Engineering Notes

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Jet Decay Rate Effects on Hover Jet-Induced Loads

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Nomenclature

A = local circular area on the flat plate
A_e = effective jet exit area
C_p = pressure coefficient, $(p-p_\infty)/q_{max}$
D_e = effective jet exit diameter, $\sqrt{4A_e\pi}$
D_n = nominal jet exit diameter, = 2.54 cm
ΔL = jet-induced lift loss
$\dot{m}$ = initial jet mass flow rate
p = static pressure
p_∞ = static pressure away from jet exit
q = dynamic pressure
q_{max} = maximum jet exit dynamic pressure
r = radial coordinate
R = jet-to-crossflow velocity ratio, $=\sqrt{q_{jet}/q_{crossflow}}$
T = jet thrust
V_e = effective jet exit velocity
X = coordinate in plane of plate, aligned with crossflow direction
Y = transverse coordinate
Z = coordinate perpendicular to plate with origin at center of jet orifice

Introduction

THE objective of this Note is to explain the mechanisms for observed jet decay rate effects on jet-induced loads on a flat plate for crossflow and hover configurations. Typical examples of recent data are presented[1] for the effect of jet decay rate upon integrated loads on a flat plate, induced by the jet issuing at right angle from the plate into still air (hover). Knowledge of these jet-induced loadings is of particular importance for jet VTOL aircraft design, because they lead to an effective loss in the lift force available in hover.[2] This results in the need for engines with a larger installed thrust which can significantly alter vehicle performance.[2] These new hover jet decay and lift loss data are shown to compare favorably with previous data.[3] The new data were generated as the result of an apparent inconsistency between existing lift loss ΔL vs jet decay rate trends in hover,[3] and similar trends for a jet issuing perpendicular to a flat plate into a uniform subsonic crossflow.[4-6] This second configuration is representative of the flow in the vicinity of the jet exhaust for a VTOL aircraft during transition from hover to forward flight, and has been studied experimentally by several investigators.[7-11] The present data confirm these opposite ΔL vs decay rate trends for the hover and crossflow cases. These opposite effects are explained in light of the different physical mechanisms which determine the jet mixing and trajectory, i.e., entrainment, blockage, and the vortex pair associated with a jet in a crossflow.[7-10]

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Apparatus and Procedure

Details of the apparatus and data reduction procedures have been presented in Ref. 1. The jet, 2.54 cm in diameter, issues from a 30:1 area ratio contraction nozzle and plenum camber, fed from an air compressor. The nozzle is aligned so that the jet centerline is perpendicular to the flat plate, and the jet exit plane lies in the plane of the plate. Jet decay rate has been altered through the use of a pair of cylindrical centerbodies, or plugs, 1.91 cm in diameter, that are aligned with the jet axis with their tips submerged various distances below the jet exit in the nozzle. One tip is flat (flat plug), while the other in hemispherical (round plug). Jet flow rate has been measured by a turbine flowmeter. Jet dynamic pressure profiles have been measured using a pitot static probe and a capacitance-type pressure transducer. The plate is fitted with static pressure taps for measurement of the jet-induced pressures, and these are numerically integrated to obtain the lift loss ΔL.

These centerbodies affect the jet decay rate by generating nonuniform jet exit dynamic pressure profiles that lead to increased turbulent mixing. Data for different plug locations have been compared using a technique similar to that developed by Ziegler and Wooler.[12] The measured maximum jet exit dynamic pressure q_{max} and mass flow rate $\dot{m}$ are used to compute the jet thrust T and an effective jet exit area A_e or diameter D_e for a circular equivalent jet having the same $\dot{m}$ and a uniform exit plane q. These T and D_e values have been used to nondimensionalize all data for comparison purposes. The details of this procedure are discussed in Ref. 1. Nominal jet exit Mach number is fixed at 0.4, and Reynolds number based on the nominal jet diameter equals 2.6×10^5.

Results

Examples of the effect of the round-tipped plug on the jet centerline dynamic pressure decay are shown in Fig. 1. The jet with no plug decays the slowest, with a potential core existing

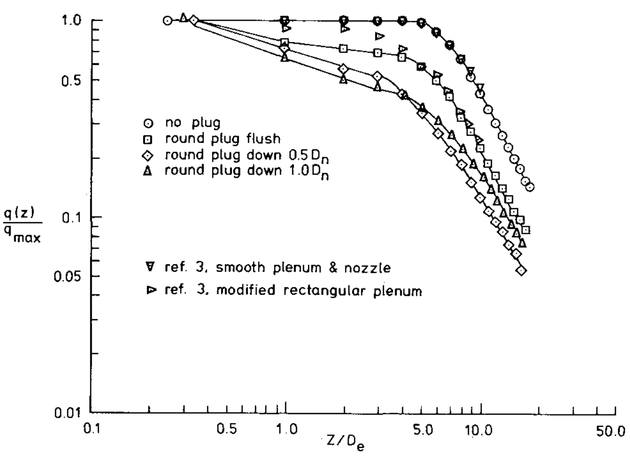

Fig. 1 Effect of plug tip location on jet centerline dynamic pressure decay (hover).

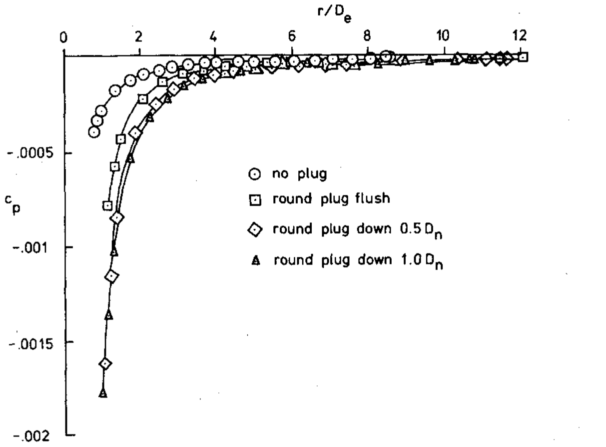

Fig. 2 Effect of plug tip location on radial pressure coefficient distribution on plate (hover).

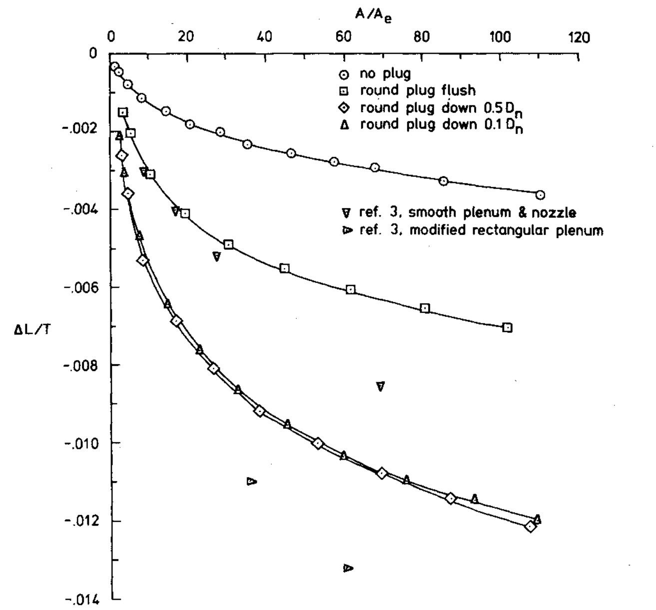

Fig. 3 Nondimensional lift loss $\Delta L/T$ for round-tipped plug configurations in hover compared with unplugged jet.

for the first four jet diameters. The configuration with the round plug tip flush (nearly an annular jet[13]) decays more rapidly. This is followed by the round plug down one nominal jet diameter, with the round plug down 0.5 D_n having the quickest decay, as judged for $Z/D_e > 5$. The effect of the centerbody is to alter the length of the flow development region of the jet. Also shown on Fig. 1, for comparison purposes, are examples of the decay data of Gentry and Margason.[3] Radial pressure coefficient data for these same nozzle-plug configurations are shown in Fig. 2. These data have been averaged circumferentially, with deviations from the mean value at a fixed r/D_e no larger than 5%. These C_p's have been computed using $q_{\max}$ as the reference pressure (note that pressure data listed in Appendix C of Ref. 1 are in units of lb/ft^2). The C_p values near the jet become more negative when a centerbody is placed in the nozzle. The round plug down 0.5 and 1.0 D_n have essentially the same C_p distribution, having the most negative values. The no-plug case has the smallest magnitudes of induced C_p values, with the round plug flush yielding intermediate values of C_p. These pressure coefficient data have been numerically integrated to obtain the jet-induced lift loss ΔL shown in Fig. 3, nondimensionalized by the thrust T. The $\Delta L/T$ values increase as the circular area on the plate increases, eventually approaching a constant value as C_p drops to zero. The round plug down 0.5 and 1.0 D_n configurations display the largest $\Delta L/T$ values (about 1.2% at $A/A_e = 100$), followed in order by the round plug flush and no-plug configurations. Also shown on Fig. 3 are data of Gentry and Margason[3] for a similar jet-in-hover configuration. Although the two experimental setups were different, the range of $\Delta L/T$ values is similar.

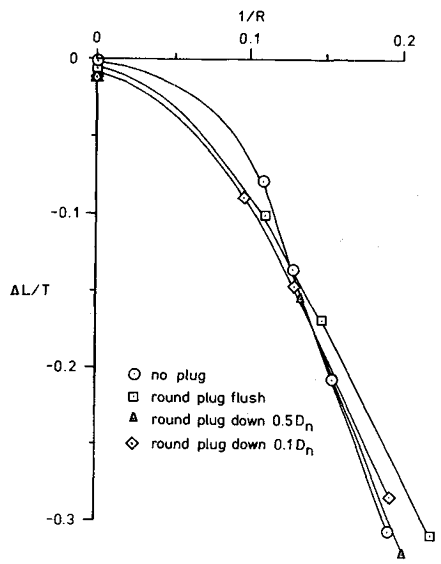

Fig. 4 Comparison between current hover data and crossflow data of Refs. 4-6.

In Fig. 4, the current $\Delta L/T$ data at $A/A_e = 43$ are plotted for comparison with data from Refs. 4-6 for the jet in a crossflow. The current data are for $1/R = 0.0$ where R is the jet-to-crossflow velocity ratio.

Discussion

These new jet decay and $\Delta L/T$ data for a jet in hover, obtained using the same apparatus as in Refs. 4-6, are consistent with the earlier work of Gentry and Margason.[3] Quicker jet decay is seen to lead to more negative C_p values on the plate near the jet exit and to a larger nondimensional jet-induced lift loss $\Delta L/T$. The same trend is observed in Ref. 1 for configurations with a flat-tipped centerbody, called a flat plug in that report. Although detailed jet spreading measurements have not been taken, it is believed that the quicker jet decay rate is an indication of increased entrainment. It is this entrained flow which then causes the negative C_p values around the jet, leading to the lift loss. These losses reach as high as $0.01T$ for $A/A_e = 100$. Thus, for minimum $\Delta L/T$ in hover, it is desirable for the jet to decay as slowly as possible.

The $\Delta L/T$ vs jet decay trends in Refs. 4-6 for a jet in a crossflow (Fig. 4) are opposite to current results for a jet in hover. Quicker jet decay in the crossflow configurations leads to a smaller $\Delta L/T$, as well as decreasing the jet-induced pitching moment due to the fore-to-aft asymmetry of the flow.[4] Detailed plate pressure distribution data show this is due to a pinching in toward the jet exit of the negative C_p region on the plate in the lee of the jet.[5,6] These plate surface pressure distributions are similar to those of Fearn and Weston[9] for jets with no centerbody, but are more similar to those of Ousterhout[11] when a centerbody is added. This opposite effect of jet decay upon $\Delta L/T$ is explained by the dominance of the jet vortex pair[7,8,10] in determining the flowfield and plate C_p values for the jet in a crossflow. Quicker jet decay, leading to enhanced turbulent mixing of the jet with the crossflow, must result in a weakening of this organized vortex pair, thereby decreasing the jet-induced

$\Delta L/T$. However, no detailed flowfield surveys have been presented in Refs. 4-6 to substantiate this conclusion.

Acknowledgment

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Technical Comments

Comment on "Calculation of Rotor Impedance for Articulated-Rotor Helicopters in Forward Flight"

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THE paper by Kato and Yamane (*Journal of Aircraft*, Vol. 16, ~~July 1979~~, pp. 470-476) is very interesting and certainly adds to our understanding of rotor impedance in forward flight. There are two oversights in the paper, however, that should be corrected. First, the introduction states that in their Ref. 2[1] "numerical results are given in terms of steady-state thrust and moment derivatives for steady ($\omega=0$) shaft incidence as well as blade pitch controls." To the contrary, one will find that Figs. 4-13 of Ref. 2 give theoretical and experimental unsteady frequency response due to unsteady shaft incidence ($\omega \neq 0$) and unsteady pitch controls.

Second, Fig. 6 of the paper by Kato and Yamane indicates that the H-force variation with pitching rate approaches a constant as ω goes to zero. In forward flight, however, a steady value of pitch incidence α gives a nonzero change in H-force. Therefore, the pitch incidence derivative $\partial H/\partial\dot{\alpha}=(1/i\omega)\partial H/\partial\alpha$ must go to infinity as ω goes to zero. The source of this discrepancy may be in Eq. (6) of the paper, in which it appears that the contribution of pitch angle $U\alpha$ is missing from the vertical velocity H_a.

On the other hand it should be emphasized that the above oversights are small, and do not negate the overall quality of the paper.

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[1] Peters, D.A., "Hingeless Rotor Frequency Response with Unsteady Inflow," NASA SP-352, Feb. 1974, pp. 1-12.

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Index categories: Helicopters; Vibration; Aeroelasticity and Hydroelasticity.

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PROFESSOR Peters's comments and his interest in our paper are greatly appreciated. We would like to offer the following comments.

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