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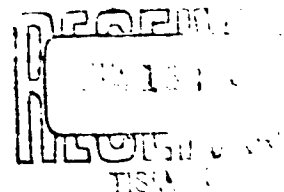
WIND TUNNEL INVESTIGATION OF THE
FORCES AND MOMENTS ACTING ON A
CRUCIFORM FINNED MODEL WITH
FIXED AND FREELY SPINNING TAIL
ASSEMBLIES AT A MACH NUMBER
OF 2.0

NOL

8 APRIL 1963

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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AERODYNAMIC RESEARCH REPORT 198

WIND TUNNEL INVESTIGATION OF THE FORCES AND MOMENTS
ACTING ON A CRUCIFORM FINNED MODEL WITH FIXED AND FREELY
SPINNING TAIL ASSEMBLIES AT A MACH NUMBER OF 2.0

Prepared by:
William E. DeGrafft

ABSTRACT: Spinning cruciform finned models were tested to determine the normal force, pitching moment, side force and yawing moment characteristics at a Mach number of 2.0 and a free stream Reynolds number of 3.98×10^6 per foot.

The models had fin cant angles of 0, 2 and 4 degrees. In addition the models with the 2 and 4 degree fin cant angles were constructed so that the fin assembly could rotate either with the body as a single unit or rotate freely with the body locked.

The tests showed that for the spin rates developed during the test, the normal force and pitching moments for all models are independent of spin rate and fin cant angle. The yawing moment is reduced on the average by a factor of 0.76 if the fins are allowed to rotate freely while the body is held stationary.

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This report presents the experimentally determined side forces and yawing moments acting on spinning missiles with cruciform canted fins. Motivation for this investigation was provided by a similar investigation conducted by Mr. John Wright at the Naval Ordnance Laboratory on the EV-II Rocket (reference (1)). At the suggestion of Mr. Kenneth Baker (RMMO-42) of the Bureau of Naval Weapons models with both fixed and freely spinning tail sections were investigated. This work was accomplished for the Bureau of Naval Weapons (RMMO-42) under Task Number RMMO-42-009/212-1/F008-09-01.

R. E. ODENING
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Commander

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By direction

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INTRODUCTION

The work presented in this report is an extension of the work reported in reference (1), although the test techniques, instrumentation and data reduction are considerably different.

Forces and moments which lie in the plane of the velocity vector and the model longitudinal axis are referred to as normal forces and pitching moments. Forces and moments acting perpendicular to the normal forces and pitching moments are referred to as side forces and yawing moments. The forces and moments of concern in this investigation are static and Magnus forces and moments.

The static forces and moments can be attributed to four separate effects.

- a. angle of attack
- b. configurational asymmetry
- c. combined angle of attack and roll angle (induced effects)
- d. combined angle of attack and fin cant angle

The Magnus forces and moments are due to combined angle of attack and spin rate. The models tested in this investigation had no intentional configurational asymmetry so that forces and moments due to effect b. are due only to small unintentional asymmetries.

If a model is mounted on a sting so that it is free to rotate about its longitudinal axis, then the total side forces and yawing moments due to effects c. and d. and the Magnus effect can be measured. The induced forces and moments (effect c.) have a frequency of four cycles per revolution with an average contribution of zero over one cycle. Mean values of the side forces and yawing moments obtained in this way will then yield the side forces and yawing moments due to combined angle of attack and fin cant angle and the Magnus effect.

Bolz, in his analysis of the dynamic stability of a rolling missile (reference (2)) includes the yawing moment due to combined angle of attack and fin cant angle and Magnus effect. It has also been noted by Murphy in reference (3) that if the ratio of the spin rate to the total velocity of the missile is constant, the spin rate is directly proportional to the fin cant angle. Under this condition, the yawing moments due to combined

angle of attack and fin cant angle and the Magnus effect can be combined into a single "Magnus type" moment dependent only on combined spin rate and angle of attack. This means that in order to determine the separate effects of spin rate and fin cant angle on the side forces and yawing moments, the forces and moments must be measured when the model is spinning at rates either above or below the steady-state spin rate. The model tested in this investigation has an internally mounted air turbine so that spin rates above the steady-state value can be achieved.

In Appendix A the conditions for the dynamic stability of both fixed and freely spinning tail configurations are discussed. It is shown that under normal conditions the overall dynamic stability of a fixed tail configuration is improved both dynamically and aerodynamically if the tail section is allowed to spin while the main body does not spin. Freely spinning tail configurations are tested in order to determine the reduction in the side force and yawing moment which can be achieved.

Aside from the overall improvements in dynamic stability offered by the freely spinning cruciform tail configurations, flight instabilities arising from roll resonance should in many cases be eliminated or greatly alleviated. The tail section with its very small axial moment of inertia can be designed to spin rapidly through the resonant spin rate. It has also been demonstrated in free flight tests (reference (4)) that missiles with spinning monoplane finned tail sections have good dynamic stability characteristics.

SYMBOLS

The data are referred to the non-rolling axes system (Figure 1) and are presented in the form of force and moment coefficients about a center of gravity 2" forward of the model base.

A	maximum body cross-sectional area of models $\frac{\pi d^2}{4}$
C_m	pitching-moment coefficient $\frac{M_y}{qAd}$
C_N	normal-force coefficient $\frac{F_z}{qA}$
C_n	yawing-moment coefficient $\frac{M_z}{qAd}$
C_Y	side-force coefficient $\frac{F_Y}{qA}$
d	maximum body diameter of models

F_Y, F_Z	forces in directions of Y and Z non-rolling axes
M	Mach number
M_Y, M_Z	moments about Y and Z non-rolling axes
p	spin rate about X non-rolling axis
P_∞	static pressure
q	dynamic pressure $\frac{\gamma P_\infty M^2}{2}$
α	angle of attack
γ	ratio of specific heat at constant pressure to specific heat at constant volume, equals 1.4

APPARATUS AND TESTS

The tests were conducted in NOL Supersonic Tunnel Number 1 using the Mach number 2.0 nozzle. This is a blowdown tunnel (reference (5)) using an atmospheric air supply and fixed geometry nozzle blocks for Mach number change. The data were recorded on magnetic tape on a high-speed, analog-to-digital data system and reduced to coefficient form on an IBM 7090 computer. The supply pressure was 14.4 psia and the supply temperature was 75°F resulting in a Reynolds number of 3.98×10^6 per foot and a Reynolds number based on model length and diameter of 4.64×10^6 and 6.63×10^6 , respectively.

The models tested are the 2" diameter, 7 caliber long AN spinner body with three interchangeable sets of rectangular, canted, cruciform fins. Geometric characteristics of the models are shown in Figure 2. The fin sections are identical in plan-form and have fin cant angles of 0, 2 and 4 degrees.

Both the main body and the fin sections were mounted on the model sting support on separate sets of ball bearings. This mounting arrangement allowed the entire configuration to rotate as a single unit or the fin section to rotate with the body fixed. The main body also had an internally mounted air turbine allowing the entire configuration to be driven above the steady-state spin rate. The air was supplied to the turbine by a passage through the center of the sting support and exhausted at the model base. The strain gages were protected from the air exhausted from the turbine by a cylindrical metal shield.

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Angles of attack investigated ranged from -10° to $+10^{\circ}$ for all models. The test spin rates of the various models are tabulated below.

Model	Rotating Parts	Fin Cant Angle (deg)	Spin Rate (rpm)
1	Body and fins	0	0 - 2530
2	"	2	2466 - 5240
3	"	4	4350 - 6270
4	Fins alone	2	2290 - 2520
5	"	4	3540 - 4640

For each angle of attack the normal force, pitching moment, side force, yawing moment and spin rate were measured. The forces and moments were measured by means of an electrical strain gage balance (reference (6)). Sting deflection due to the normal and side loads was computed as part of the data reduction. The spin rate was measured by one of the photoelectric tachometers mounted in the model.

Models 1, 2 and 3 were driven by the air turbine to spin rates above their steady-state values. When the maximum spin rate for the air supply available was obtained the air turbine was shut off and the spin rate was allowed to decay to its steady-state spin rate. During this coast-down period the forces, moments and spin rates were recorded continuously. In addition the forces, moments and the spin rate were recorded for several seconds at the model steady-state spin rate. Models 4 and 5 were tested only at their steady-state spin rate since the turbine could not drive the fin section independently of the main body.

The strain gage instrumentation is not considered optimum for the models tested for two reasons. First, the sensitivity of the yaw gages was low compared to the side loads encountered. This required the use of very high sensitivities on the read out equipment. The yaw gage sections probably could have been machined thinner to increase their sensitivity and still withstand the wind tunnel starting loads. An upper bound on the gage sensitivity is, of course, imposed by the requirement for an air passage in this balance. Second, the aft gages were located very close to the model base. Some drift in the aft yaw gage readings was noticed during the wind-off readings. This drift was probably due to the transient cooling effect of the air in the model base region, on the aft gages.

RESULTS AND DISCUSSION

The results of the tests are presented in Figures 3 through 7. The normal force, pitching moment coefficients, and steady-state spin rates of Models 2 and 5 are given as functions of angle of attack, and the yawing moment coefficients are given as a function of spin rate with angle of attack as a parameter.

The normal force and pitching moment coefficients for models 1 through 5 are presented in Figures 3 and 4. The effects of fin cant angle and spin rate for all models tested are within the scatter of the data so that the single mean value curves apply for all configurations. The models are statically unstable for the center of gravity position used in the data reduction. This c.g. position, however, is considerably further aft than it would be in a normal missile configuration and was chosen for convenience in calibration procedures used in a data read out system abandoned prior to the test.

The side force and yawing moment coefficients showed considerable scatter and were not symmetrical for positive and negative angles of attack. Some of this scatter can be attributed to the particular strain gage balance used in these tests as discussed in the previous section. There are also several aerodynamic reasons to which the scatter and asymmetry in the data can be ascribed. As mentioned earlier, there are induced side forces and yawing moments which oscillate with a frequency of four cycles per revolution. The Magnus contribution to the side forces and yawing moments measured is the result of the distortion of the body wake due to the spin rate of the body. This wake in itself is an unsteady flow phenomenon. Another factor which makes accurate readings of the side loads difficult is the fact that slight misalignments of the model with the air stream in the X - Z plane (see Figure 1) along with model asymmetries can create side loads of the same order of magnitude as the total yawing moment at low spin rates.

Plots of the yawing moment coefficients for models 1, 2 and 3 as a function of spin rate with angle of attack as a parameter were made. These plots showed that at a given angle of attack a single curve could be faired through the data for the 3 models, within the scatter of the data. The reason for this is believed to be that the models were not spun sufficiently above their steady-state spin rates to isolate the independent effects of spin rate and fin cant angle. These curves were then averaged for positive and negative angles of attack so that they would be symmetrical in angle of attack and are presented in Figure 5. The same procedure was used in the presentation of the yawing moment coefficients for models 4 and 5 as given in Figure 6.

The maximum side force coefficient obtained in all of the tests did not exceed 0.04. Since this value was so low, the scatter in these data did not permit a successful correlation, and for this reason the side force coefficients are not presented.

The ratios of the yawing moment coefficients for the models where only the fins were spinning (models 4 and 5), to the yawing moment coefficients, for the models where the fins and body spun as a single unit (models 1, 2 and 3), are given in the table below.

Spin Rate (rpm)	Angle of Attack (deg)	C_{nF}/C_{nBF}
2000	2	.82
	4	.69
	6	.69
	8	.68
	10	.74
4000	2	.88
	4	.89
	6	.76
	8	.70
	10	.72

There is a reduction in C_n for the models with only the fins spinning over the entire angle of attack range. The amount of the reduction increases with angle of attack up to 8 degrees with a slight decrease at 10 degrees.

The steady-state spin rates of models 2 and 4 are shown in Figure 7. They are nearly identical, with model 2 having slightly higher values. Measured values of the steady-state spin rates of models 3 and 5 were erratic and are not presented. Assuming that the values for models 2 and 4 are correct, then according to linear theory the spin rate of models 3 and 5 should be approximately 5000 rpm. This fact along with the observations that the steady-state spin rates of models 3 and 5 are not symmetric with angle of attack and considerably below 5000 rpm indicates that bearing friction had a marked influence on the steady-state spin rates measured. Tests on models 3 and 5 were made toward the end of the test program using the original set of bearings.

CONCLUDING REMARKS

The normal force and pitching moment coefficients of the models are unaffected by the fin cant angles and spin rates encountered in the tests. Reductions of the yawing moment coefficients from 10 to 30 percent were observed with configurations having freely spinning tail sections.

There appear to be several areas in which further experimental effort should be directed. The most important is to determine the characteristics of free spinning tail configurations at high angles of attack since the adverse effects of the yawing moment due to spin rate on the dynamic stability are more pronounced at high angles of attack. Tests should also be made at spin rates sufficiently higher or lower than the steady-state spin rate so that the separate effects of fin cant angle and spin rate can be observed. Sufficient static tests should also be made so that the static and dynamic contributions to the yawing moment can be separated. This separation of components of the total yawing moment is necessary in order to use the data in a computer program for six-degree-of-freedom motion studies. Since freely spinning finned bodies usually accelerate or decelerate rapidly to their instantaneous steady-state spin rate, it should be determined whether or not the side moment due to spin rate depends on the time rate of change of the spin rate.

There are two improvements which could be made to increase the accuracy of the side force and yawing moment data. The aft strain gages should be carefully protected from the air flow in the base region of the model. Both the forward and aft yaw gage sections should be made more sensitive, due to the small loads encountered.

The testing procedure could be improved by carefully determining the static side loads, produced by misalignments of the model with the flow and model asymmetries. In order to measure accurate values of the steady-state spin rates some method of monitoring the bearing life should be employed.

Additional theoretical and experimental work on missile configurations with freely spinning tail sections is planned in the near future.

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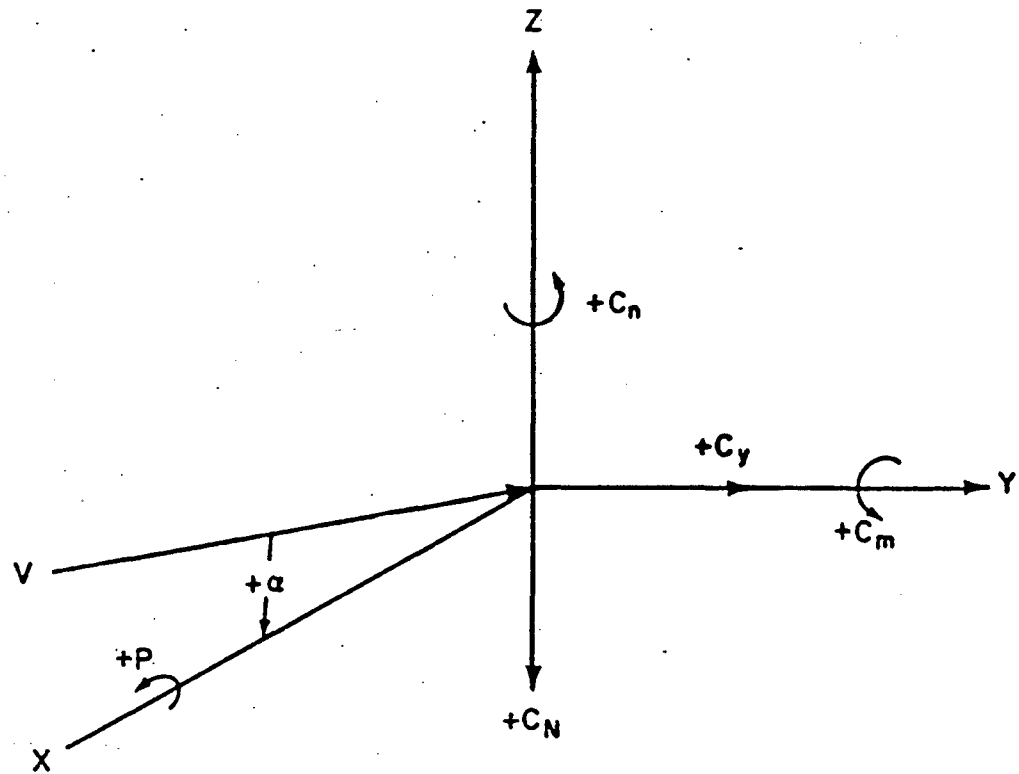


FIG.1 NON-ROTATING AXES SYSTEM

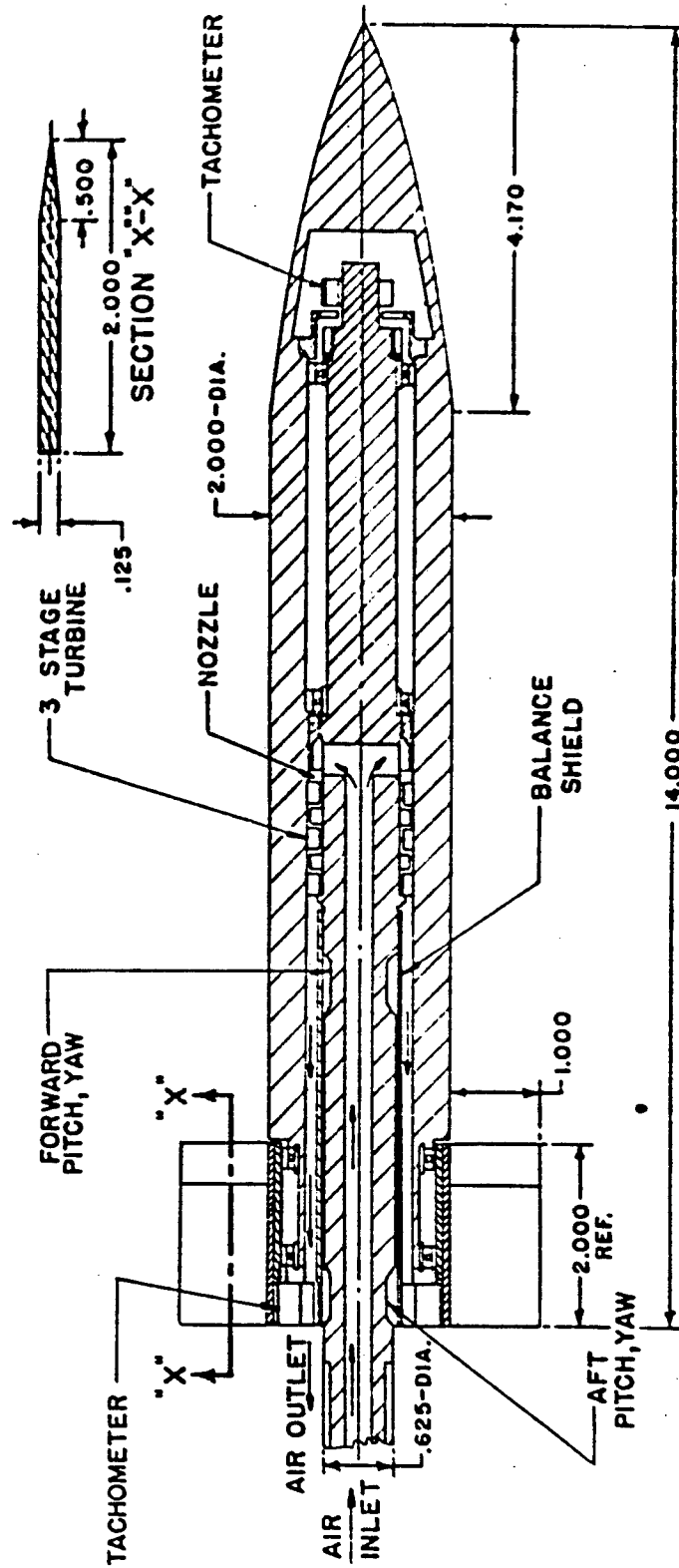


FIG.2 DRAWING OF MODELS TESTED

$M = 2.0$

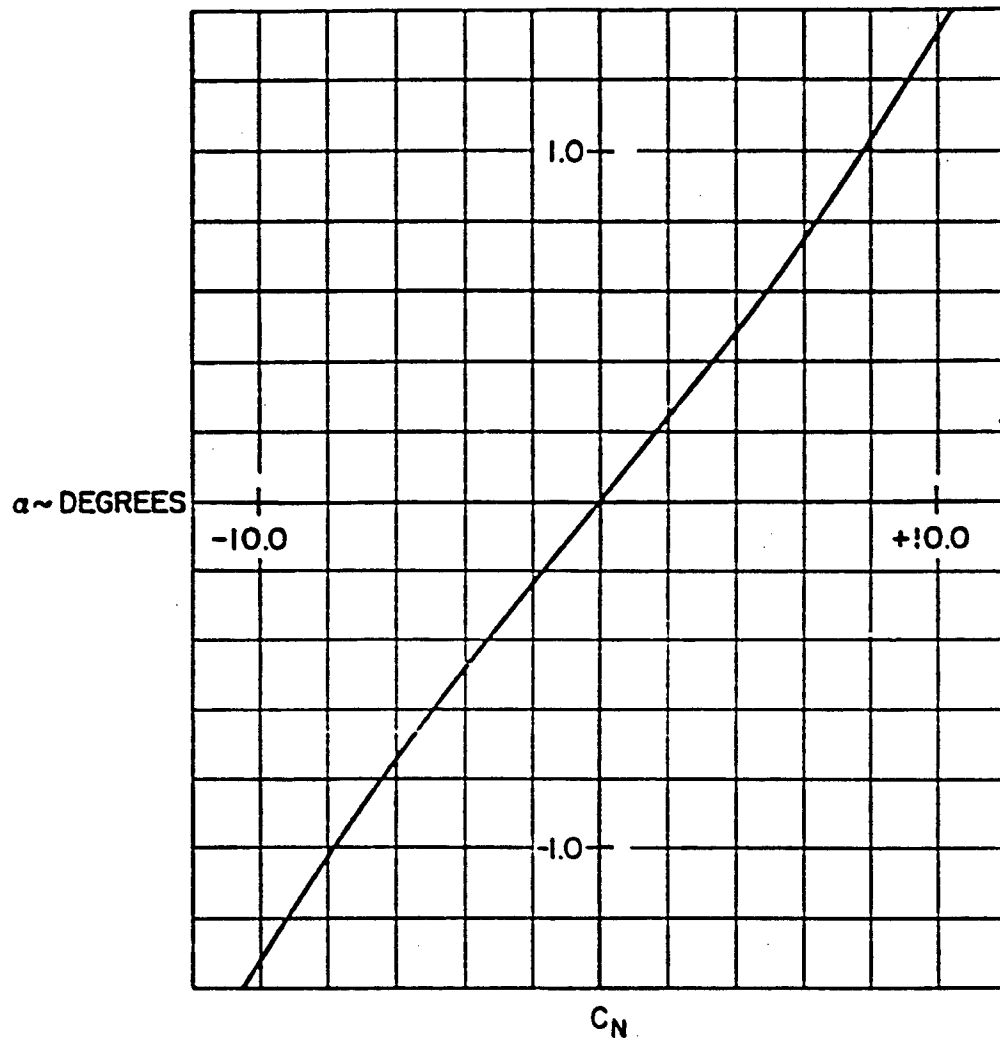


FIG. 3 NORMAL-FORCE COEFFICIENT AS A FUNCTION OF ANGLE OF ATTACK, ALL MODELS

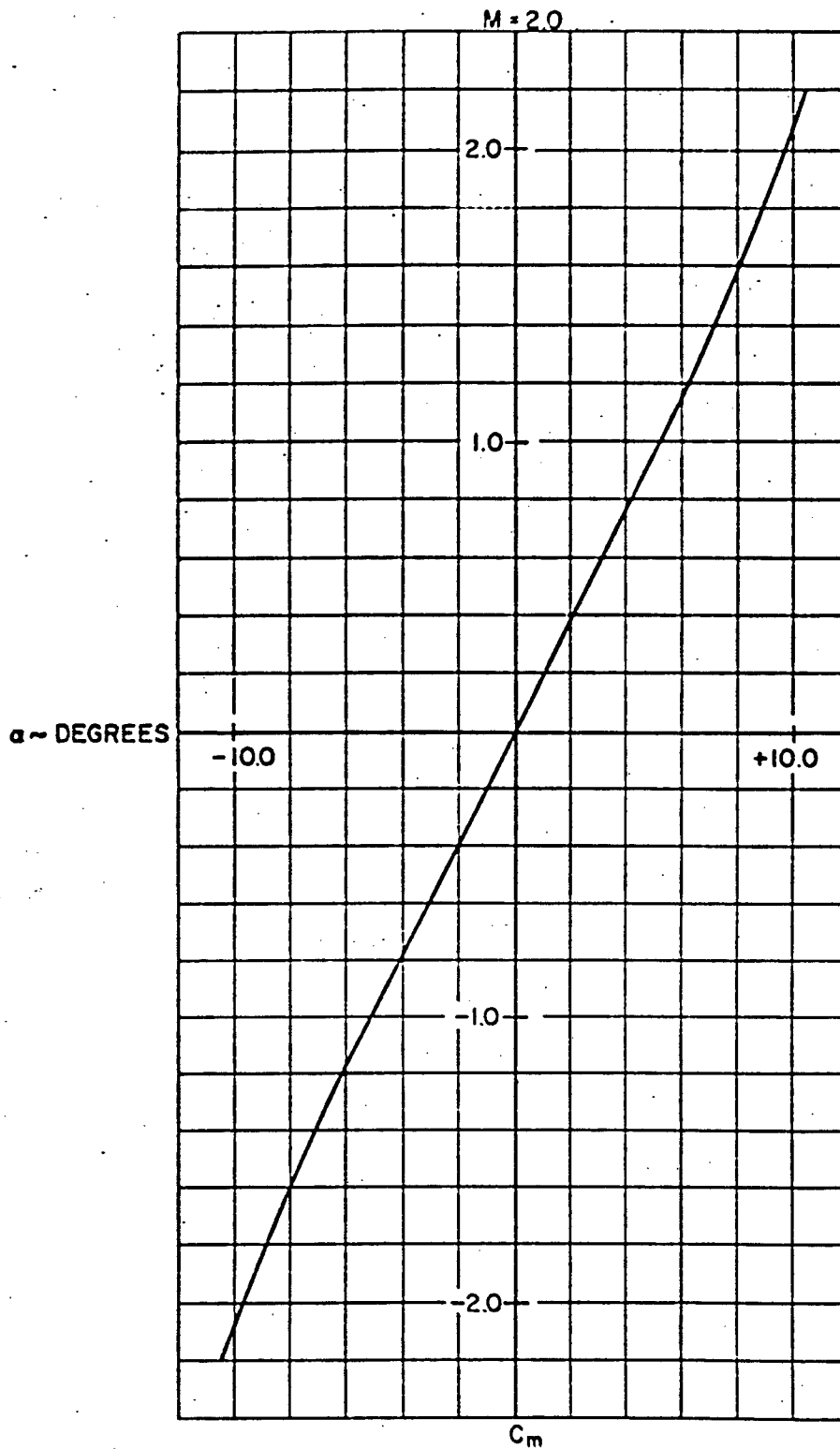


FIG. 4 PITCHING-MOMENT COEFFICIENT AS A FUNCTION OF ANGLE OF ATTACK, ALL MODELS

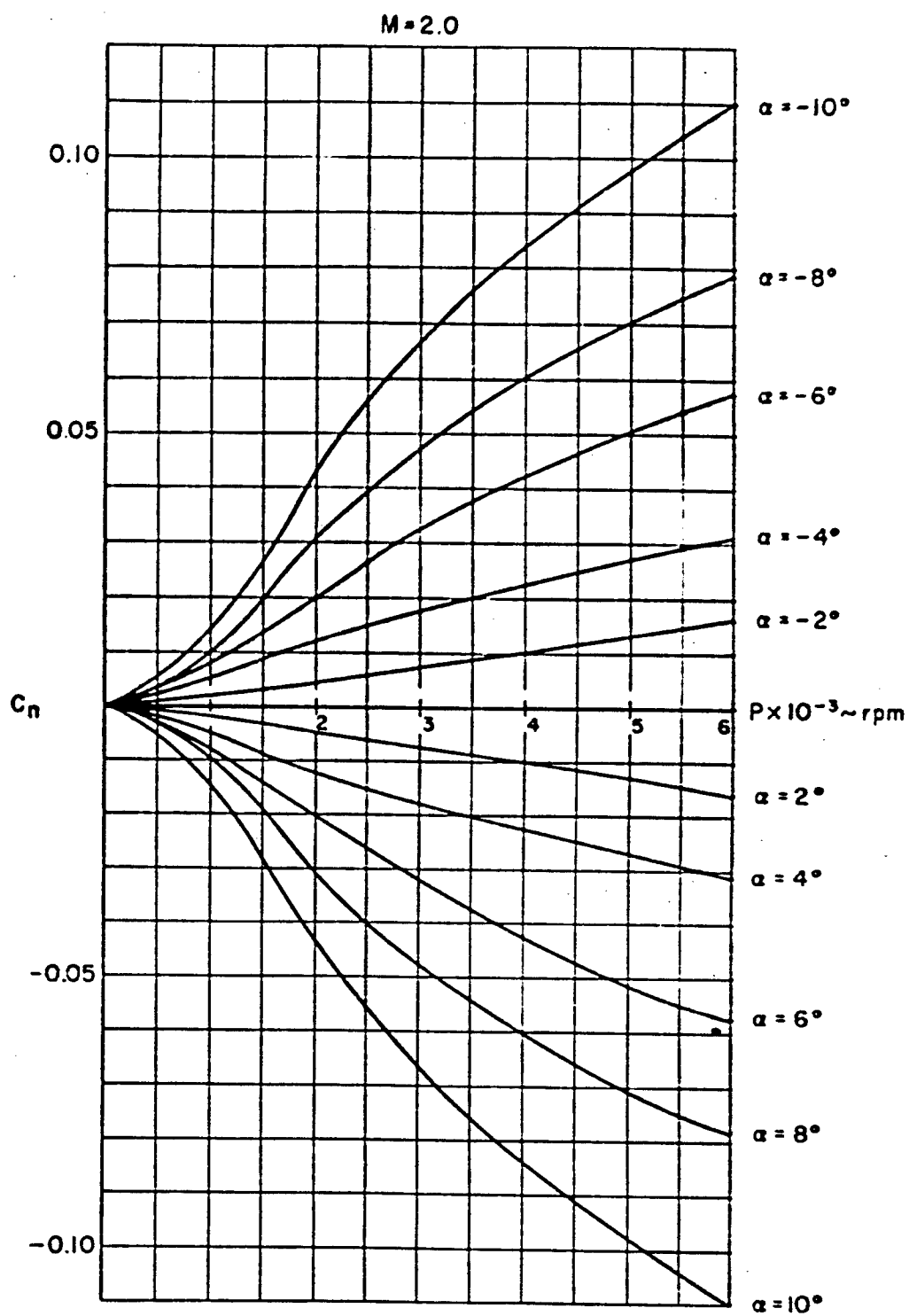


FIG. 5 YAWING-MOMENT COEFFICIENT AS A FUNCTION OF SPIN RATE AND ANGLE OF ATTACK FOR FIXED TAIL SECTIONS, MODELS 1, 2, 3

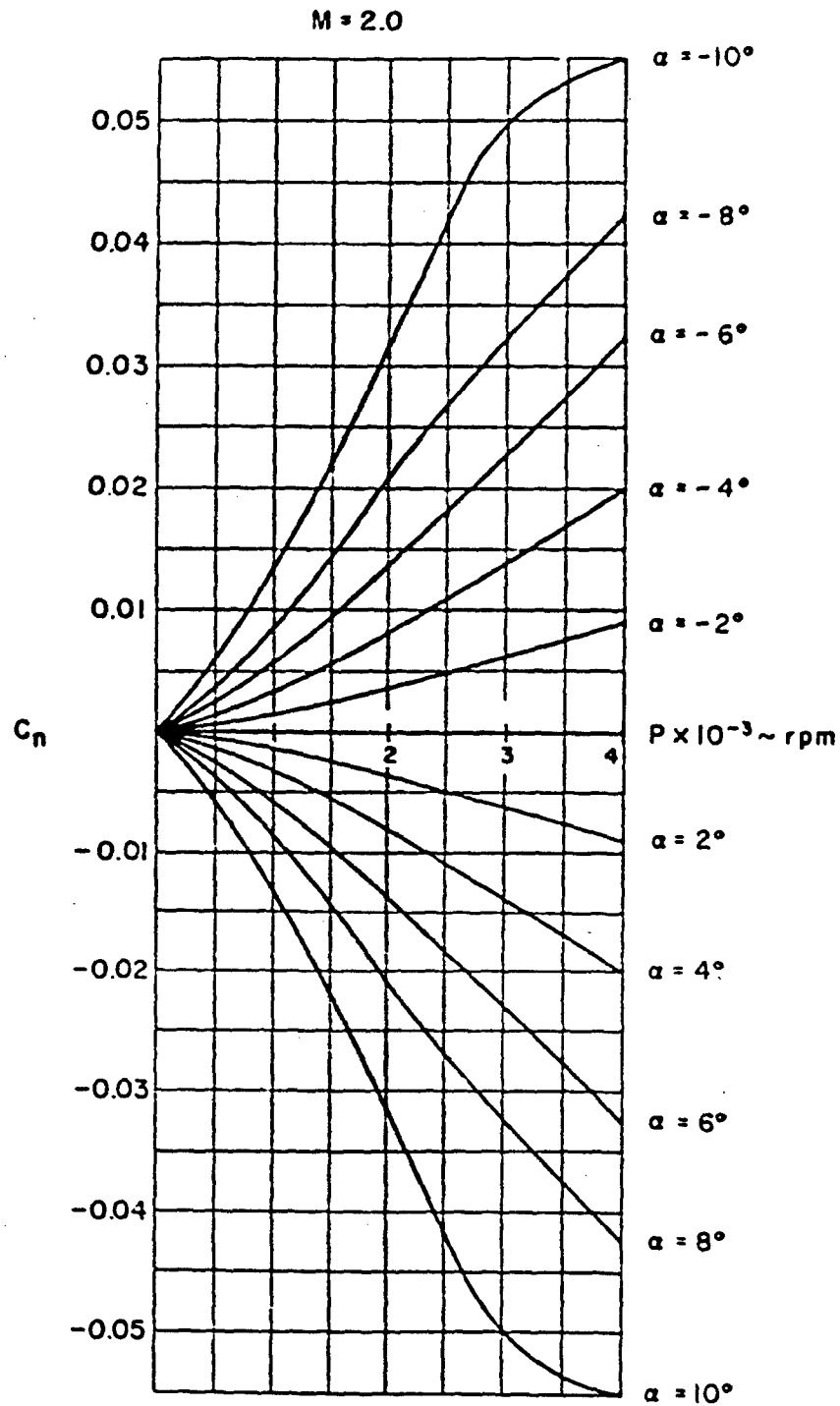


FIG. 6 YAWING - MOMENT COEFFICIENT AS A FUNCTION OF SPIN RATE AND ANGLE OF ATTACK FOR FREE SPINNING TAIL SECTIONS, MODELS 4, 5

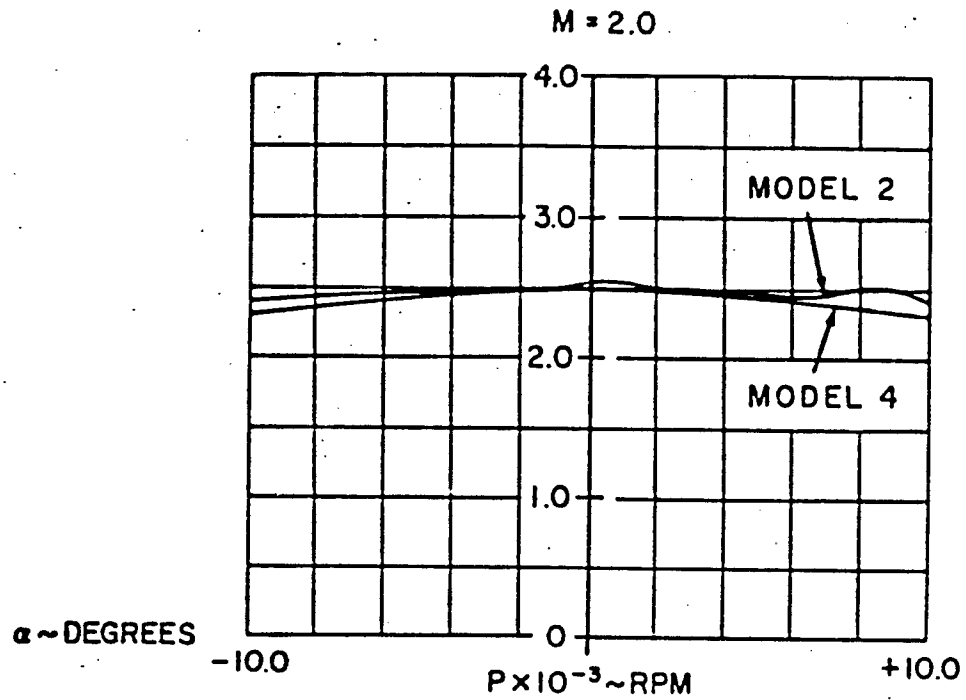


FIG. 7 STEADY-STATE-SPIN RATES AS A FUNCTION OF ANGLE OF ATTACK FOR FIXED AND SPINNING TAIL SECTIONS, MODELS 2 AND 4

APPENDIX A

A-1. The symbols used in this appendix not previously defined are

$$C_{m\alpha} = \frac{\partial C_m}{\partial \alpha} \quad \text{pitching-moment coefficient derivative}$$

$$C_{mq} = \frac{\partial C_m}{\partial \left(\frac{qd}{V}\right)} \quad \text{pitch-damping coefficient derivative}$$

$$C_{n_{p\alpha}} = \frac{\partial}{\partial \left(\frac{pd}{V}\right)} \left[\frac{\partial C_n}{\partial \alpha} \right] \quad \text{Magnus moment coefficient derivative}$$

$$C_{z\alpha} = \frac{\partial C_z}{\partial \alpha} \quad \text{normal-force coefficient derivative}$$

$$I \quad - \quad \text{transverse moment of inertia}$$

$$I_x \quad - \quad \text{axial moment of inertia}$$

$$m \quad - \quad \text{mass of missile}$$

$$V \quad - \quad \text{total velocity of missile}$$

$$\rho \quad - \quad \text{air density}$$

A-2. The conditions which must be satisfied in order that a missile having a constant spin rate and total velocity and flying at a constant altitude is dynamically stable, are

$$\frac{C_{z\alpha}}{m} + \frac{C_{mq}}{I} d^2 + \tau \left(- \frac{C_{z\alpha}}{m} + \frac{C_{mq}}{I} + \frac{2C_{n_{p\alpha}}}{I_x} d^2 \right) < 0 \quad (A-1)^*$$

where

$$\tau = \frac{\frac{pI_x}{2I}}{\sqrt{\left(\frac{pI_x}{2I}\right)^2 - \frac{C_{m\alpha} \rho v^2 A d}{2I}}}$$

$C_{n_{p\alpha}}$ is a "Magnus type" stability derivative composed of static and dynamic effects

A-3. In many cases

$$\left| \frac{C_{mq} d^2}{I} \right| \gg \left| \frac{C_{z\alpha}}{m} \right|$$

so that the stability conditions to a good approximation are

$$\frac{C_{mq}}{I} \pm \tau \left(\frac{C_{mq}}{I} + \frac{2C_{np\alpha}}{I_x} \right) < 0 \quad (A.2)$$

A-4. The stability conditions for a missile configuration where only the tail section rotates are (assuming that the axial moment of inertia of the tail section alone is approximately equal to zero)

$$\frac{C_{mq}}{I} \pm \frac{p' C_{np\alpha}}{\sqrt{\frac{-C_{m\alpha} \rho v^2 A d I}{2}}} < 0 \quad (A.3)$$

where the primed quantities refer to the freely spinning tail configuration. All other quantities are assumed to remain the same.

A-5. Rewriting equation (A.2), the stability conditions, for the case where the entire configuration is spinning, become

$$\frac{C_{mq}}{I} \pm \frac{p}{\sqrt{\frac{-C_{m\alpha} \rho v^2 A d I}{2}}} \left(\frac{C_{mq} I_x}{2I} + C_{np\alpha} \right) < 0 \quad (A.4)$$

assuming that

$$\frac{-C_{m\alpha} \rho v^2 A d}{2I} \gg \left(\frac{p I_x}{2I} \right)^2$$

A-6. Assuming that $p = p'$ and that $C'_{np\alpha}$ and $C_{np\alpha}$ are negative and all other terms are equal for the two configurations, the overall dynamic stability is improved if the tail section is allowed to freely rotate. There is a dynamic improvement since the main body is not rotating and an aerodynamic improvement since the Magnus moment contribution of the main body is eliminated ($C_{np\alpha} > C'_{np\alpha}$).

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DESCRIPTIONS	CODES	DESCRIPTIONS	CODES
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Fin-stabilized	FINST	2.0	2000
Missile	MISL	Pitching	PITC
Model	MODE	Yawing	YAWE
Wind tunnel	WINU	Reynolds no.	REYN
Forces	FORC	Rate	RATE
Moments	MOVE	Missiles (Test)	MISLT
Cruciform	CRUC	Missiles (Characteristics)	MISLC
Fixed	FIXE	Fins	FINS
Spinning	SPIN		
Tail	TAIL		
Assembly	ASSM		

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(NOL technical report 63-79)
WIND TUNNEL INVESTIGATION OF THE FORCES AND
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- Aerodynamics
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- tests
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