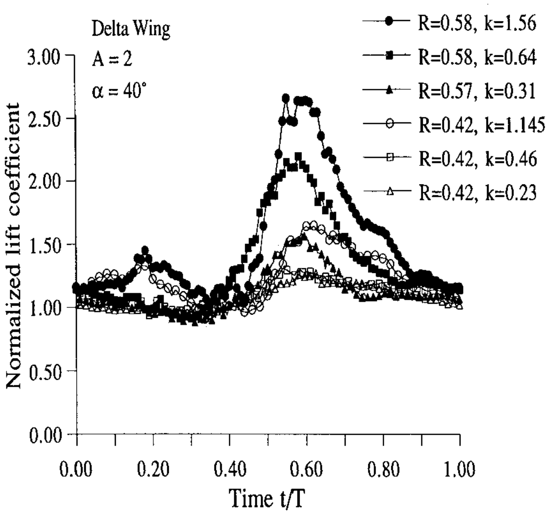


Fig. 13 Variation of phase-averaged lift coefficient normalized by the steady-state one, $C_L/C_{L\infty}$, for aspect ratio $A = 2$ delta wing, $\alpha = 40$ deg.

tion of the reduced frequency, and all the curves collapse for a given amplitude of the freestream velocity (Figs. 8 and 9). However, for the wing with a large aspect ratio ($A = 4$), vortex shedding takes place (Fig. 7). Consequently, the reduced frequency is an important parameter, and the lift coefficient curves do not collapse (Fig. 10, $\alpha = 30$ deg).

With increasing aspect ratio, vortex shedding and lift force variation become more similar to that of the 2-D wing (Figs. 10 and 11). However, the maximum values of the lift coefficient for the 2-D wing are much higher. In fact, the NACA 0012 airfoil in the poststall region can have lift coefficients exceeding 10 at an optimum reduced frequency.[8] This phenomenon is because a large coherent vortex stays on the chord for an appreciable portion of the cycle.

The phase-averaged lift coefficient trends are consistent with the time-averaged lift force data. Again, the response of delta wings at aspect ratios higher than one has a transitional behavior between the $A = 1$ and the 2-D wing. At low angles of attack, the leading-edge vortices are attached, thus the phase-averaged lift coefficient is not a function of the reduced frequency, and all the curves collapse for a given amplitude of the freestream velocity (Fig. 12, $A = 2$, $\alpha = 10$ deg). However, at large angles of attack vortex shedding starts to take place, and we begin to observe deviations for the phase-averaged lift coefficients (Figs. 9 and 13).

Conclusions

The effects of the reduced frequency on the lift of delta wings in an unsteady freestream have been investigated in this study. The time-averaged and phase-averaged lift measurements are independent of reduced frequency for delta wings at a small angle of attack and with a small aspect ratio. In these cases, the leading-edge vortices are attached and there is no intrinsic time scale. Since the reduced frequency can be interpreted as the ratio of the convection time of the vortex on the chord to the period of the freestream variation, the reduced frequency loses its meaning under these conditions. With increasing angle of attack or aspect ratio, vortex shedding occurs. The time required for the leading-edge vortex to convect along the chord becomes an intrinsic time scale. Consequently, the lift is a function of the reduced frequency. For a 2-D wing, reduced frequency is always a controlling parameter on the lift in a poststall regime because vortex shedding exists for all times.

Acknowledgment

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References

[1]Lee, M., and Ho, C. M., "Lift Force of Delta Wings," *Applied Mechanics Reviews*, Vol. 43, No. 9, 1990, pp. 209–221.

[2]Rediniotis, O. K., Stapountzis, H., and Telionis, D. P., "Vortex Shedding Over Delta Wings," *AIAA Journal*, Vol. 28, No. 5, 1990, pp. 944–946.

[3]Gad-el-Hak, M., and Ho, C. M., "The Pitching Delta Wing," *AIAA Journal*, Vol. 23, No. 11, 1985, pp. 1660–1665.

[4]Patel, M. H., "The Delta Wing in Oscillatory Gusts," *AIAA Journal*, Vol. 18, No. 5, 1980, pp. 481–486.

[5]Ericsson, L. E., and Reding, J. P., "Fluid Dynamics of Unsteady Separated Flow. Part II. Lifting Surfaces," *Progress in Aerospace Sciences*, Vol. 24, No. 4, 1987, pp. 249–356.

[6]Gursul, I., Lin, H., and Ho, C. M., "Vorticity Dynamics of 2-D and 3-D Wings in Unsteady Free Stream," AIAA Paper 91-0010, Jan. 1991.

[7]Lambourne, N. C., and Bryer, D. W., "The Bursting of Leading-Edge Vortices: Some Observations and Discussions of the Phenomena," Aeronautical Research Council, R. & M. No. 3282, London, April 1961.

[8]Gursul, I., and Ho, C. M., "High Aerodynamic Loads on an Airfoil Submerged in an Unsteady Stream," *AIAA Journal*, Vol. 30, No. 4, 1992, pp. 1117–1119.