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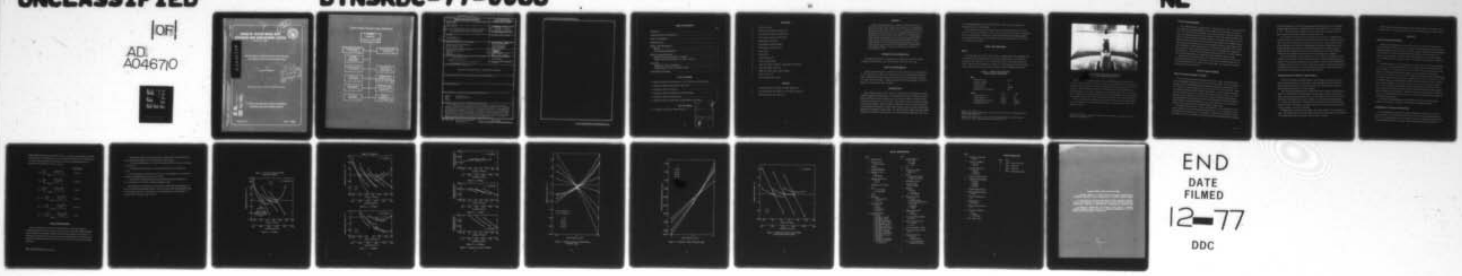

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

STATIC STABILITY DERIVATIVES IN PITCH AND ROLL OF A MODEL CIRCULATION CONTROL ROTOR

by

Joseph B. Wilkerson

AVIATION AND SURFACE EFFECTS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

October 1977 Report 77-0066

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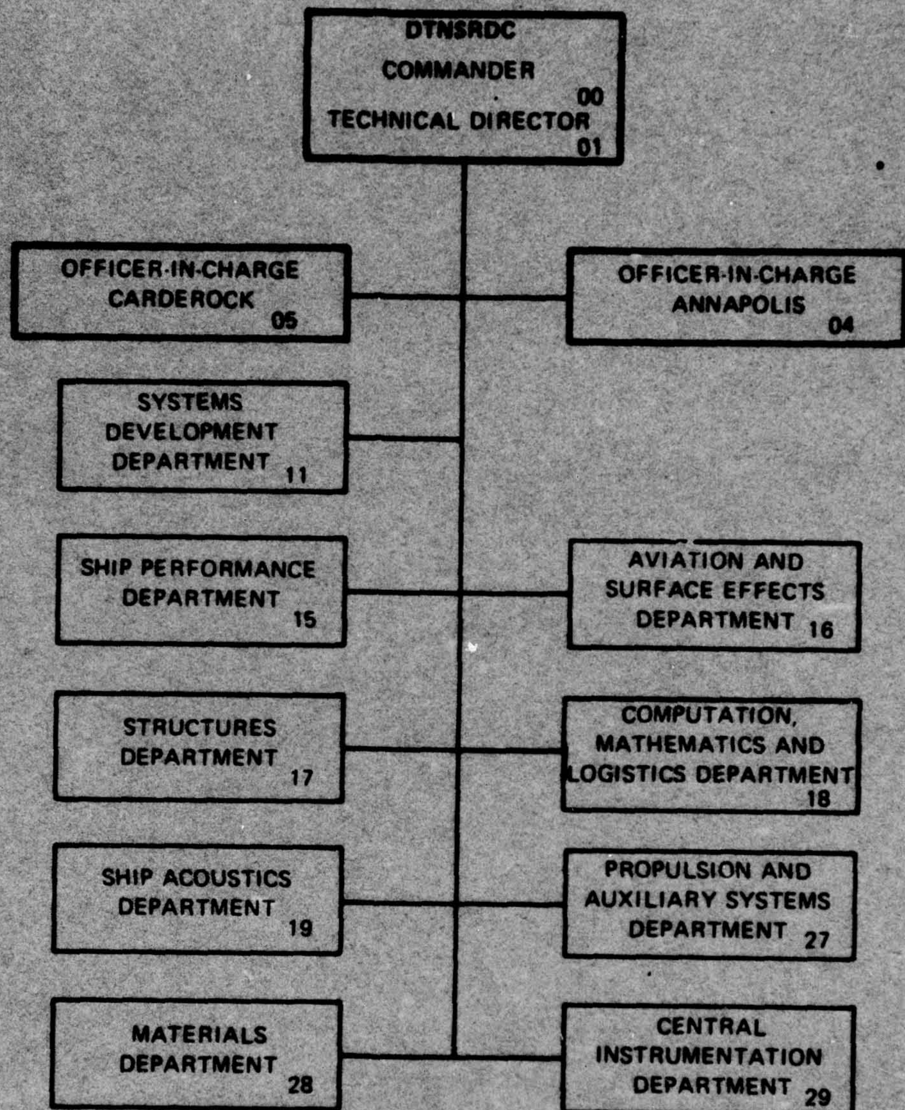

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Static stability derivatives of a circulation control rotor (CCR) were obtained from wind tunnel evaluation of a model rotor. The derivatives show general characteristics similar to those of a conventional rotor in the advance ratio range $0.20 \leq \mu \leq 0.30$. The conventional characteristic of a destabilizing static-speed-stability term for hingeless rotors appears to be magnified for low advance ratios in the CCR system. At higher advance ratios the static-speed-stability term becomes neutral and then strongly stable for CCR. Other derivatives show the same tendency toward neutral stability as speed is increased beyond an advance ratio of 0.30. If this model trait is corroborated by future full-scale CCR evaluation, it will represent a significant advantage in stability characteristics over current hingeless rotors.

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NOTATION

b	Number of blades
C_ℓ	Roll moment coefficient, $\ell/(\rho V_T^2 \pi R^3)$
C_m	Pitch moment coefficient, $m/(\rho V_T^2 \pi R^3)$
C_T	Rotor thrust coefficient, $T/(\rho V_T^2 \pi R^2)$
$\bar{c}$	Rotor blade, mean chord
ℓ	Roll moment, positive roll right
m	Pitch moment, positive nose up
R	Rotor radius
T	Rotor thrust
U	Vehicle flight speed
V_T	Rotor tip speed in $R\Omega$
W	Velocity component normal to rotor plane, positive down
α_s	Rotor shaft angle, positive aft
θ_c	Blade tip, collective pitch angle in degrees
μ	Advance ratio, U/V_T
σ	Rotor solidity factor, $b\,\bar{c}/\pi R$

Subscripts

u	Denotes derivative with respect to vehicle flight speed
w	Denotes derivative with respect to w or velocity component
α	Denotes derivative with respect to α

ABSTRACT

Static stability derivatives of a circulation control rotor (CCR) were obtained from wind tunnel evaluation of a model rotor. The derivatives show general characteristics similar to those of a conventional rotor in the advance ratio range $0.20 \leqslant \mu \leqslant 0.30$. The conventional characteristic of a destabilizing static-speed-stability term for hingeless rotors appears to be magnified for low advance ratios in the CCR system. At higher advance ratios the static-speed-stability term becomes neutral and then strongly stable for CCR. Other derivatives show the same tendency toward neutral stability as speed is increased beyond an advance ratio of 0.30. If this model trait is corroborated by future full-scale CCR evaluation, it will represent a significant advantage in stability characteristics over current hingeless rotors.

ADMINISTRATIVE INFORMATION

The work reported herein was authorized and funded by the Naval Air Systems Command (AIR-320D) under Task Area W1423.001, Work Unit 1-1619-200.

UNITS OF MEASUREMENTS

All data recorded during this experiment were either measured in or converted directly to U.S. customary units. Hence, U.S. customary units are the primary units used in this report. Metric units are given either adjacent to the U.S. units in parentheses or opposite U.S. units in the case of graphs. Angular measurement is the only exception. The unit of degrees is not converted to radians on graphs.

INTRODUCTION

Static stability derivatives of the rotor are an important part of the helicopter dynamic stability and general handling qualities. The circulation control rotor (CCR) system obtains pitch-and-roll trim and control moments via cyclic variation of blown air from the trailing-edge slots on the upper surface of the blades. Rotor thrust is directly controlled by changes in the collective blowing. Although CCR is controlled by collective and cyclic blowing, the rotor airfoils are still responsive to angle-of-attack variations caused by inflow and shaft-angle perturbations throughout the flight regime. This dual dependency suggests that static stability derivatives of a CCR may differ from those of a conventional alpha dependent rotor system.

It is therefore important to evaluate those derivatives and to assess their impact on the handling qualities of a CCR helicopter.

Static stability derivatives were evaluated from a wind tunnel model of a CCR with respect to velocity and shaft angle of attack. These derivatives and the method of obtaining them are reported herein. Evaluation of vehicle dynamic stability and handling qualities is being conducted under Navy contract by Kaman Aerospace Corporation for the CCR, full-scale technology demonstrator.

MODEL AND PROCEDURE

MODEL

The CCR model was an 80-in. (2.032-m)-diam., two-bladed rotor with trailing-edge slots for circulation control blowing. Details of the design tradeoffs that led to this particular configuration were reported in 1973.[1] General characteristics of the model are shown in Table 1. Figure 1 shows the model in the Center 8- by 10-ft subsonic wind tunnel. Details of model performance characteristics were previously reported by Wilkerson and Linck.[2]

TABLE 1 – CIRCULATION CONTROL ROTOR, MODEL GEOMETRY

Blade:		
Diameter in Feet	6.67	
Number of Blades	2	
Chord in Inches	3.2	
Solidity Ratio	0.0509	
Geometric Twist in Degrees	-8.63	
Airfoil:	*Root*	*Tip*
Thickness Ratio, t/c	0.25	0.15
Camber Ratio, δ/c	0.0625	0.0
Trailing-Edge Radius, R_{te}/c	0.0497	0.0403
Slot-Height Ratio, h/c	0.0015	0.00312

[1] Wilkerson, J.B., *"Design and Performance Analysis of a Prototype Circulation Control Helicopter Rotor,"* NSRDC ASED-290 (Mar 1973).

[2] Wilkerson, J.B. and D.W. Linck, *"A Model Rotor Performance Validation for the CCR Technology Demonstrator,"* American Helicopter Society Preprint 902 (May 1975).

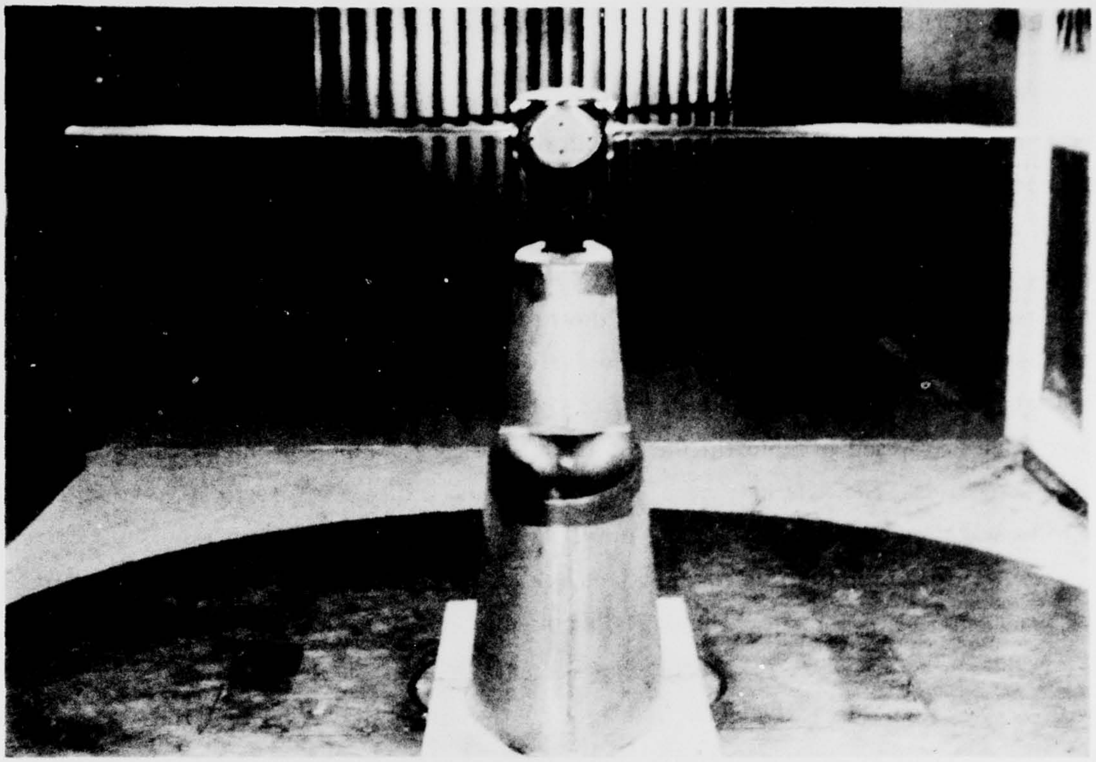

Figure 1 – Model of Circulation Control Rotor in 8- by 10-Ft Subsonic Wind Tunnel

Model [illegible] were located in the rotor head, which allowed direct control of both cyclic and collective blowing to the blades. Control rods extended from the rotor head, down through the hollow rotor shaft, and into the wind tunnel control room, below the test section and model. The CCR model was "flown" in the wind tunnel to the desired thrust and moment condition by use of these control rods. Any control setting could be repeated later in the experiment by use of dial and scale indicators, which provided accurate position setting and recording. Specific characteristics of the control system have been reported by Reader.[3]

Forces and moments were digitized and recorded by a Beckman system analog-to-digital converter as measured by the wind tunnel balance frame and six-component, Toledo-scale, strain gage readout.

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[3]Reader, K.R., "*Evaluation of A Pneumatic Valving System for Application to a Circulation Control Rotor*," NSRDC Report 4070 (May 1973).

EVALUATION PROCEDURE

The stability derivatives evaluated were of a quasi-static nature. That is, the rotor model was trimmed to a preselected thrust level with nearly zero shaft moments, and data were taken. The velocity was then perturbed, with controls fixed, and a second set of data was taken, after allowing time for forces and moments to settle. Static stability derivatives with respect to speed were evaluated from the two data sets. Derivatives with respect to shaft angle required the wind tunnel to be shut down; the shaft angle was then changed by hand, and the data point was repeated at the new shaft angle for the same control settings. Each data set included 12 frames of data from each of the six force components. The average of these frames was used to represent the rotor force for each component in calculating the static derivatives. The data have been limited to advance ratios $\mu \geqslant 0.15$ to avoid conditions of rotor wake recirculation in the wind tunnel, which would give erroneous results.

Derivatives were evaluated for pitch and roll moment in the wind axes with respect to velocity and rotor shaft angle. The derivative of rotor thrust in the body (shaft) axes was also evaluated with respect to velocity and rotor shaft angle. The derivatives of side force, drag, and yaw were not evaluated.

RESULTS AND DISCUSSION

DERIVATIVES WITH RESPECT TO SPEED

The variation of pitch and roll moments, with respect to speed, was obtained about several trimmed-flight conditions for each of three rotor shaft angles. These data (Figures 2a through 2c) show a speed-destabilizing, pitching-moment variation at a low advance ratio ($\mu < 0.30$) that is typical of hingeless rotor systems; however, the model data show a significant stabilizing pitching moment for higher advance ratios at each of the three shaft angles. This rather sudden change at $\mu \approx 0.30$ also corresponds to rotor peak efficiency at $\mu \approx 0.30$. Together, these data indicate that CCR may have a unique advantage in speed-stabilizing, pitching moments at the higher advance ratios. If this characteristic of CCR is corroborated by the full-scale technology demonstrator, it will be quite important, since conventional hingeless rotors incur most of their stability problems at higher speeds.

The rolling moment response to velocity perturbations is a cross-coupled term of somewhat less importance than the primary pitch response; however, it has a significant effect on such problems as spiral divergence. These variations in rolling moment are shown in Figures 2a through 2c for the same conditions as the previously discussed pitching moment variations.

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The expected response of left roll is encountered with increased velocity for all conditions. However, Figure 2c does show a diminished effect of this response for $\alpha_s = -10$ deg and $\mu > 0.35$. The improvement in stability and control characteristics, indicated for CCR at higher speeds, must be verified through the full-scale flight tests.

One explanation for this behavior lies in the basic manner of trim. At higher speeds CCR must use more cyclic blowing on the retreating side of the disc to maintain roll moment trim and on the rear of the disc to maintain pitch moment trim. Simply put, this means a greater percentage of the blade lift is being generated by blowing at higher speeds, and it is known that this portion of lift does not exhibit strong responses to changes in velocity – compared to the α dependent portion of lift. It is therefore easy to see how CCR may exhibit more docile stability characteristics than its conventional rotor counterpart.

Rotor thrust responses to speed variations are shown in Figures 3a through 3c for three different rotor shaft angles. These responses are typical of conventional rotors, being quite small for $\alpha_s = 0$ deg and becoming more and more negative as the rotor shaft (tip-path plane) is inclined to the wind. At $\alpha_s = -10$ deg, a speed increase produces more inflow, reducing the overall blade section angle of attack, thereby, reducing rotor thrust. Both the process and the effect are quite the same as for the conventional helicopter.

DERIVATIVES WITH RESPECT TO SHAFT ANGLE

Variations of rolling and pitching moments with shaft angle were obtained at several advance ratios about the $\alpha_s = -5$ deg position. Large shaft-angle increments were used (± 5 deg) to evaluate the sensitivity; however, results show fairly uniform moment variations, indicating that local derivatives are well represented.

The conventional destabilizing static stability with respect to angle of attack is shown in Figure 4 for the CCR model. Pitching moment becomes negative for more forward shaft angles at all advance ratios evaluated; however, the data indicate that the effect is much less pronounced at the higher advance ratios. Evaluation of a specific numerical derivative at $\alpha_s = -10$ deg is not possible since it depends on the faired curve between only three widely spaced data points. Nevertheless, the qualitative trend of the data is toward neutral stability at higher advance ratios for this shaft angle.

Rolling moment variation with shaft angle is also shown in Figure 4 for several advance ratios. This response shows a roll to the right as the shaft is tilted forward, and the magnitude of the rolling moment becomes stronger as advance ratio is increased.

Rotor thrust decreased for forward shaft tilt as shown in Figure 5. This thrust response is similar to that for a conventional rotor as was the CCR thrust response to speed changes.

ANALYSIS

PREDICTED CHARACTERISTICS

Rolling and pitching moment responses to velocity were analytically predicted by the computer program for CCR performance prediction. Rotor geometry, airfoil data, and blade-flapping frequencies of the model were used to allow a direct comparison to the corresponding wind tunnel data. First the thrust-and-moment trim condition of the wind tunnel data reference case was evaluated. Then the control settings of that case were used to evaluate forces and moments at the perturbed velocities. (The program was not allowed to retrim the rotor.)

Predicted variations in the rotor moments are shown in Figure 6 for the same conditions, i.e., V_T, θ_c, α_s, as the data shown in Figure 2a. The rolling moment response compares very well to the data. It is essentially linear for each of the three cases, and the slopes are in fair agreement. Predicted pitching moment response is also in fair agreement in the range $0.20 \leqslant \mu \leqslant 0.30$. However, for $\mu < 0.20$, the predicted pitching moment response is moderately destabilizing, whereas the model data show a stronger adverse response. Likewise, for $\mu > 0.30$, the predicted response is toward moderate stability, whereas the model data were very stable. The key word is moderate; for the predicted *trends* are correct, even at the low and high advance ratios. However, the magnitude is not as great as the data would indicate. Also, it must be pointed out that the strong data responses mentioned previously are each based on a single data point as shown in Figure 2a. While this tendency of the data must be considered correct as it is reflected again in Figure 2b and 2c, there may be legitimate concern about the magnitude at these extremities.

In general, the predicted values show good agreement with the model data, giving credence to the prediction capability for the full-scale, rotor-stability derivatives.

DIMENSIONAL FULL-SCALE DERIVATIVES

The preceding data are shown in the form of dimensionless coefficients since they are from a model rotor. It should be noted that the data reflect the high model-blade stiffness relative to the full-scale hingeless rotor, which may result in some changes in derivatives owing to reduced flapping response of the model. Still, calculating dimensional full-scale, static stability derivatives from the presented data allows a comparison to analytically derived full-scale derivatives. The following equations are provided for this purpose. The derivatives are to be taken from model data in dimensionless form and then dimensionalized by the characteristics of the full-scale vehicle of interest.

		English Units
$m_u = \dfrac{\partial C_m}{\partial \mu}$ Figure 2	$\left(\dfrac{\rho V_T^2 \pi R^3}{V_T}\right)_{fs*}$	ft-lb/fps
$\ell_u = \dfrac{\partial C_\ell}{\partial \mu}$ Figure 2	$\left(\dfrac{\rho V_T^2 \pi R^3}{V_T}\right)_{fs}$	ft-lb/fps
$T_u = \dfrac{\partial C_T/\sigma}{\partial \mu}$ Figure 3	$\left(\dfrac{\sigma\rho V_T^2 \pi R^2}{V_T}\right)_{fs}$	lb/fps
$m_w = 57.3 \dfrac{\partial C_m}{\partial \alpha}$ Figure 4	$\left(\dfrac{\rho V_T^2 \pi R^3}{\mu V_T}\right)_{fs}$	ft-lb/fps
$\ell_w = 57.3 \dfrac{\partial C_\ell}{\partial \alpha}$ Figure 8	$\left(\dfrac{\rho V_T^2 \pi R^3}{\mu V_T}\right)_{fs}$	ft-lb/fps
$T_w = 57.3 \dfrac{\partial C_T/\sigma}{\partial \alpha}$ Figure 9	$\left(\dfrac{\sigma\rho V_T^2 \pi R^2}{\mu V_T}\right)_{fs}$	lb/fps

CONCLUDING REMARKS

The data discussed in this report were obtained from a wind tunnel model of a circulation control rotor in order to assess the characteristics of its static stability derivatives which contribute to the dynamic stability and general flying qualities of the vehicle. The data have shown general traits that are typical of conventional hingeless rotors and have also provided forewarnings of distinct differences between CCR and its conventional counterpart. Specifically:

*Note: fs subscript denotes full-scale quantities.

1. Rotor thrust variation with speed and angle of attack follow conventional trends as these are primarily determined by the overriding rotor inflow changes.

2. Static speed stability appears to follow conventional trends in the advance ratio range $0.20 \leq \mu \leq 0.30$.

3. The model data have indicated a strong destabilizing static speed stability for $\mu < 0.20$.

4. The model data have indicated near neutral static speed stability for $\mu \approx 0.30$ and an unusually strong stabilizing characteristic for $\mu > 0.30$.

5. The variation of rolling moment with speed tends toward neutral stability for $\alpha_s = -10$ deg and $\mu > 0.35$, which is unusual for hingeless rotors.

These trends have been observed and measured on a model CCR of approximately 15-percent scale with fairly high blade stiffness. It has been shown that responses different from the conventional rotor may be explained by the dual dependence of CCR on lift due to blowing as well as lift due to angle of attack.

Figure 2 – Variation of Pitch and Roll Moment with Speed

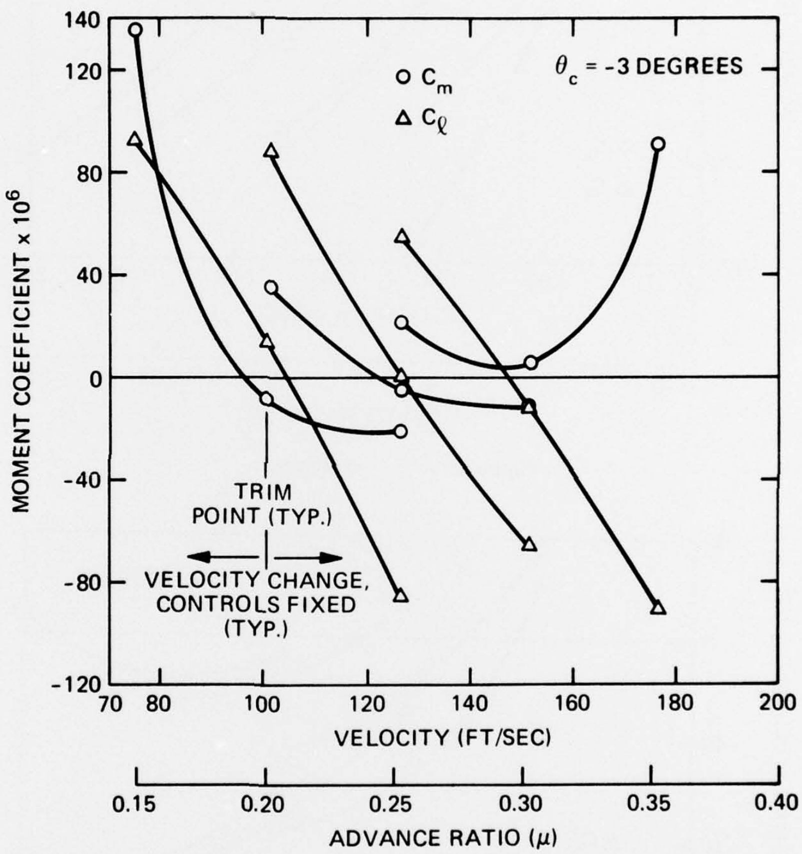

Figure 2a – α_s = 0 Degrees

Figure 2 (Continued)

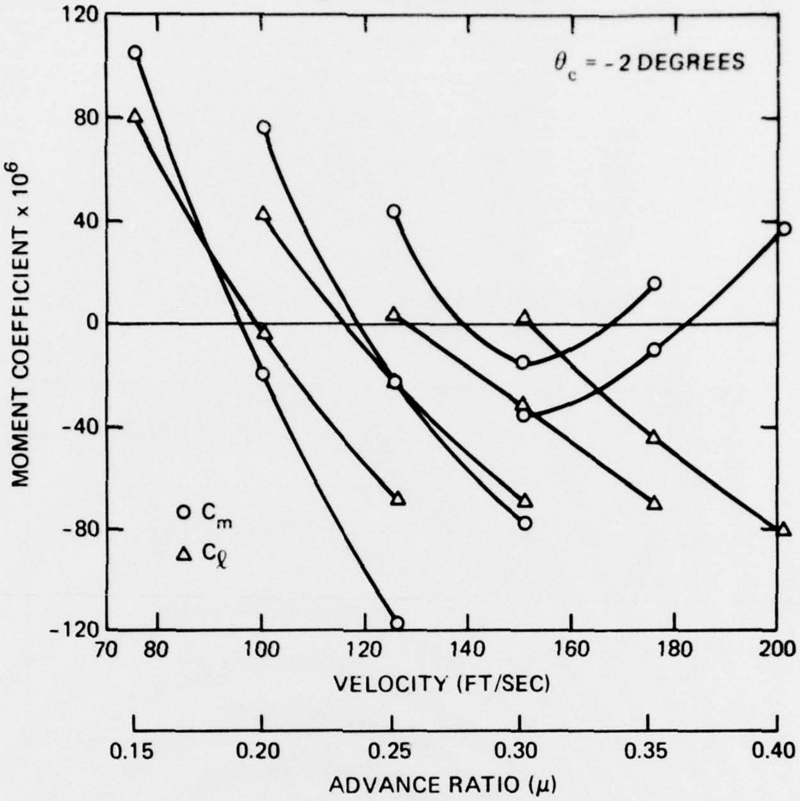

Figure 2b – α_s = -5 Degrees

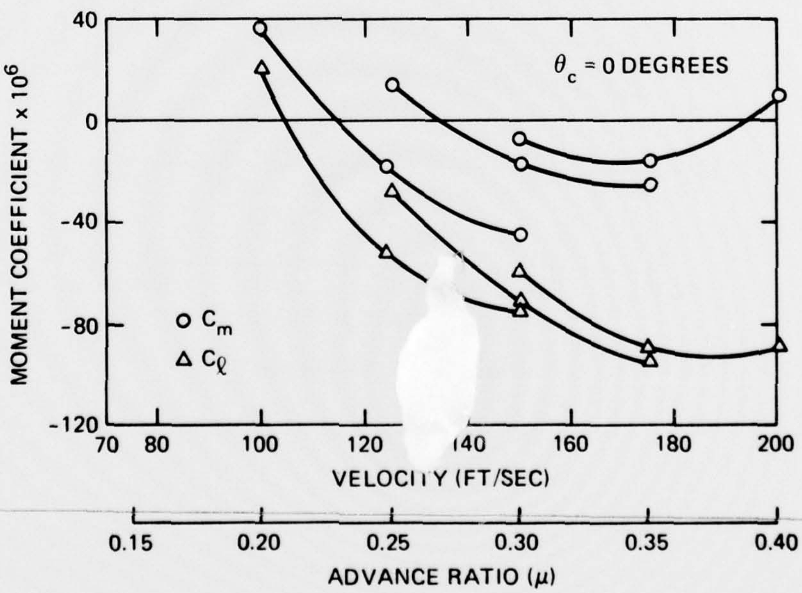

Figure 2c – α_s = -10 Degrees

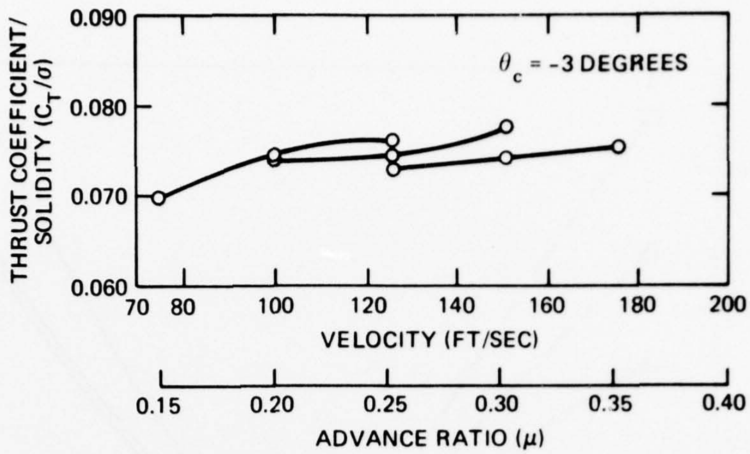

Figure 3a – α_s = 0 Degrees

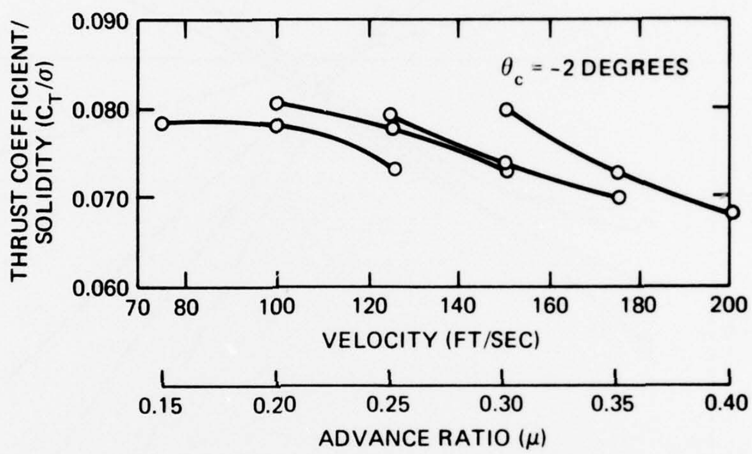

Figure 3b – α_s = -5 Degrees

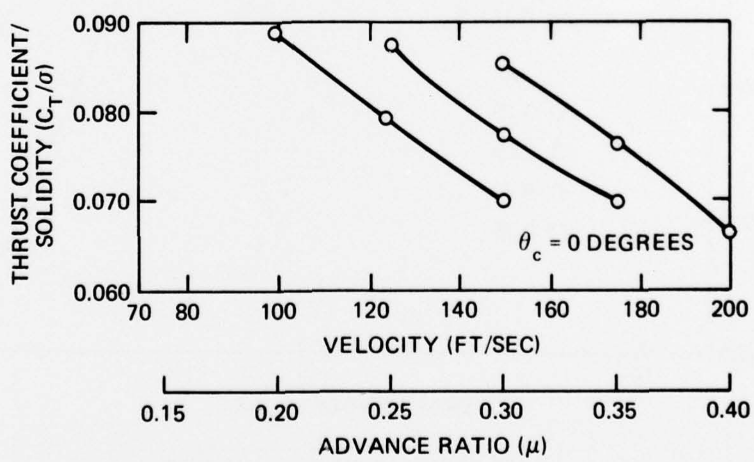

Figure 3c – α_s = -10 Degrees

Figure 3 – Variation of Thrust with Speed

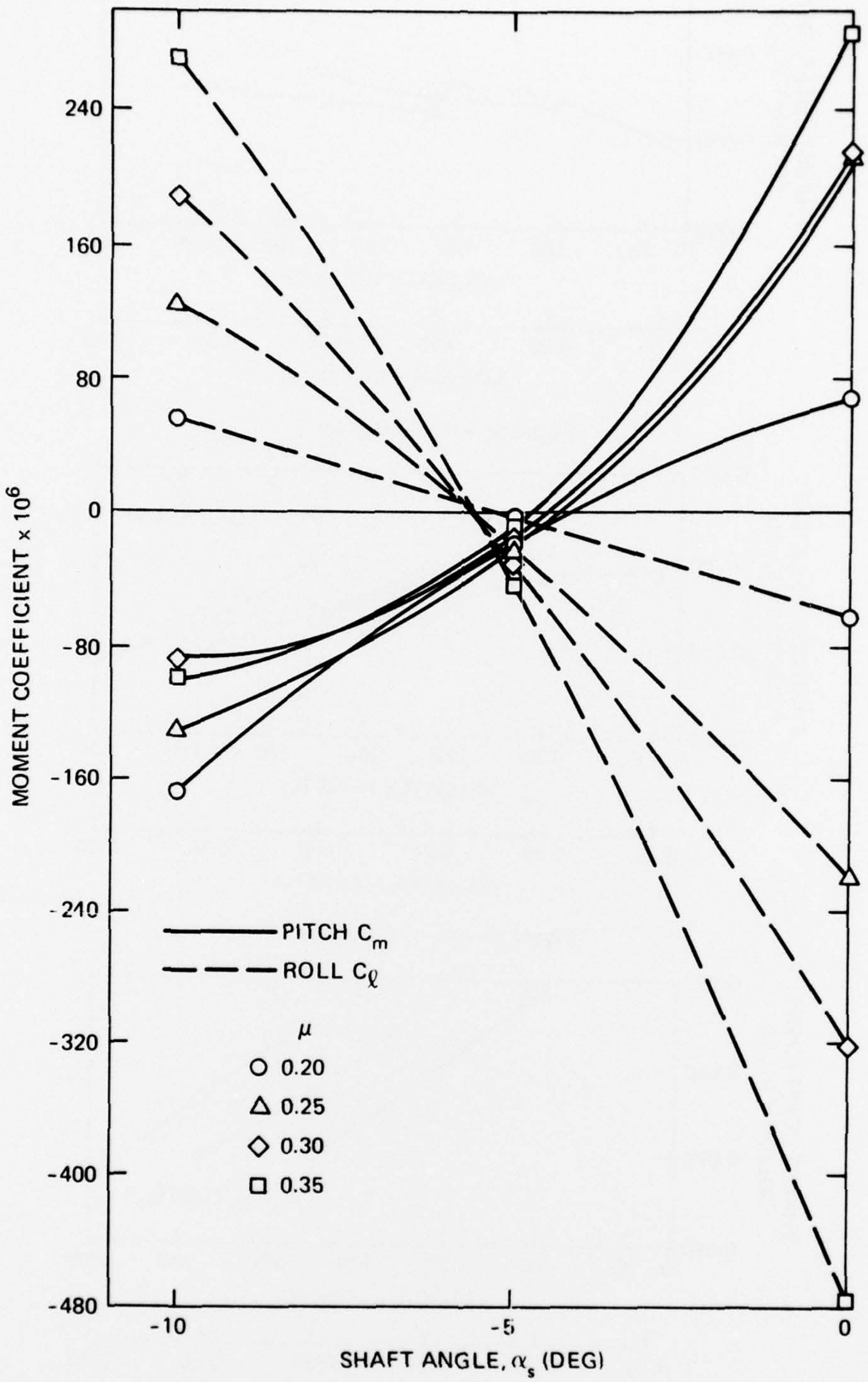

Figure 4 – Variation of Pitch and Roll Moment with Shaft Angle

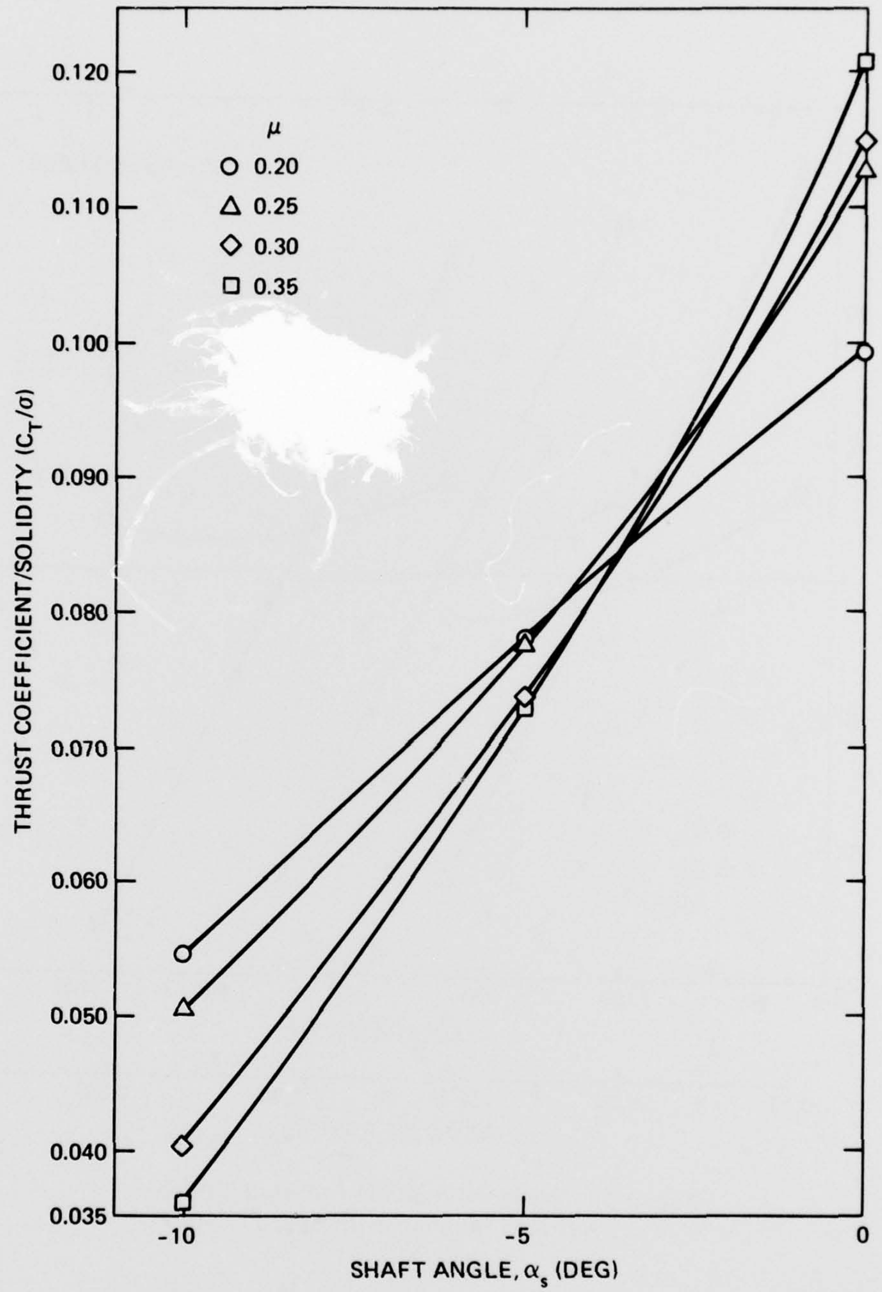

Figure 5 – Variation of Thrust with Shaft Angle

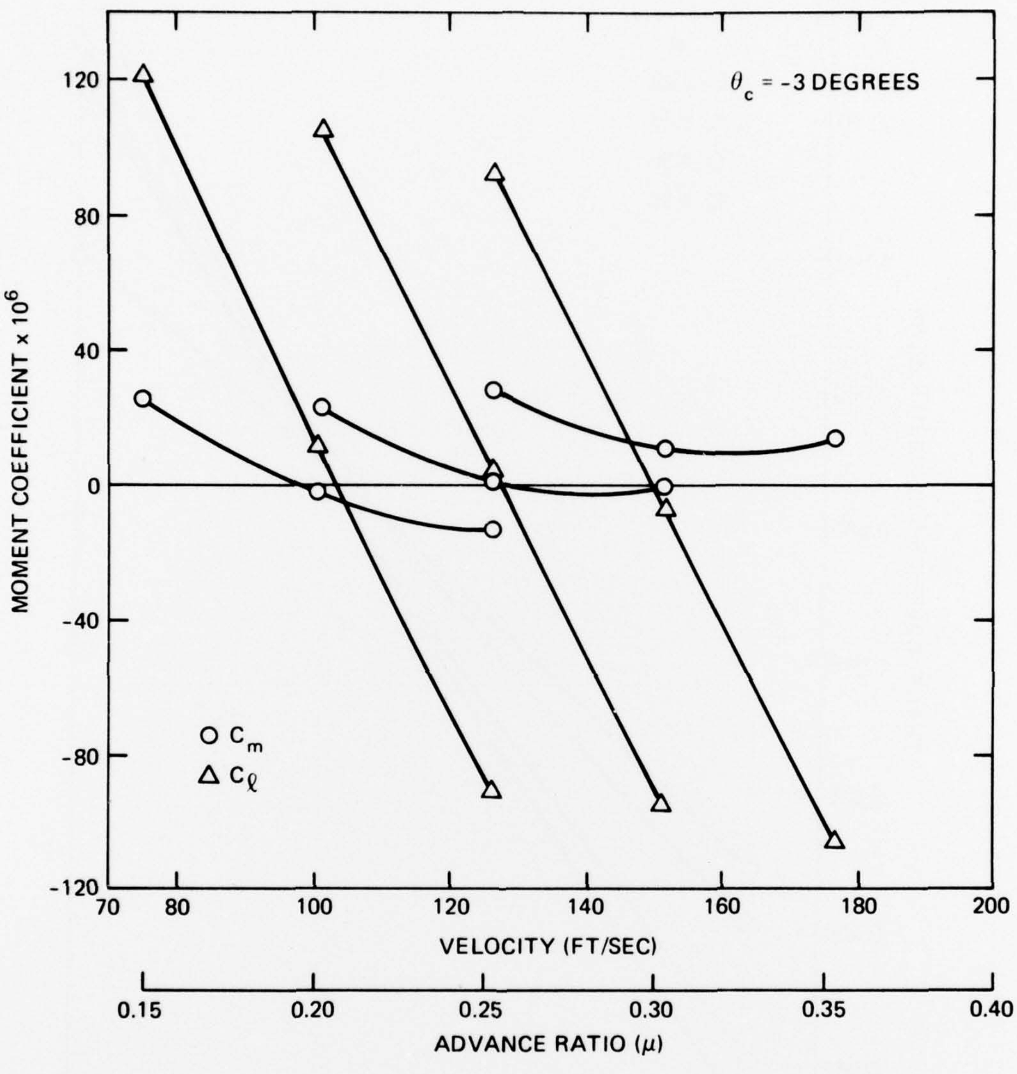

Figure 6 – Predicted Variation of Model Pitch and Roll Moment with Speed

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