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NOMENCLATURE

A	rotor disk area, πR^2
$\bar{c}$	blade mean chord, $\pi \sigma R/N$
C_{f_c}	pitch link load coefficient
C_{m_x}	blade beamwise bending moment coefficient
C_{m_z}	blade chordwise bending moment coefficient
C_T	rotor thrust coefficient
F_c	pitch link load
M_x	blade beamwise bending moment
M_z	blade chordwise bending moment
N	number of blades
r	blade radial coordinate
R	rotor radius
T	rotor thrust (shaft axes)
V	tunnel air speed
α_F	nacelle angle of attack; 90° for helicopter configuration and 0 for airplane configuration (axial flow)
ρ	air density
σ	rotor solidity (total blade area divided by rotor disk area)
Ω	rotor rotational speed

COMPARISON OF CALCULATED AND MEASURED BLADE LOADS ON A FULL-SCALE TILTING PROPROTOR IN A WIND TUNNEL

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ABSTRACT

The loads measured in a wind tunnel on a full-scale tilting proprotor are compared with calculated results. The data consists primarily of oscillatory beamwise bending moments at 35% radial station, oscillatory spindle chord bending moments, and oscillatory pitch link loads. The measured and calculated results as a function of thrust are compared over a range of nacelle angles from 0 to 75°, and a range of speeds from 80 to 185 knots.

INTRODUCTION

A full-scale, gimballed proprotor was tested in the Ames 40- by 80-ft Wind Tunnel during 1970. These tests provided data on the performance, blade loads, and aeroelastic stability characteristics of the rotor system (ref. 1). It is the purpose of the present paper to compare the measured rotor blade loads with calculated results obtained using the rotorcraft analysis described in reference 2. The objective is to provide the background required for the use of that analysis in the design, evaluation, and testing of tilting proprotors.

WIND TUNNEL TEST

The principal parameters describing the rotor are given in Table 1. A complete description of the rotor geometric, structural, inertial, and aerodynamic characteristics is given in references 3 and 4.

The blade loads data are given in reference 1. Data are available as a function of rotor thrust for pylon angles from 0 to 75^{o}, and speeds from 80 to 185 knots. The critical loads for this rotor were identified as the oscillatory beamwise bending moment at the .35R radial station; the oscillatory spindle chord bending moment; and the oscillatory pitch link force. The oscillatory load is one-half the difference between the maximum and minimum load values occurring in a roto revolution. The beamwise bending moment was measured relative to the blade principal axes (rotated by the local blade pitch angle relative to the shaft axes). The spindle chord moment was measured just inboard of the blade pitch bearing and outboard of the spindle/yoke junction, relative to the rotor shaft axes. The data will be presented here in terms of coefficients, defined as follows:

$$\frac{C_m}{\sigma} = \frac{M}{\rho A(\Omega R)^2 R\sigma/N} = \frac{M}{\rho \Omega^2 R^4 \bar{c}}$$

Table 1. Proprotor Parameters

Rotor type	Gimballed, stiff-inplane
Number of blades, N	3
Radius, R	3.81 m
Solidity, σ	0.089
Lock number, γ	3.67
Pitch/flap coupling, δ_3	-15°
Swashplate phase angle, $\Delta\Psi_s$	15°
Precone, β_p	2.5°
Tip airfoil	NACA 64-208 (a = 0.3)
Root airfoil	NACA 64-935 (a = 0.3)

$$\frac{C_{f_c}}{\sigma} = \frac{F_c}{\rho A(\Omega R)^2 \sigma / N} = \frac{F_c}{\rho \Omega^2 R^3 \bar{c}}$$

$$\frac{C_T}{\sigma} = \frac{T}{\rho A(\Omega R)^2 \sigma}$$

where M is the bending moment (with subscript x for the beamwise moment and subscript z for the chordwise moment), F_c is the pitch link load, and T is the rotor thrust (in shaft axes). The rotor was trimmed using longitudinal cyclic control so that the longitudinal flapping relative to the shaft was zero. The lateral cyclic control was zero. For nacelle tilt angles of α_p = 0 and 5^o the longitudinal cyclic was zero as well.

ANALYTICAL MODEL

The analysis used to calculate the rotor loads is described in detail in reference 2. The following degrees of freedom were used to define the blade motion: gimbal pitch and roll; 3 coupled flap-lag bending modes per blade; rigid pitch mode for each blade; and 1 elastic torsion mode per blade. Little influence on the blade loads was found using 2 to 6 bending modes or 0 to 2 elastic torsion modes. Ten harmonics of the motion were calculated for each degree of freedom. A blade rigid pitch frequency of 36 Hz was used, based on reference 1. Higher values of the control system stiffness would decrease the calculated control loads.

Static, two-dimensional airfoil characteristics were used, with a correction for yawed-flow effects and a tip-loss factor (see ref. 2). The calculated inflow varied linearly over the rotor disk. The mean induced velocity was calculated from momentum theory with the ideal value multiplied by a factor of K_f = 2.0 (see ref. 2) to account for nonideal induced power loasses, which are expected to be large for this rotor due to its high twist and small number of blades (values of K_f = 1.2 to 1.5 would be typical of conventional helicopter rotors at these advance ratios).

In the calculations the rotor was trimmed to a specified thrust and to zero longitudinal flapping angle by adjusting the collective pitch and longitudinal cyclic pitch controls. For pylon angles of α_p = 0 and 5^o the cyclic control was zero and only the thrust was trimmed.

RESULTS AND DISCUSSION

The measured and calculated oscillatory bending moments as a function of blade radial station are compared in figures 1 and 2. The moments for $r/R < 0.1$ are relative to the shaft axes, while the moments for $r/R > 0.1$ are relative to the local blade principal axes. The correlation is generally good, although the predicted beamwise bending moment (C_{m_x}) is somewhat low at $r/R = 0.16$.

The measured and calculated oscillatory loads as a function of thrust are compared in figures 3 to 5 for the beamwise bending moment at 0.35R (C_{m_x}), in figures 6 and 7 for the spindle chord bending moment (C_{m_z}), and in figures 8 to 10 for the pitch link load (C_{f_c}). The loads are presented (a) for three speeds at a nacelle angle of 75^o in figures 3, 6, and 8; (b) for four nacelle angles at 140 knots in figures 4, 7, and 9; and (c) for two nacelle angles at 177-185 knots in figures 5 and 10. The rotor rotational speed was 565 rpm for nacelle angles from 15^o to 75^o, and 458 rpm for nacelle angles of 0 and 5^o.

The oscillatory beamwise bending moments are predicted well in figure 3, although the loads increase somewhat faster than predicted at the highest thrust. The predicted loads at 140 knots (fig. 4) are high for $\alpha_p = 60^o$ and low for $\alpha_p = 15^o$; the slope with thrust is predicted well for all four nacelle angles. The predicted loads are low for α_p = 0 (fig. 5), but the magnitude of the loads is small in airplane configuration.

The oscillatory spindle chord bending moments are predicted well in figure 6, except for the results at 140 knots and high thrust. That the measured loads at 140 knots are lower than the loads at 120 knots is unexpected however, and suggests that the data is as likely to be in error as the analysis for these points. The predicted loads are low for α_p = 15° (fig. 7).

The oscillatory pitch link loads are underpredicted by about 250 to 300 N for all cases (figs. 8 to 10), including the nominally axial flow condition of $\alpha_p = 0$ (fig. 10). The source of the oscillatory pitch link loads for $\alpha_p = 0$ is not known, but it appears to be extant for all operating conditions. It is also noted that for 80 knots (fig. 8) the increase in pitch link load at high thrust (presumably due to stall) is not predicted.

The rotor power is predicted well for α_p = 0 to 60° (airplane and tiltrotor configurations), but is overpredicted at α_p = 75°. An induced power loss less than that predicted is not probable (as is confirmed by nonuniform inflow calculations), so the profile power is being overpredicted. This can be attributed to deficiencies in the stall model since the inboard portion of this highly twisted rotor blade is stalled at α_p = 75° even for moderate thrust.

CONCLUDING REMARKS

The blade bending moments and pitch link loads measured on a full-scale proprotor in a wind tunnel have been compared with calculated results. The correlation is generally good for the oscillatory bending moments. The oscillatory pitch link loads are underpredicted for all cases, including the nominally axial flow condition of $\alpha_p = 0$. Based on this correlation, the analysis can be reliably used in the design and evaluation of tilting proprotors.

Improving the prediction of the proprotor blade and control loads will require consideration of the details of the flow field. Specifically, dynamic stall and nonuniform inflow may be expected to influence the loads. However, it is difficult to investigate the influence of the detailed characteristics of the rotor aerodynamics without correspondingly detailed measurements (at least the time histories of the loads). In addition, current dynamic stall and nonuniform inflow models, which are all empirical to some extent, were not developed for the aerodynamic environment that characterizes the tilting proprotor. Hence it may be anticipated that further development of these models will be required before they provide any significant improvement in the loads predictive capability for proprotors.

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2. Johnson, Wayne, "A Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics," NASA TM 81182, June 1980

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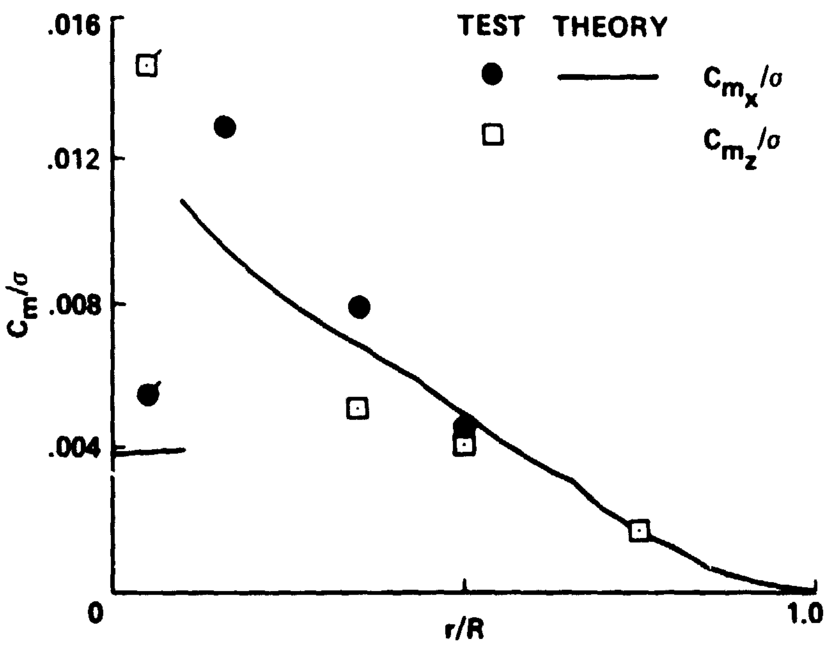

Figure 1. Oscillatory beamwise bending moment as a function of radial station for $\alpha_p = 75^{\circ}$, $\Omega = 565$ rpm, V = 120 knots, and $C_T/\sigma = 0.102$ (flagged symbols are measurements on spindle).

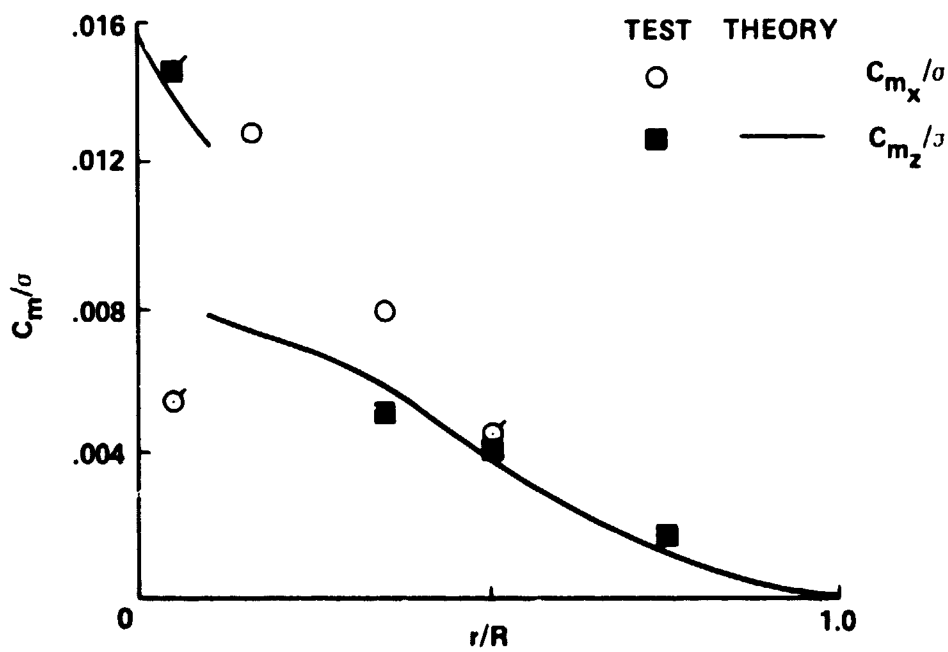

Figure 2. Oscillatory chordwise bending moment as a function of radial station for $\alpha_p = 75^\circ$, $\Omega = 565$ rpm, V = 120 knots, and $C_T/\sigma = 0.102$ (flagged symbols are measurements on spindle).

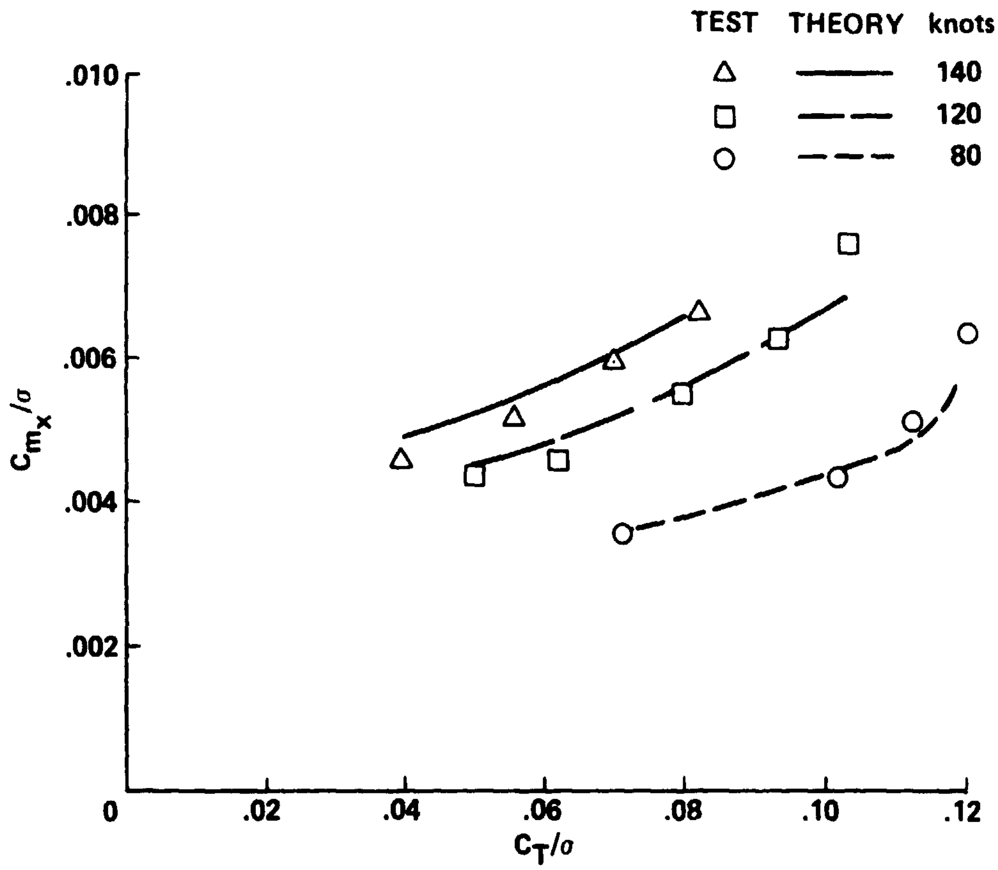

Figure 3. Oscillatory beamwise bending moment at 0.35R as a function of thrust for α_p = 75° and Ω = 565 rpm.

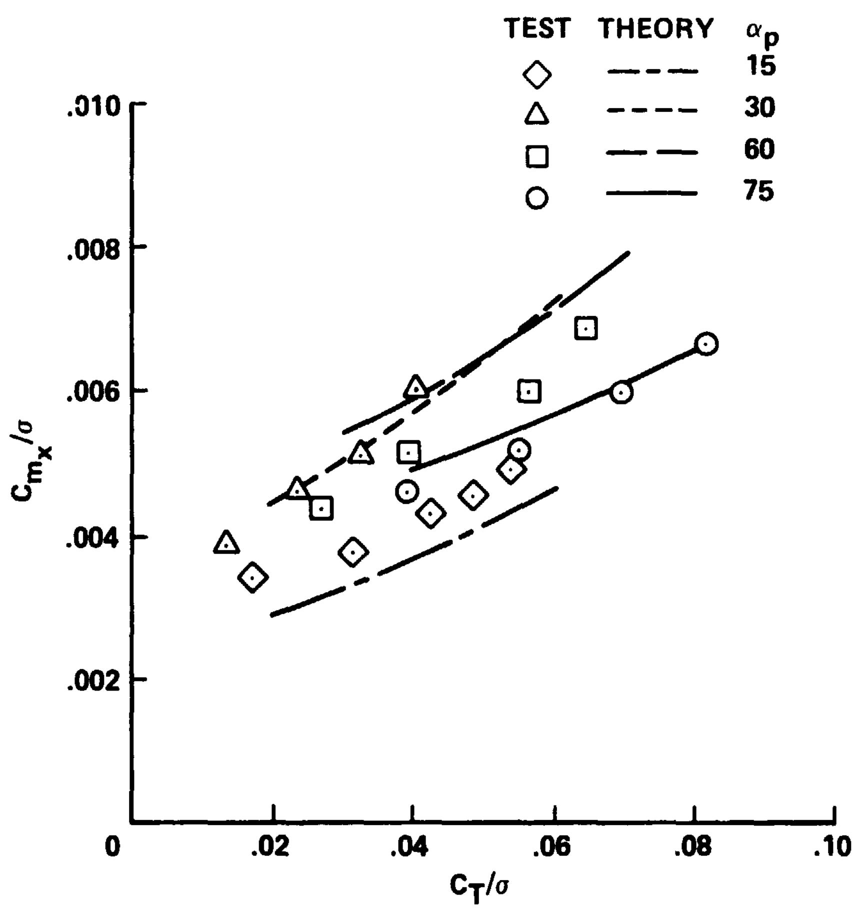

Figure 4. Oscillatory beamwise bending moment at 0.35R as a function of thrust for Ω = 565 rpm and V = 140 knots.

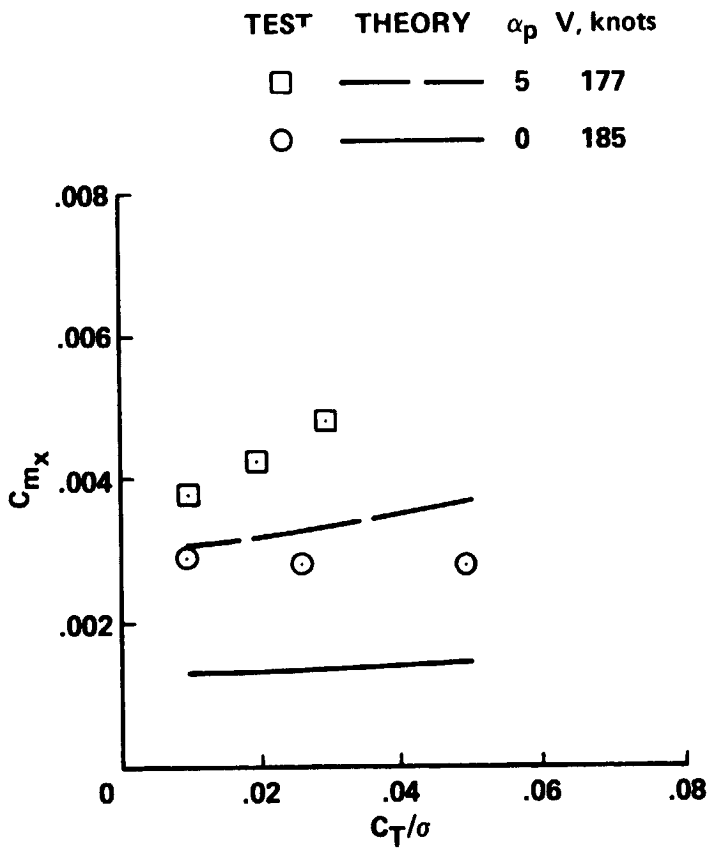

Figure 5. Oscillatory beamwise bending moment at 0.35] as a function of thrust for Ω = 458 rpm and V = 177-185 knots.

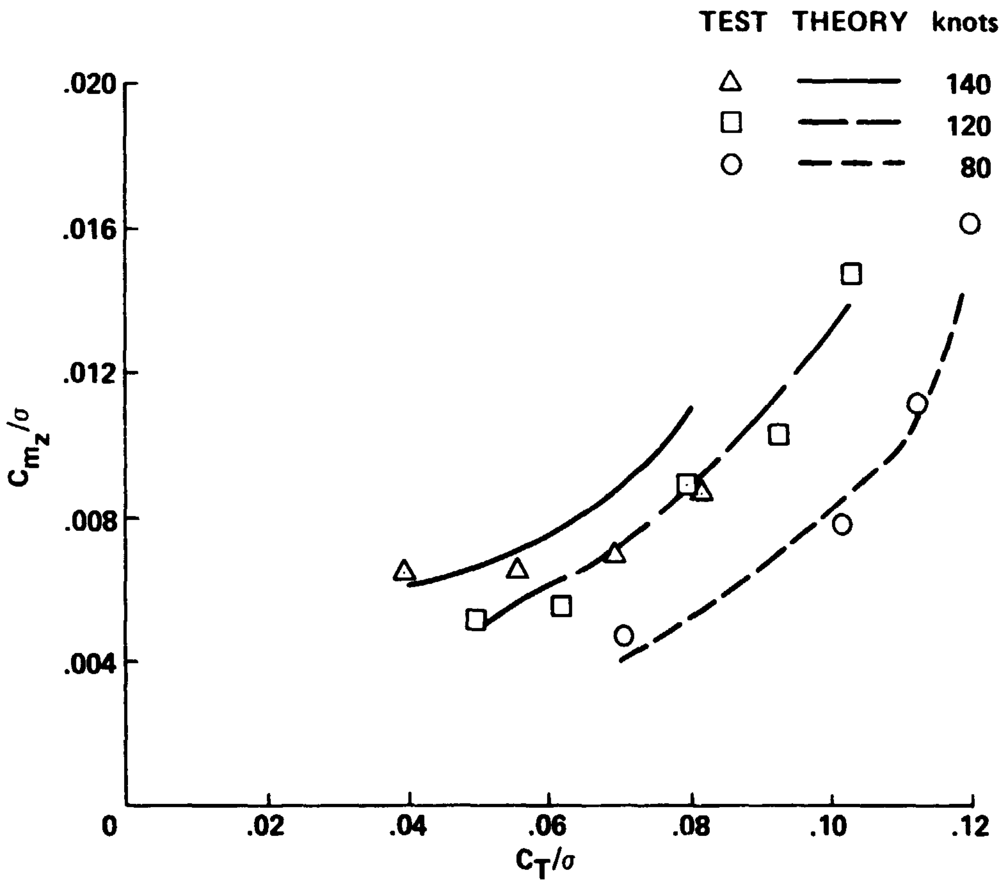

Figure 6. Oscillatory spindle chord bending moment as a function of thrust for $\alpha_p = 75^o$ and $\Omega = 565$ rpm.

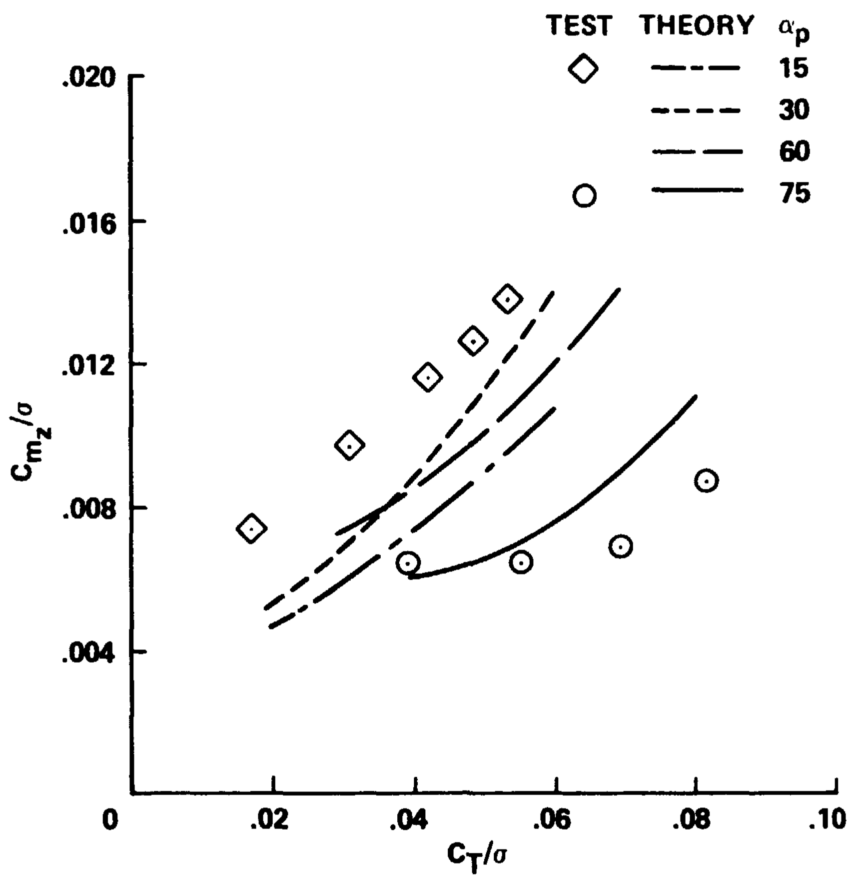

Figure 7. Oscillatory spindle chord bending moment as a function of thrust for $\Omega = 565$ rpm and V = 140 knots.

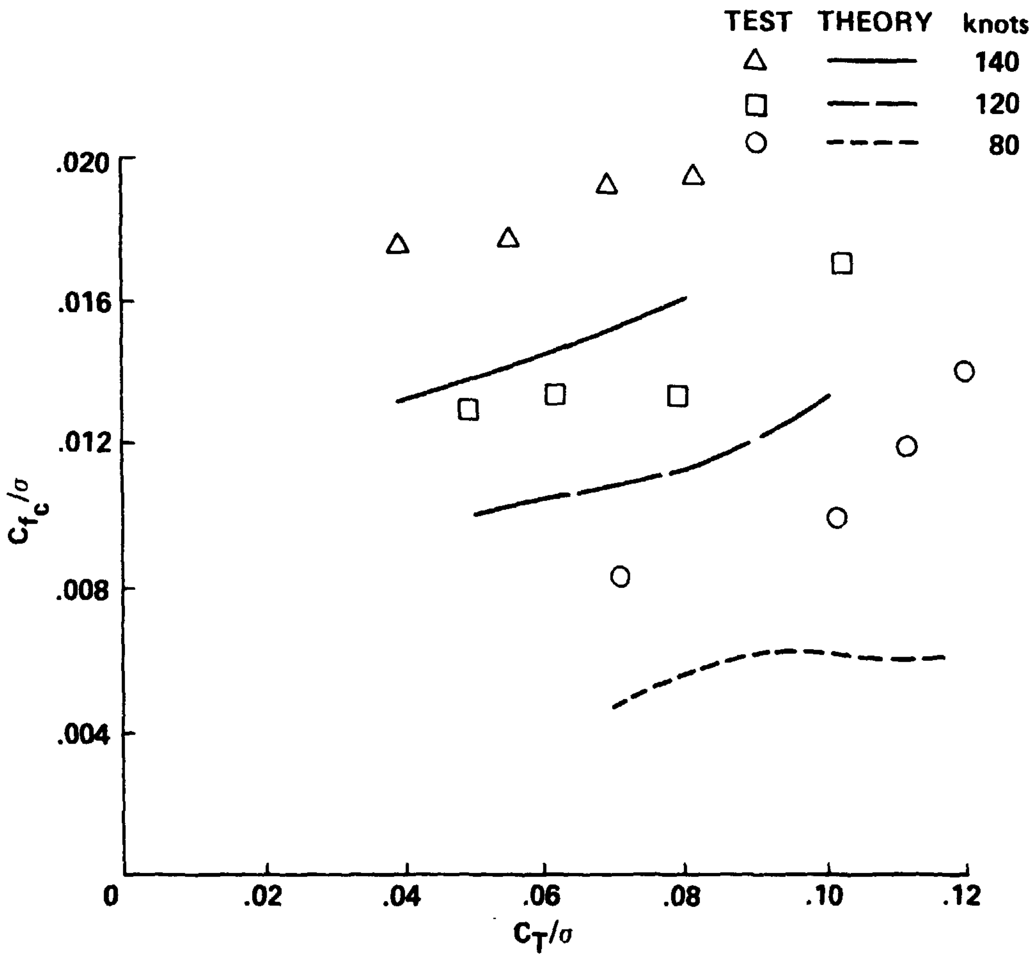

Figure 8. Oscillatory pitch link load as a function of thrust for $\alpha_F = 75^{\circ}$ and $\Omega = 565$ rpm.

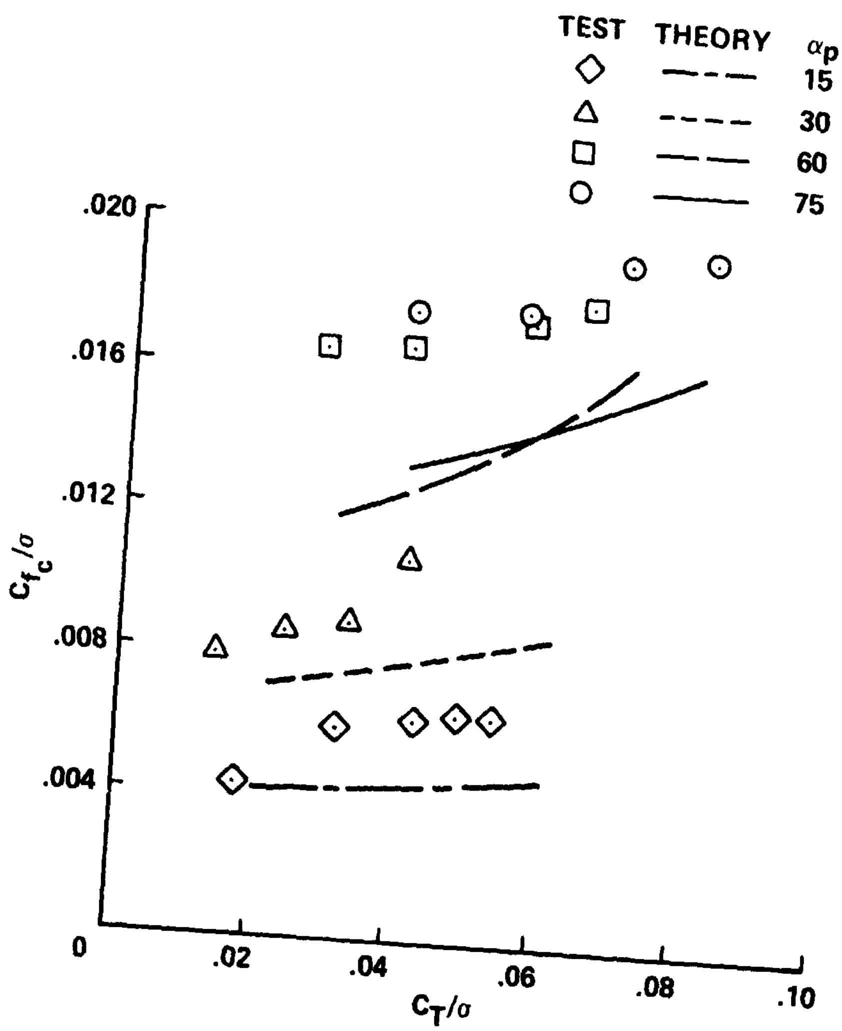

Figure 9. Oscillatory pitch link load as a function of thrust for Ω = 565 rpm and V = 140 knots.

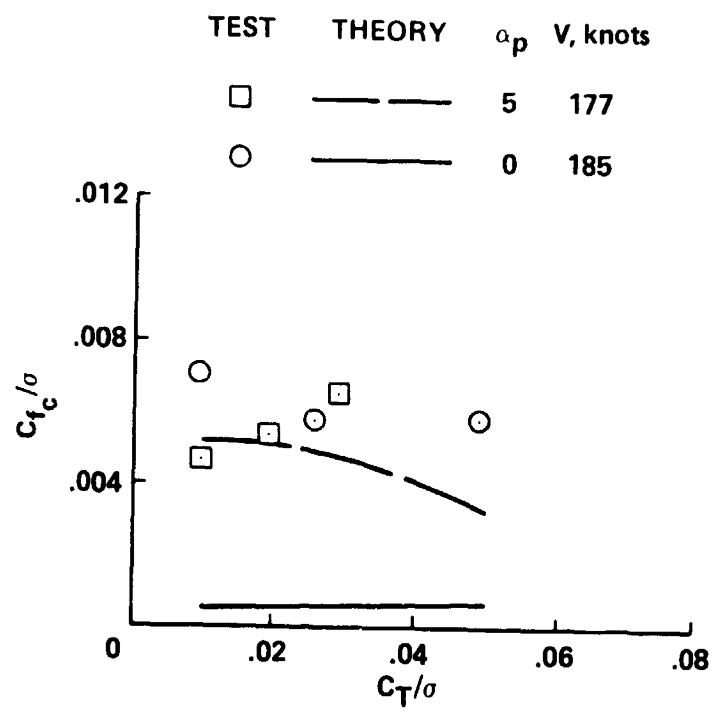

Figure 10. Oscillatory pitch link load as a function of thrust for Ω = 458 rpm and V = 177-185 knots.

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