tunnel. The accuracy of the velocity components determined by this method depends on 1) the coupling angle determined by the two lateral locations of the velocimeter, 2) the statistical uncertainty due to sampling, and 3) systematic uncertainties resulting from positioning and calibration errors.[4] The effect of these uncertainties on the ultimate measurement accuracy is currently being studied.

Preliminary Velocimeter Evaluation

A limited flow survey of the flow generated by a two-bladed, 0.76-m-diam, industrial-type air circulation fan was conducted in order to evaluate system performance. The survey was made across the fan face parallel to the plane of rotation and through the axis of symmetry at a distance of 0.56 fan diameters from the fan on the downstream side. The fan rotated in a clockwise direction when viewed from the downstream side.

The data presented in Fig. 3 were obtained while operating the velocimeter at a range of 6.4 m and a laser output power of 2.5 W. A light aerosol of mineral oil seeding was introduced on the upstream side of the fan to reduce data acquisition time; however, excellent signals were also obtained with the natural seeding present in the area of the fan. A desktop computer and a counter-type signal processor were used for data acquisition and reduction. Seventy velocity samples were acquired per data point; a 95% confidence interval for 70 samples is shown in Fig. 3.

A slight asymmetry of the velocity profile is apparent from Fig. 3. This behavior was caused by the influence of a wall located at a distance of two fan diameters from and parallel to the axis of symmetry.

It is interesting to note that a velocity shear of 41 (m/s)/m near the fan center was resolved from a range of 6.4 m. This shear does not necessarily represent the limit of resolution of the velocimeter since the test flow was selected primarily for reasons of convenience and was not intended to be used to determine the limiting performance of the velocimeter.

Velocimeter Applications

In its current configuration, the velocimeter is designed for use in the Ames 40- × 80-ft Wind Tunnel. However, it should be emphasized that the basic design does not preclude use of the system in the Ames 80- × 120-ft Wind Tunnel or at the Ames Outdoor Aerodynamic Research Facility. To operate in these other facilities, it is necessary to extend the range capability to 20 m, and a replacement output lens system has been designed and fabricated to meet this requirement. To accept these lenses the velocimeter requires minor modifications, and a test at the longer range has not yet been performed.

The first use of the velocimeter is planned for Dec. 1982 at which time it will be used to make a flow quality survey in the Ames 40- × 80-ft Wind Tunnel.

References

[1]Zalay, A.D., Brashears, M.R., Jordan, A.J., Shrider, K.R., and Vought, C.D., "Measurement of a Flow Around V/STOL Aircraft with an LDV System," *Journal of Aircraft*, Vol. 17, Dec. 1980, pp. 835-836.

[2]Orloff, K.L., "Spanwise Lift Distribution on a Wing from Flowfield Velocity Surveys," *Journal of Aircraft*, Vol. 17, Dec. 1980, pp. 875-882.

[3]Biggers, J.C. and Orloff, K.L., "Laser Velocimeter Measurements of the Helicopter Rotor-Induced Flowfield," *Journal of the American Helicopter Society*, Vol. 20, Jan. 1975, pp. 2-10.

[4]Orloff, K.L. and Snyder, P.K., "Laser Doppler Anemometer Measurements Using Nonorthogonal Velocity Components: Error Estimates," *Applied Optics Journal*, Vol. 21, Jan. 1982, pp. 339-344.

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Helicopter Rotor Performance Evaluation Using Oscillatory Airfoil Data

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Introduction

IN helicopter design, the accurate evaluation of the rotor performance is an important step for an efficient design of the rotor. From an aerodynamic point of view the performance of the rotor depends mainly on the sectional aerodynamic properties of the blades, under steady and unsteady flow conditions. Under certain conditions, such as in hover or in flight with low forward velocity, two-dimensional steady-state sectional data may be quite sufficient, but at high forward speeds with the blade experiencing flapping and pitching oscillations, it becomes quite essential to use the unsteady aerodynamic data to get not too conservative estimates of the rotor performance. Nagabhushanam[1,2] has developed a blade response program for the case of forward flight. In that program, two-dimensional steady-state aerodynamic data were used to get the response characteristics, thus giving a conservative estimate of blade response. Hence it is quite necessary to use the unsteady aerodynamic data in the Nagabhushanam program to get a realistic picture. The results of such a calculation as compared with those obtained by Nagabhushanam are presented in this Note.

Theoretical Analysis

The generalized differential equation for the blade response is given by

$$\frac{\partial^2}{\partial x^2}\left(EI\frac{\partial w^2}{\partial x^2}\right)-\frac{\partial}{\partial x}\left(N(x)\ \frac{w}{x}\right)+m(x)\ \frac{\partial^2 w}{\partial t^2}=T(x,t) \quad \text{(1a)}$$

where $T(x,t)$ is the external force, i.e., the aerodynamic force, acting on the blade. The deflection $w(x,t)$ and the aerodynamic load $T(x,t)$ are interdependent and in general it is difficult to get a closed-form solution for $w(x,t)$. Using generalized coordinates the deflection $w(x,t)$ is expressed as

$$w(x,t)=\sum_{i=l}^{m} Q_i(t) f_i(x) \quad \text{(1b)}$$

where $Q_i(t)$ is the general coordinate, $f_i(x)$ is the ith natural mode shape, and m is the number of modes considered.

Because of the orthogonal property of the mode shapes, the left-hand side of Eq. (1a) for any mode becomes independent of the other modes, but the aerodynamic load $T(x,t)$ contains contributions from all modes and hence Eq. (1a) cannot be solved independently for each mode. The numerical procedure developed for solving Eq. (1a) is explained in Appendix I of Ref. 1.

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In solving Eq. (1a), one can use either steady-state two-dimensional aerodynamic data C_L and C_D with a quasisteady assumption or, more appropriately, the unsteady aerodynamic data to calculate the aerodynamic load in the blade response program. From the blade response program[1] one obtains the instantaneous incidence of any blade section with respect to resultant velocity. During a given revolution on the advancing side of the blade flow, Mach numbers are high and the incidences are usually small, while on the retreating side, the incidences are high and the flow Mach numbers are small. Owing to reverse flow on the retreating side, the incidence may be greater than 180 deg. Hence at low Mach numbers, aerodynamic data are required in the range of incidence from 0 to 360 deg and at least up to stalling angles in the high Mach number range.[3,4]

To calculate the rotor performance, the two-dimensional steady-state data obtained either theoretically or experimentally are sometimes used. However, for more accurate calculation, unsteady data must be used. One simple method of calculating sectional lifts and moments is to use the Theodersen method, according to which the lift per unit span is given by

$$L = (a\rho b^2/2)\,[\ddot{Z} + U\dot{\alpha} - b\bar{x}\ddot{\alpha}] + a\rho Ub[\dot{Z} + U\alpha + b\dot{\alpha}(\tfrac{1}{2} - \bar{x})]\,C(k) \tag{2}$$

for the incompressible case. Here the in-plane velocity U is given by $U = \Omega r + V\sin\psi$, where V is the forward velocity, r the radius, Ω the rotational speed, and ψ the azimuth angle of the blade. In general, the inertia terms $(\ddot{Z}, \ddot{\alpha})$ are neglected since their contributions to aerodynamic loads are small. Considering only the circulatory part of the lift and the damping term in the noncirculatory part, we have the lift coefficient

$$C_L = a\left\{\left[\alpha + \frac{\dot{Z}}{U} + \frac{b\dot{\alpha}}{U}(\tfrac{1}{2} - \bar{x})\right]C(k) + \frac{b\dot{\alpha}}{2U}\right\} \tag{3}$$

Since the rotor blade travels through a range of Mach numbers during its revolution, the compressibility effects on C_L have to be considered. In Eq. (3), a and $C(k)$ are dependent on the Mach number. From Refs. 5-7 it is found that for low values of k, the effect of Mach number (M) on $C(k)$ can be neglected and only the dependence of a on M need be considered. With such an assumption, Harris[6] has shown that good agreement between experimental and theoretical results could be obtained at low reduced frequency up to an advance ratio of $\mu = 0.55$. In the present example, in the range of $0.55 \leq M \leq 0.9$ in which compressibility effects in general need be considered, the range of reduced frequency (k) is small, i.e., $0.02 \leq K \leq 0.04$. For $M < 0.5$, one can neglect Mach number effects on both $C(k)$ and a. Hence, in the entire range of Mach number and reduced frequency encountered in the present example, the effect of M on $C(k)$ is neglected, while its effect on a is considered. With the above assumptions, the lift coefficient is given by

$$C_L = a\left\{\left[\alpha + \frac{\dot{Z}}{U} + \frac{b}{U}\dot{\alpha}(\tfrac{1}{2} - \bar{x})\right]\sqrt{F^2 + G^2} + \frac{b\dot{\alpha}}{2U}\right\} \tag{4}$$

where

$$C(k) = \sqrt{(F^2 + G^2)}\,e^{i}\tan^{-1}(G/F)$$

In the above equation (4), since k is small $(K \ll 1.0)$, the phase angle $\tan^{-1}G/F \rightarrow 0$ and hence is neglected. Now expressing heaving and pitching oscillations as a harmonic of the rotational frequency and considering only the first harmonic motion, we have $\omega = \Omega$ and $k = \Omega b/U$, so that

$$\dot{\alpha} = \frac{d\alpha}{dt} = \frac{d\alpha}{d\psi}\frac{d\psi}{dt} = \frac{d\alpha}{d\psi}\Omega \quad \text{and} \quad \dot{Z} = \Omega\frac{dZ}{d\psi} \tag{5}$$

Using these relations, Eq. (4) can now be written as

$$C_L = a\left\{\left[\alpha + \frac{\Omega}{U}\frac{dZ}{d\psi} + \frac{b\Omega}{U}\frac{d\alpha}{d\psi}(0.5 - \bar{x})\right]\sqrt{F^2 + G^2} + \frac{b\Omega}{2U}\frac{d\alpha}{d\psi}\right\}$$

$$= a\left\{\left[\alpha + \frac{\Omega}{U}\frac{dZ}{d\psi} + K\frac{d\alpha}{d\psi}(0.5 - \bar{x})\right\}\sqrt{F^2 + G^2} + \frac{K}{2}\frac{d\alpha}{d\psi}\right\} \tag{6}$$

The expression for C_L is used in the present example of a helicopter rotor with the following data.

The rotor diameter is 13 m; the blade chord is 0.4 m; the number of blades is 4 (NACA 0012 airfoil section); the blade section is a NACA 0012 airfoil; $\Omega = \omega = 33.8$ rad/s; the collective pitch (θ_0) is 17.2 deg; the forward velocity is 345 kmph; and the advance ratio $\mu = 0.435$.

Using the blade response program of Ref. 1, the computations were made with the unsteady aerodynamic data as calculated from Eq. (6) and also with appropriate two-dimensional data for the steady case using quasisteady assumption. Since no unsteady two-dimensional data were available in the stall and poststall regions, in these regions even for the unsteady case steady-state data have been used. The iso-(α) incidence, iso-Mach number, and iso-C_L lines are generated using computer graphics for a typical blade section at $X/R = 0.91$. From these data the "figure-of-eight" curves for α vs M and C_L vs M are obtained with steady and unsteady aerodynamic data for the C_L.

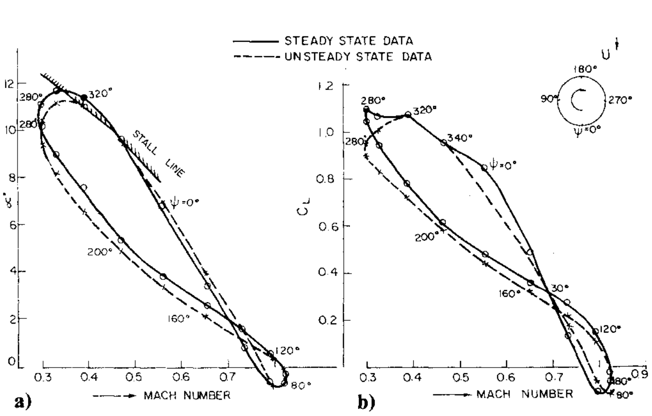

Fig. 1 a) Figure-of-eight plot for α vs M using steady and unsteady data; b) figure-of-eight plot for C_L vs M using steady and unsteady data.

Results and Discussion

In the following discussion the quantities α_{SS}, $C_{L_{SS}}$ and α_{US}, $C_{L_{US}}$ will refer to the values of incidence and lift calculated with steady and unsteady aerodynamic data, respectively.

Figure 1a shows the α vs M plot (figure-of-eight) for a typical blade section of $X/R = 0.91$. This section is chosen to represent the data, since it is usually around this section that the maximum aerodynamic loading occurs. From the figure it is observed that for a given Mach number with a range of azimuthal angle from 80 to 340 deg, $\alpha_{SS} > \alpha_{US}$, while in the remaining region, from 340 deg through zero to 80 deg, the $\alpha_{US} > \alpha_{SS}$. The stall angle at the respective azimuthal position, i.e., in the range 300 deg $< \psi <$ 340 deg, the data with steady-state aerodynamic load indicate these regions to be stalled, while with the unsteady data, the incidence level reached in this region is fairly equal or slightly higher than the steady-state stall angle. However, it is well known that the dynamic stall angle is very much higher than the steady stall angle, and hence from the present study we see that, while the results in the steady-state aerodynamic data predict a stalled region in the azimuthal region 300 deg $\leq \psi \leq$ 340 deg, actually the flow is not stalled, as seen from the results with unsteady data, and this is more realistic since the effect of unsteady motion is taken into consideration adequately. Next from the C_L vs M plot in Fig. 1b, it is seen that for a given Mach number in the range of ψ from 80 to 320 deg, $C_{LSS} > C_{LUS}$; in the 320 deg $\leq \psi \leq$ 340 deg range, $C_{LUS} \approx C_{LSS}$; but in the 40 deg $\leq \psi \leq$ 80 deg range, $C_{LUS} > C_{LSS}$. An interesting observation to be made in the range of ψ from 340 deg to zero to 30 deg is that even though $\alpha_{US} > \alpha_{SS}$, $C_{LUS} < C_{LSS}$. This is mainly due to the usual life deficiency due to oscillation. Again, as the blade proceeds from $\psi = 80$ to 320 deg, the effective flow Mach number decreases, which means an increase in the sectional lift curve slope so that one can expect an increase in C_L. However, owing to blade oscillation, and the associated trailing vortex, both the lift and the incidence are reduced. The change from this trend is seen only in the retreating side of the disk, wherein over a certain region (from 340 to 30 deg) even though $\alpha_{US} > \alpha_{SS}$, $C_{LUS} < C_{LSS}$.

Around $\psi = 270$ deg, the reduction in C_L with unsteady data is more than one could expect from the corresponding reduction in the incidence. One reason for this is that in this region, the effective chordwise velocity being small, there is an increase in the reduced frequency $(K = \omega b/U)$, and hence, owing to the large unsteady effect, the lift reduction is enhanced.

In the region around $\psi = 330$ deg, $C_{LSS} = C_{LUS}$. From Fig. 1a, it is seen that the calculation with steady-state data indicates a small region of stall, while a similar calculation with unsteady data gives a distribution equal to the steady stall angle. However, in this region if one were to use unsteady aerodynamic data from dynamic stall experimental results the C_{LUS} would have increased.

Conclusions

From the present analysis the following conclusions have been drawn. Over a major portion of the rotor disk, in general, $C_{LUS} < C_{LSS}$ and $\alpha_{US} < \alpha_{SS}$. The reduction in C_L with unsteady data is due to the reduction in α as well as the reduction in the lift curve slope due to unsteady effects. Analysis with steady-state data gives an overall increase in lift and shows a region of stall, while the results with unsteady data show no blade stalling and the overall lift is also reduced, and the reduction in sectional C_L at some azimuth position $(\psi = 0)$ is of the order of 10%, which is not negligible.

References

[1] Nagabhushanam, J., "Helicopter Rotor Blade Response Program," HAL-DB-AERO-003, 1976.

[2] Mil, M.L. et al., "Helicopters—Calculation and Design, Vol. II, Vibration and Dynamic Stability," NASA TTF-519, May 1968.

[3] Gregory, N. and Wilby, P.G., "NPL 9615 and NACA 0012: A Comparison of Aerodynamic Data," ARC C.P. 1261, Nov. 1968.

[4] Critzos, C.C., Heyson, H.H., and Boswinkle, R.W. Jr., "Aerodynamic Characteristics of NACA 0012 Airfoil Section at Angles of Attack from 0° to 180°," NACA TN 3361, Jan. 1955.

[5] Timman, R., Van De Vooren, A.I., and Greianus, J.H., "Aerodynamic Coefficients of an Oscillating Airfoil in 2-D Subsonic Flow," *Journal of Aeronautical Sciences,* Vol. 18, Dec. 1951, pp. 797-802.

[6] Harris, F.D., Targarin, F.J., and Fisher, R.K., "Rotor High Speed Performance Theory vs Test," *Journal of the American Helicopter Society,* Vol. 15, No. 3, July 1970, pp. 35-44.

[7] Minihinnick, I.T., "Subsonic Aerodynamic Flutter Derivatives for Wings and Control Surfaces (Compressible and Incompressible Flow," RAE Report Structure 87, July 1950.

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