unsteady problem $(u_z)_0$ and $(v_z)_0$ oscillate about their steady values and appear to be exactly one-quarter period out of phase. This is also the case for $w(\infty,T)$ and D. A phase change in the skin-friction components occurred in a problem also considered by Homsy and Hudson: they analytically investigated the unsteady development of almost solid-body rotation, i.e., $s=1-\epsilon$, $|\epsilon| \ll 1$. It can be shown from their results that the departures of $(u_z)_0$ and $(v_z)_0$ from their steady values are $(4\sqrt{\pi}T^{3/2})^{-1}\epsilon\cos 2T$ and $(4\sqrt{\pi}T^{3/2})^{-1}\epsilon\sin 2T$, respectively, i.e., a phase difference of $\pi/4$.

It is hoped that the results of other investigations will be published in the near future.

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Large-Amplitude Fluctuations of Velocity and Incidence on an Oscillating Airfoil

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Introduction

DUE to the complexity of unsteady effects, the three-dimensional aerodynamic behavior of a helicopter blade-section in forward flight has been extensively investigated in the course of the last few years.[1] Recent results[2] have shown that unsteady flows over the rotor blade can be modeled through two-dimensional oscillating airstreams over pitching airfoils. Therefore, most of the experimental and theoretical studies undertaken on this topic have tackled the problem by investigating unsteady flows for airfoils oscillating either in pitch,[3-5] or in translation parallel or normal to the undisturbed airstream.[6-8] A proper simulation of the flow surrounding the rotor blade requires considering incidence oscillations combined with simultaneous velocity fluctuations of the airstream. A recent work[9] has presented surface pressure measurements performed on a pitching airfoil in a fluctuating airstream. Unsteady effects are observed from the pressure distributions obtained at the same instantaneous angle of attack, with and without velocity oscillations of the airstream. In the present study, unsteady flow features due to large-amplitude fluctuations of both velocity and incidence induced by an airfoil executing cyclic time-dependent fore-and-aft translations, are investigated from lift, drag, and skin-friction measurements.

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Experimental Setup

The tests were conducted in a low-turbulence (<0.2%) open circuit wind tunnel (0.5×1×3 m). Under steady flow conditions, the range of static Reynolds numbers $Re_c = V_\infty c/\nu$ was $5.7\times 10^4 \le Re_c \le 4\times 10^5$. The model consisted of a rectangular wing (span $l=0.495$ m and chord $c=0.3$ m), with a NACA 0012 profile with an angle of steady stall incidence of about 12 deg. This airfoil was supported by a frame oscillating sinusoidally in translation of amplitude A and rotational frequency $\omega = 2\pi f$ which could be obtained in the ranges: $0\le A \le 0.17$ m and $0 \le f \le 5$ Hz. Consequently, the reduced amplitude $\lambda = A\omega/V_\infty$, and the reduced frequency $k = c\omega/2V_\infty$ were respectively varied from 0 to 1.2 and from 0 to 1.6.

As exemplified on the diagram of Fig. 1, the static angle of attack α_0 is set up anywhere between −25 deg and 25 deg; and the airfoil is oscillating in translation along the X_δ oscillation axis. The angle δ between the X_δ axis and the freestream direction can be adjusted from 0 deg to 90 deg. When $\delta=0$ deg (or $\delta=90$ deg), the airfoil oscillates in translation parallel (or normal) to the undisturbed airstream. The angle i between the resultant velocity V and the chord airfoil is defined by:

$$i=\alpha_0 - i_0 \text{ and } i_0 = \text{arctg}[\lambda\cos\omega t\sin\delta/(1+\lambda\cos\omega t\cos\delta)] \quad (1)$$

The amplitude of fluctuating velocity is given as follows:

$$V^2 = V_\infty^2(1+2\lambda\cos\omega t\cos\delta + \lambda^2\cos^2\omega t) \quad (2)$$

So, large-amplitude fluctuations of both velocity and incidence can be obtained with the maximum incidence coinciding with the minimum velocity. For two static angles of attack $\alpha_0 = 20$ deg and $\alpha_0 = 6$ deg, Fig. 1 gives the periodic variations of resultant velocity V and incidence i vs ωt, in the following conditions: $\delta = 17$ deg; $\lambda = 0.744$; $k=0.66$. As an example it can be seen that for $\alpha_0 = 20$ deg the instantaneous

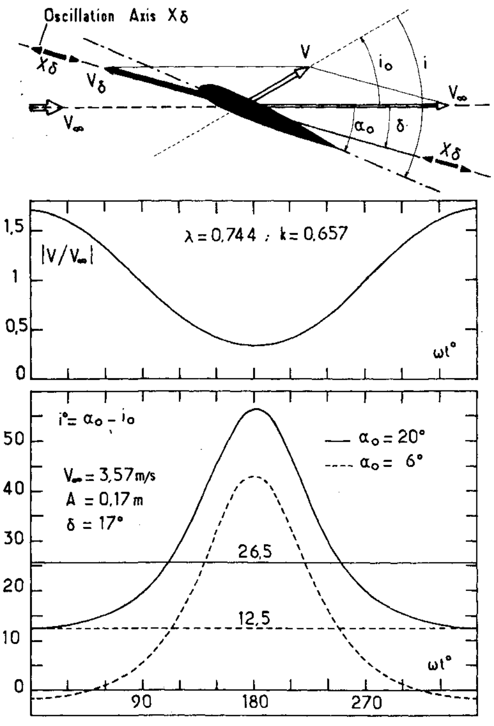

Fig. 1 Amplitude fluctuations of velocity and incidence.

angles of attack are varying from 12.8 deg to 57 deg around a mean incidence of 26.5 deg.

The measurements of aerodynamic forces have been carried out by means of a torsion-dynamometer[6] dynamically calibrated. Details of experimental procedures relative to lift, drag, and skin-friction measurements by hot-film gages, are given in Refs. 6, 8, and 10. All of the instantaneous measurements of forces and skin friction were digitized and stored by an 800-channel data acquisition system. These data were then harmonically analyzed to yield the time-averaged and the N-Fourier harmonics in the following form:

$$G/G_S = C_0 + \sum_{n=1}^{N} C_n \cos(n\omega t + \Phi_n) \tag{3}$$

where G is the unsteady value and G_S the steady one.

Results and Discussion

The evolutions of instantaneous lift L and drag D are shown on Figs. 2 and 3, for $V_\infty = 3.57$ m/s; $\delta = 17$ deg; $\lambda = 0.744$; $k = 0.657$, in the case of $\alpha_0 = 20$ deg. In order to give the best evaluation of truly unsteady effects, the variations of quasisteady lift L_{QS} and drag D_{QS} which should be obtained when the airfoil behavior remains quasisteady, are also presented on the figures. L_{QS} and D_{QS}, represented by dotted lines, have been calculated from the amplitude fluctuations of Eqs. (1) and (2), previously described on Fig. 1. For incidences above 25 deg, it has been assumed that the stalled airfoil has a steady aerodynamic behavior similar to that of a flat plate set at an incidence i in an airstream of velocity V. The unsteady values L, D, and the quasisteady ones L_{QS}, D_{QS}, have been nondimensionalized by the steady lift $L\alpha_0$, and drag $D\alpha_0$, obtained under the corresponding static conditions: $\alpha_0 = 20$ deg, and $V_\infty = 3.57$ m/s.

The measured time histories of L and D are represented on Figs. 2 and 3 by dashed lines corresponding to the Fourier 4-harmonics analysis of Eq. (3). Fig. 2 reveals a significant increase of the instantaneous lift L which remains above the steady lift $L\alpha_0$ over the whole period. Its time-averaged value ($C_0 = 1.86$) is also greater than the quasisteady one (1.34). A similar overshoot of the instantaneous drag D is readily observable on Fig. 3, where D meets the steady value $D\alpha_0$ for $\omega t \simeq 240$ deg. Both $L/L\alpha_0$ and $L_{QS}/L\alpha_0$ (or $D/D\alpha_0$ and $D_{QS}/D\alpha_0$) ratios, are decreasing as velocity decreases, but it is noteworthy that the $L/L\alpha_0$ and $D/D\alpha_0$ curves are phase-lagged and have a nonsymmetrical behavior for $0 \leq \omega t \leq 180$ deg and for 180 deg $\leq \omega t \leq 360$ deg. As an example, the unsteady aerodynamic load appears to be higher at $\omega t = 90$ deg for decreasing velocity, than at $\omega t = 270$ deg when velocity is increasing; nevertheless for both phases $\omega t = 90$ deg and $\omega t = 270$ deg instantaneous velocity V and incidence i have the same value ($V = V_\infty$, $i = 20$ deg). On the tops of Figs. 2 and 3 the L/L_{QS} and D/D_{QS} ratios plotted vs ωt, clearly demonstate the significant departure from the expected quasisteady behavior. Indeed the time-averaged value is about 2.7 for both lift and drag; and the strongest unsteady effect appears near the maximum incidence ($\omega t = 180$ deg), where L and D respectively reach the values of $7L_{QS}$ and $8D_{QS}$.

Similar favorable effects of unsteadiness on lift, accompanied by overshoots of drag and pitching moment, have been already pointed out when the airfoil is oscillating either in pitch[3,4] or in translation parallel to the undisturbed airstream.[6,7,10] These strong unsteady features have been analyzed and explained by a vortex shedding process on the upper side of the airfoil, giving rise to dynamic stall and dynamic reattachment over a part of the period. This significant viscid-inviscid interaction occurred when the airfoil was going toward highest incidences for the pitching airfoil, and toward lowest velocities for the translating airfoil. Concerning the upper side of the airfoil, Fig. 4 gives the time histories of skin friction τ/τ_s from $x/c = 0.04$ to $x/c = 0.8$, measured at $\alpha_0 = 20$ deg; $Re_c = 0.7 \times 10^5$; $\delta = 17$ deg; $\lambda = 0.744$; $k = 0.657$. It can be seen from these waveforms, that when there are simultaneous fluctuations of incidence and velocity, a rolling vortex phenomenon also appears[3,7] near the leading edge ($x/c = 0.12$) and develops along the airfoil upper surface. This strong vortex is convected downstream with a speed of propagation of about $0.45\ V_\infty$.

Conclusion

From the preceding results it is apparent that when combined fluctuations out of phase of velocity and incidence are simulated, unsteady flow features are of a similar nature to those observed when incidence or velocity oscillations are separately simulated. It should be interesting in the future to investigate the unsteady effects involved by cyclic time-dependent motions which allow one to obtain oscillations in

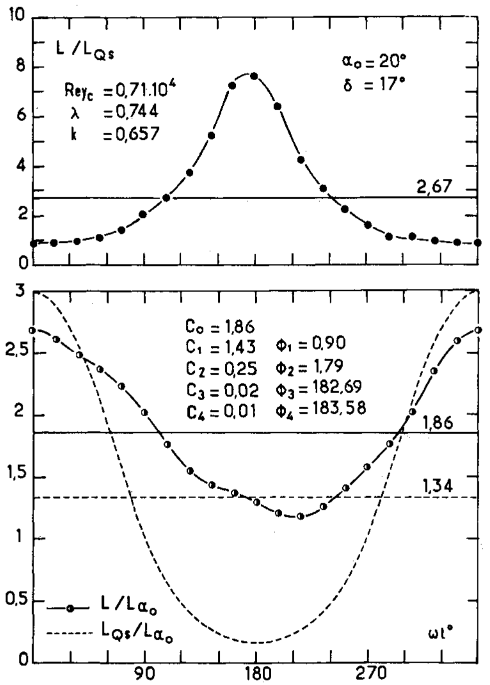

Fig. 2 Unsteady effects on lift.

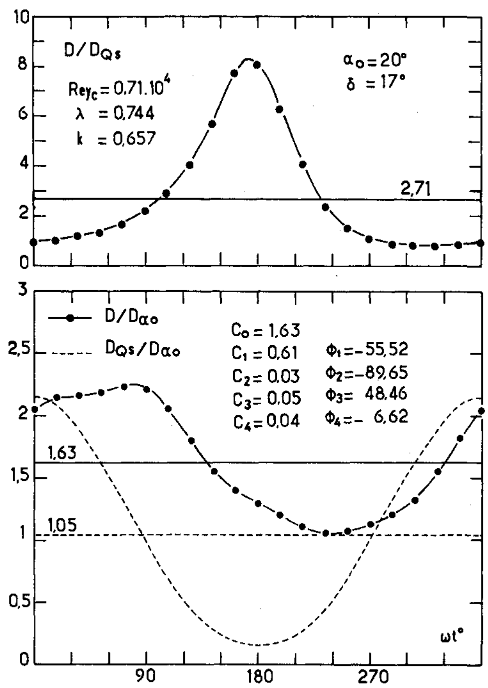

Fig. 3 Unsteady effects on drag.

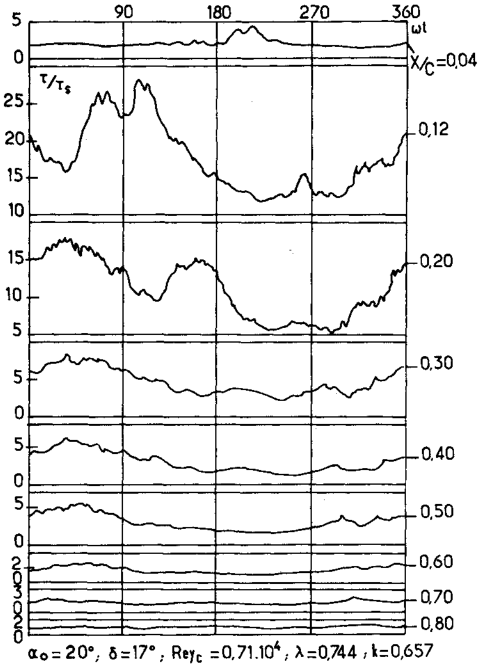

Fig. 4 Waveforms of skin friction on the upper surface.

phase of incidence and velocity. It can be concluded that such kinds of combined two-dimensional flows would bring a new contribution in modeling the basic three-dimensional rotor problem.

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Improved Free-Vortex, Subsonic Aerodynamic Window

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I. Introduction

AERODYNAMIC windows have been developed to take the place of more conventional solid windows in laser systems where the high intensity of the laser beam precludes the use of solid windows. They serve to contain the gas in the laser, maintain a desired laser cavity pressure, and optically transmit the laser beam into the outside environment. Various types of aerowindows have been developed since the introduction of the first high-energy laser, the GDL. Most of them are supersonic,[1-3] but some are subsonic, such as the free-vortex window developed for use with atmospheric lasers.

It has been observed that in this type of subsonic aerowindow, significant optical distortions are caused by the large-scale turbulent mixing that takes place in the shear layer at the jet boundary with the ambient. The reason for this observation is as follows. The window jet is optically matched to the laser gas; thus, the index of refraction of the window jet differs, sometimes significantly, from the index of air. As a result, a "marble cake" effect takes place in the shear layer. Ambient air and jet gas mix together in this flow region, giving rise to large-scale index variations that cause the observed optical distortions.

Sutton[4] has shown that the phase aberration produced by turbulent refractive index changes is given by:

$$\frac{\Delta I}{I_0} = \frac{I_0 - I}{I_0} = 2\left(\frac{2\Pi}{\lambda}\right)^2 \overline{\langle \Delta n \rangle^2 \Lambda \delta}$$

where I_0 is the nondegraded laser radiation intensity, I the interface degraded intensity, $\overline{\langle \Delta n \rangle^2}$ the square of rms refractive index variations, and λ the laser wavelength. From this relation we see that the width of the turbulent interface δ and the value of the typical turbulence scale size Λ have a pronounced effect on laser beam degradation. We also know that in turbulent shear layers, Λ is proportional to δ. Thus, by reducing the width of the refractive index shear zone, reduction in the phase aberration can be achieved.

In the present study we demonstrated a novel approach for reducing the optical distortions caused by index fluctuations in the subsonic free-vortex aerowindow flow. The scheme is based on eliminating the index of refraction discontinuity at the intensely sheared free-mixing layer, and taking it at a location where the two gases are made to flow in parallel with similar or identical velocities, thus reducing the width of the index discontinuity and the associated turbulence scale size. As a result, the optical quality of the flow is significantly improved and laser beam intensity losses reduced.

II. Experiments and Results

Experiments were carried out on an improved free-vortex subsonic aerodynamic window depicted in Fig. 1. A compact inlet divided into two chambers by a splitter plate serves to generate the two parallel flowing jets of the aerowindow. These traverse the laser exit and exhaust through a diffuser into the atmosphere. Each jet is supplied with gas from a

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