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AERODYNAMIC COEFFICIENTS OF THE M483A1 DETERMINED FROM SPARK RANGE TESTS

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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13. ABSTRACT (Maximum 200 words)

The aerodynamic coefficients of the M483A1 have been refined based on the analysis of 65 BRL Transonic Range tests. Both the original M483A1 tests (1975) and the latest tests from 1987-1989 were analyzed utilizing a six degree-of-freedom technique during September-October 1990. The Magnus moment was found to be extremely nonlinear with angle of attack and Mach number. The size of the slow arm limit cycle was computed along with the region of dynamic instability due to a large positive Magnus moment at moderate yaw levels. The values of the axial force, normal force, pitching moment, damping moment, and Magnus moment are presented.

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I. Introduction

The M483A1 projectile was the result of a modification of the XM483 configuration. This modification consisted of shortening the boattail length from 0.5 calibers to 0.25 calibers. This was determined to be neccessary as the XM483 exhibited a very large positive Magnus moment at Mach numbers less than 1.0. This large positive Magnus moment caused the projectile to be dynamically unstable (fast mode) at fairly low angles of attack (yaw angles) resulting in projectiles falling short of their design range. Reference 1 presents the analysis of spark-range and yawsonde firings of the XM483. Also presented in Reference 1 are the results of yawsonde firings of a modified XM483 (Mod 21B) which is now the configuration of the M483A1.

Figure 1 is a sketch of the M483A1. The M483A1 (20 each) was fired in the Ballistic Research Laboratory (BRL) Transonic Range (TR) Facility in the mid 1970's along with 105mm and 155mm models of the XM795. The results of these tests are given in Reference 2. Non-linear Magnus moment data are obtained from reductions utilizing the Eglin Six-Degree-of-Freedom (6DOF) Aeroballistic Range Facility Data Analysis System (ARFDAS) program. Reference 2 discusses the very non-linear Magnus moment discovered during initial attempts utilizing cubic and quintic expansion (with angle of attack) terms. The 6DOF model was changed to perform a table lookup of estimated values of the Magnus moment derivative ($C_{n_{p\alpha}}$). This change produced satisfactory analysis results. However, with only 20 projectiles tested between Mach numbers 0.65 and 1.91, the many data gaps in Mach number and angle of attack resulted in a partial aerodynamic data package.

Recently, the exterior shape of the M483A1 has been selected as a baseline for the development of several new projectiles. The aerodynamic data base of the M483A1 was determined not to be of sufficient quality when the importance of development programs is considered. The BRL designed a TR test program, consisting of 45 additional firings, to supplement the 1970's data. This program was carried out from 1987 thru 1989. This report discusses the results of these new tests in combination with the earlier tests which were re-analyzed in concert with the new test data.

II. Procedure

1. Test Facility

The projectiles were fired thru the 207 meter long, spark-shadowgraph instrumented section of TR. Reference 3 describes the details of this facility. The shadowgraphs taken are then used to determine the position and attitude of the test projectile as a function of time and distance. There are twenty-five shadowgraph stations in the range. During the tests conducted in 1975, only eighteen of the twenty five stations were timed.

The expected measurement accuracy is 0.1 degrees in attitude and 0.003 meters in position.

Table 1. M483A1 Physical Properties

Period	Diameter mm	Length mm	CG mm	CG Cal.	Mass kg	I_x $kg-m^2$	I_y $kg-m^2$
1975	154.74	898.0	565.0	3.65	46.88	0.1585	1.695
1988	154.74	896.7	562.9	3.64	46.86	0.1575	1.687

2. Test Projectiles

The projectile configuration is shown in Figure 1. Actual projectile hardware was utilized for the tests. The dimensional characteristics and physical properties of each projectile tested were measured prior to firing. Key characteristics are given in Table 1.

As shown in Table 1, only minor differences between the 1975 and 1988 projectiles were measured. The reference CG for the data presented in this report is 3.64 calibers measured from the nose. The stability computations utilize the 1988 physical properties.

3. Data Reduction

Data reduction procedures were formulated by using epicycles to fit the spark-range data (Ref 4). This method is often called the linear theory. The data analysis technique and system utilized for this report is fully described in Reference 5. Slight modifications to the baseline system (Eglin-ARFDAS) were made for compatibility with in place procedures at BRL. Some notational and scaling differences exist between References 4 and 5. The system used in this report allows for the simultaneous reduction of up to five experimental data sets. This is a powerfull technique as the only additional unknowns, required to be determined, are the initial conditions of each added data set. The aerodynamic coefficients to be determined are common to each data set. A total of sixty-five single shots and nineteen multiple fit groups were reduced during this activity utilizing the six-degree-of-freedom methodology.

The analysis process is judged to be adequate when the resultant fits to the data set approach the measurement capabilities of the facility presented above.

The standard method of modeling the expected non-linearities with angle of attack for each coefficient and its derivative is given below:

$$\epsilon = sin(\alpha)$$

$\alpha =$ Total Angle of Attack

Axial Force Coefficient

$$C_X = C_{X_o} + C_{X2}\epsilon^2 + C_{X4}\epsilon^4$$

Normal Force Coefficient

$$C_N = C_{N\alpha o}\epsilon + C_{N\alpha 3}\epsilon^3 + C_{N\alpha 5}\epsilon^5$$

$$C_{N\alpha} = C_{N\alpha o} + C_{N\alpha 3}\epsilon^2 + C_{N\alpha 5}\epsilon^4$$

Magnus Force Coefficient

$$C_{Yp} = C_{Yp\alpha o}\epsilon + C_{Yp\alpha 3}\epsilon^3$$

$$C_{Yp\alpha} = C_{Yp\alpha o} + C_{Yp\alpha 3}\epsilon^2$$

Pitching Moment Coefficient

$$C_m = C_{m\alpha o}\epsilon + C_{m\alpha 3}\epsilon^3 + C_{m\alpha 5}\epsilon^5$$

$$C_{m\alpha} = C_{m\alpha o} + C_{m\alpha 3}\epsilon^2 + C_{m\alpha 5}\epsilon^4$$

Pitch Damping Coefficient

$$C_{mq} = C_{mqo} + C_{mq\alpha 2}\epsilon^2 + C_{mq\alpha 4}\epsilon^4$$

Magnus Moment Coefficient

$$C_{np} = C_{np\alpha o}\epsilon + C_{np\alpha 3}\epsilon^3 + C_{np\alpha 5}\epsilon^5$$

$$C_{np\alpha} = C_{np\alpha o} + C_{np\alpha 3}\epsilon^2 + C_{np\alpha 5}\epsilon^4$$

A lesson learned from Reference 2 was that adding additional polynomial terms to account for M483A1 non-linearities in Magnus moment was not sufficient. The 1975 tests contained data with projectile yaw exceeding fifteen degrees. The technique chosen for the analysis contained in this report (different from Reference 2) was to create a table of Magnus moment (C_{np}) as a function of angle of attack (α) and Mach number. As the projectile motion is numerically integrated in the 6DOF code, a two way table interpolation is done to determine C_{np} at each angle of attack and Mach number. This value of C_{np} is then added to the standard $C_{np\alpha}$ equation by the following technique.

$$C_{np\alpha_{base}} = C_{np}/\epsilon$$

now:

$$C_{np\alpha} = C_{np\alpha_{base}} + C_{np\alpha_{base}} * C_9 + C_{np\alpha o} + C_{np\alpha 3}\epsilon^2 + C_{np\alpha 5}\epsilon^4$$

where: C_9 is to be solved for.

III. Results and Discussion

Each test projectile was initially subjected to single fit reductions. The aerodynamic coefficients of the projectiles are determined by individual reductions. Following the single fits, projectiles with similiar Mach numbers are grouped together for a multiple fit reduction. These groups usually contain the extremes of mean squared yaw (low and high) available at that groups Mach number. A maximum of five projectiles can currently be utilized. In some cases, more projectiles (greater than five) are desired. However, this analyst is content with five data sets, reducing more data sets is mind boggling. The tabulated single fit results are given in Table 2 and the multiple fit results are presented in Table 3.

The precision of the single fits are seen to better the stated range accuracy. This analyst believes that the accuracy of the calibration and film reading has been considerably improved in recent years. The quality of the multiple fit validates this premise in that they also better the stated accuracy.

The 1975 rounds can be identified as having ID's of T13XXX and T14XXX while the 1988 series have ID's of T30XXX. The multiple fit groups contained combinations of rounds fired in 1975 and 1988. The rounds contained in each multiple fit are designated in the left hand column of Table 3.

The major coefficients will be discussed individually. Emphasis has been placed on the multiple fit results. Only minimal effort was expended in attempts to determine non-linearities from single fits.

1. Axial Force Coefficient

The zero-yaw axial force coefficient (also C_{D_o}) is plotted versus Mach number in Figure 2. The single and mutiple fit are separately graphed. Little difference, if any, is noted when comparisons to Reference 2 are made. The error in the axial force coefficient at zero yaw is estimated to be less than 0.004. The yaw-axial force (C_{X2}) is shown for each multiple fit. When the average yaw levels were under 5 degrees, this coefficient was estimated and held constant during the analysis. Reference 2 provided estimated values for C_{X2} as the average yaw levels were large for the M483A1 and similiar XM795.

2. Normal Force Coefficient

The normal force coefficient determination is dependant on the magnitude of projectile yaw. Assuming a typical gun launch, with a first maximum yaw of 3 degrees, the size of the slow arm K_S will be 1.5 degrees For the M483A1, this will result in the radius of the swerve vector equal to 0.015 meters. This is approximately 5 times the demonstrated range accuracy and results in a $C_{N\alpha}$ error of about 7%.

Most projectiles fired supersonically had swerve arms of less than 0.01 meters and expected coefficient errors approach 15%.

The multiple fit results are plotted in Figure 3. The cubic term was estimated on many projectiles and held constant. These estimates were based on Reference 1 and several sets of wind tunnel data. The accuracy of the zero yaw $C_{N\alpha}$ as represented by the faired line is approximately 5% subsonic/transonic and 10% supersonic.

3. Magnus Force Coefficient

The Magnus force coefficient's effect on the motion of the center of gravity is nearly an order of magnitude smaller than the normal force coefficient. However, on those multiple fit groups where the maximum yaw observed exceeded 10 degrees, this coefficient was solved for and determined. The determined value ranged from about -1.0 to -1.6. On all other groups the $C_{Yp\alpha}$ was estimated at -1.0 and held constant. See Table 3 for details. This magnitude of $C_{Yp\alpha}$ is similiar to the values determined on other projectile test programs with large enough yaw (Reference 6).

4. Pitching Moment Coefficient

The pitching moment coefficient derivative, $C_{m\alpha}$, is very non-linear with increasing Mach number as shown in Figure 3. This same trend was first observed in Ref. 1 and later detailed in Ref. 2. The 1987-1989 firings added substantially to the definition of $C_{m\alpha}$ above M=0.96. The $C_{m\alpha}$ peaks near M=0.90 at a value of 4.85. The $C_{m\alpha}$ then drops to a low value of 4.45 at M=0.96 and rapidly climbs to 4.63 near M=1.0. The supersonic peak is near M=1.5 with $C_{m\alpha}$ equal to 4.88. A downward trend then begins with $C_{m\alpha}$ falling to 4.51 near M=2.3. Tabulated $C_{m\alpha}$ are given in Table 3 for the multiple fits. The estimated accuracy of the zero yaw $C_{m\alpha}$ is about 2%.

The cubic pitching moment is very weak with a value of about -7 subsonically and less than -3 supersonically. Estimated values were utilized in many of the multiple fits. The values were obtained from Ref 2. and are consistant with other experimental data. The error in the cubic pitching moment coefficient is about +/- 3.

5. Pitch Damping Coefficient

The pitch damping coefficient, C_{m_q}, can only be determined on spin stabilized projectiles when the Magnus moment coefficient is well modeled with respect to non-linearities. Linear Theory reductions produce large coefficient scatter for C_{m_q} when Magnus non-linearities are present. Linear Theory values for C_{m_q} varied from +47 to -30 below M=1. The 6DOF multiple fit analysis reduced this variance to a range of -4 to -17. Some of the remaining variance is due to Mach number trends, however, it is estimated that trend line drawn in Figure 4 has an estimated error of magnitude 3.

No attempt was made to determine higher order terms of pitch damping as simulated test cases have shown minimal influence on the resultant motion.

6. Spin Damping Coefficient

The spin damping coefficient, C_{l_p}, was estimated based on yawsonde data contained in Reference 1. This estimate is plotted in Figure 4.

7. Magnus Moment Coefficient

The Magnus moment coefficient, C_{n_p} of the M483A1 is very non-linear with angle of attack and Mach number. When the maximum yaw angle in the data set to be analyzed is greater than 5 degrees, the use of higher order terms must be closely reviewed for adequacy. Reference 2 discusses the use of an estimated Magnus table ($C_{n_{p\alpha}}$ vs. α). The interpolated derivative is then form factored by using only linear and cubic terms to evolve the appropriate non-linear behavior with angle of attack.

For the multiple fit analysis of test data below M=1.1, a table of C_{n_p} vs α vs Mach number was estimated and input in a data file. As described in the Data Analysis Section above, the values of C_{n_p} were interpolated and then form factored into a contour which minimized the probable error of fit. This process was iterative in that the input table was adjusted several times to ensure realistic modeling over the entire range of angle of attack and Mach number.

The final coefficients are given in Table 4. This is the actual data utilized for the final multiple fit reductions.

Table 3 (Multiple Fits) shows values for $C_{n_{p\alpha}}$ above M=1.1. Below M=1.1, the approach described above was utilized and the expansion terms are not cubic/quintic. Figures 5 thru 16 present plots of C_{n_p} vs α and $C_{n_{p\alpha}}$ vs. α^2 at Mach numbers from 0.65 to 2.0.

In general, below M=0.98, $C_{n_{p\alpha}}$ is very negative (about -5) near zero yaw, crosses 0.0 at about 4 degrees and increases to a maximum of 1.0/1.25 at 6 degrees yaw. This trend is similiar to that reported in Ref. 2. However, the goodness of the $C_{n_{p\alpha}}$ trend with yaw level presented in Figures 5 to 16 is much better than Reference 2. The large quantity of data from M= 0.85 to M=1.0 greatly improved the quality of and confidence in the results. The probable errors of fit were very low (most less than 0.1 degrees) considering that 4 and 5 projectiles with maximum yaw levels exceeding 12 degrees were being simulataneosly fit.

8. Stability Considerations

The gyroscopic and dynamic stability of the M483A1 has been computed for muzzle exit conditions at ambient conditions. The equations given below are discussed in Reference 4.

Gyroscopic Stability Factor

$$S_g = \frac{2I_x^2p^2}{\pi\rho I_y C_{m\alpha} d^3 V^2}$$

Ballistic Factor

$$\sigma = \sqrt{1 - \frac{1}{S_g}}$$

Fast - Slow Vector Magnitude (Initial Conditions)

$$K_F = \frac{\bar{\alpha}_{max}}{2}$$

$$K_S = \frac{\bar{\alpha}_{max}}{2}$$

Mean Squared Yaw

$$\bar{\delta}^2 = K_{F_i}^2 + K_{S_i}^2$$

Fast Mode Damping Factor

$$\lambda_F = [\frac{\rho A}{4m}][(1 - \frac{1}{\sigma})C_{N\alpha} - (\frac{md^2}{2I_y})(1 + \frac{1}{\sigma})C_{mq} - (\frac{md^2}{I_x})(\frac{1}{\sigma})C_{np\alpha}]$$

Slow Mode Damping Factor

$$\lambda_S = [\frac{\rho A}{4m}][(1 + \frac{1}{\sigma})C_{N\alpha} - (\frac{md^2}{2I_y})(1 - \frac{1}{\sigma})C_{mq} + (\frac{md^2}{I_x})(\frac{1}{\sigma})C_{np\alpha}]$$

The gyroscopic stability factor of the M483A1 was computed for muzzle exit conditions (1/20 twist) and both a standard (15C) and cold (-40C) day. These values are presented in Table 5.

The fast and slow mode damping factors in the above equations were set equal to zero, the equations re-arranged, and solved for the two limit values of $C_{np\alpha}$. The slopes computed have been plotted in Figures 5 thru 16.

The point at which C_{np} is crossed by the negative slope is the magnitude of the slow mode (arm) limit cycle. The projectile will cone at this yaw angle (3.5 degrees at M= 0.87 - Figure 8) at steady state conditions.

If the C_{np} is crossed by the positive slope, the projectile has a fast mode dynamic instabilty. Using Figure 8 (Mach 0.87) as an example, a slight dynamic instability caused by a positive C_{np} exists from about 5 thru 9 degrees yaw. Above 9 degrees, the C_{np} falls below the boundary and the projectile is stable in both fast and slow modes.

The same answers can be achieved using the $C_{np\alpha}$ versus mean squared yaw presentations. This trend was noted in Reference 2.

The consequences of this highly non-linear dynamic stability situation does not readily lend itself to closed form prediction. A series of 6DOF trajectory simulations with initial conditions (pitch-yaw rate) being varied for purposes of computing the effect on range precision should be done. Cold, ambient, and hot atmospheres should be included along with the effect on temperature on the muzzle velocity.

IV. Conclusions

The aerodynamic coefficients of the M483A1 projectile have been computed based on spark-range tests conducted in 1975,1987,1988, and 1989.

The multiple fits showed that there were essentially no aerodynamic differences between the projectiles manufactured in the mid 1970's and late 1980's.

The probable errors of the multiple fits were very low and support a high confidence level in the determined coefficients. Overall, the quality of the Transonic Range data from the 1988 tests is the best, within the experience of the author. This indicates that both the calibration of the facility, and the film reading process have improved in recent years.

The coefficients presented in this report should be incorporated into an aerodynamic data package for the M483A1. This package should be made available to all government and private industry parties involved in the development/evaluation of projectiles with shapes similiar to the M483A1.

6 DOF Summary Output
Shot Group Number: 1

Shot Number	Mach Number	DBSQ / ABARM	CX / CX2	CNa / CNa3	CYpa / CYpa3	Cma / Cma3	Cmq / Cmq2	Cnpa / Cnpa3	Cnpa5	Clp / IX/IY	CXM / CmaM	Probable Error X(m) / Y-Z(m)	Probable Error Angle(deg) / Roll(deg)
T14052	0.651	186.9	0.155	1.929	-1.00	4.285	-11.2	0.60		-0.0285	0.00	0.0007	0.096
		21.0	1.223	7.000	0.00	-3.0	0.0	0.0	0.	0.0939	0.00	0.0038	0.000
T14053	0.667	4.8	0.159	1.544	-1.00	4.264	-6.1	-1.29		-0.0285	0.00	0.0008	0.083
		3.6	1.200*	7.000	0.00	-3.0	0.0	0.0	0.	0.0935	0.00	0.0026	0.000
T14055	0.692	146.7	0.157	1.794	-1.00	4.238	-15.0	0.82		-0.0285	0.00	0.0013	0.159
		18.9	1.445	7.000	0.00	-3.0	0.0	0.0	0.	0.0935	0.00	0.0027	0.000
T14054	0.699	3.0	0.160	2.082	-1.00	4.374	-10.0	-2.46		-0.0285	0.00	0.0009	0.098
		2.4	1.000	7.000	0.00	-3.0	0.0	0.0	0.	0.0932	0.00	0.0028	0.000
T30832	0.748	16.7	0.159	1.874	-1.00	4.480	-7.6	-2.07		-0.0285	0.00	0.0008	0.034
		5.8	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0937	0.00	0.0020	0.000
T30091	0.753	5.5	0.150	1.920	-1.00	4.481	1.6	-1.60		-0.0285	0.00	0.0009	0.077
		3.4	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0947	0.00	0.0031	0.000
T30099	0.756	10.4	0.152	2.322	-1.00	4.511	-4.4	-1.60		-0.0285	0.00	0.0009	0.034
		4.1	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0944	0.00	0.0026	0.000
T30090	0.768	5.4	0.148	1.887	-1.00	4.570	2.5	-1.67		-0.0285	0.00	0.0010	0.057
		3.3	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0949	0.00	0.0022	0.000
T30092	0.840	16.6	0.161	1.870	-1.00	4.740	-15.4	-1.62		-0.0285	0.20	0.0009	0.050
		5.0	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0949	0.00	0.0026	0.000
T30100	0.845	8.5	0.160	2.104	-1.00	4.734	-10.7	-1.23		-0.0285	0.20	0.0008	0.035
		3.2	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0944	0.00	0.0022	0.000
T30096	0.852	2.4	0.158	2.455	-1.00	4.453	3.1	-3.43		-0.0285	0.20	0.0011	0.059
		2.1	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0935	0.00	0.0029	0.000
T13816	0.860	12.7	0.169	1.730	-1.00	4.781	6.9	0.00		-0.0285	0.20	0.0015	0.113
		5.1	2.000	0.000	0.00	0.0	0.0	0.0	0.	0.0948	0.00	0.0024	0.000
T13822	0.862	94.7	0.158	2.144	-1.00	4.510	-16.4	0.22		-0.0285	0.06	0.0014	0.158
		15.0	2.000	0.000	0.00	0.0	0.0	0.0	0.	0.0937	0.00	0.0027	0.000
T30830	0.864	12.3	0.166	1.888	-1.00	4.727	-5.1	-1.72		-0.0285	0.55	0.0010	0.065
		4.6	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0950	0.00	0.0021	0.000
T30093	0.866	19.0	0.163	1.910	-1.00	4.799	-11.2	-1.93		-0.0285	0.55	0.0007	0.036
		5.4	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0951	0.00	0.0024	0.000

Table 2. Single Fit - Six Degree of Freedom Results

6 DOF Summary Output
Shot Group Number: 1

Shot Number	Mach Number	DBSQ ABARM	CX CX2	CNa CNa3	CYpa CYpa3	Cma Cma3	Cmq Cmq2	Cnpa Cnpa3	Cnpa5	Clp IX/IY	CXM CmaM	Probable Error Z(m) Y-Z(m)	Angle(deg) Roll(deg)
T30101	0.869	11.2	0.163	2.111	-1.00	4.679	-6.4	-1.66		-0.0285	0.55	0.0008	0.047
		3.7	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0942	0.00	0.0023	0.000
T30097	0.869	2.9	0.164	1.803	-1.00	4.510	-18.7	-3.36		-0.0285	0.55	0.0009	0.116
		2.7	1.800	0.000	0.00	0.0	0.0	300.0	0.	0.0940	0.00	0.0093	0.000
T13815	0.877	2.5	0.158	2.208	-1.00	4.770	-10.0	0.00		-0.0285	0.60	0.0030	0.154
		2.0	2.000	0.000	0.00	0.0	0.0	0.0	0.	0.0951	0.00	0.0034	0.000
T30164	0.878	16.2	0.167	1.906	-1.00	4.818	-11.6	-1.52		-0.0285	0.80	0.0007	0.071
		4.7	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0944	0.00	0.0024	0.000
T30168	0.886	2.8	0.171	1.975	-1.00	4.618	18.6	-4.91		-0.0285	0.80	0.0009	0.061
		2.3	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0934	0.00	0.0020	0.000
T13819	0.899	81.8	0.179	2.260	-1.00	4.607	-12.6	0.67		-0.0285	0.00	0.0015	0.121
		13.6	2.000	0.000	0.00	0.0	0.0	0.0	0.	0.0947	0.00	0.0028	0.000
T13818	0.899	5.0	0.193	1.777	-1.00	4.646	23.2	-4.36		-0.0285	0.00	0.0010	0.104
		3.2	2.000	7.000	0.00	-7.0	0.0	300.0	0.	0.0944	0.00	0.0036	0.000
T13814	0.900	29.0	0.210	1.820	-1.00	4.786	-21.6	1.74		-0.0259	0.00	0.0009	0.095
		8.4	0.000	0.000	0.00	0.0	0.0	0.0	0.	0.0947	0.00	0.0030	0.000
T13817	0.908	50.5	0.192	1.924	-1.00	4.755	0.2	-6.15		-0.0285	0.80	0.0018	0.176
		10.3	2.000	7.000	0.00	-7.0	0.0	300.0	0.	0.0944	0.00	0.0029	0.000
T30170	0.909	22.9	0.190	2.037	-1.00	4.800	-9.1	-2.10		-0.0285	0.80	0.0011	0.085
		5.7	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0945	0.00	0.0028	0.000
T30171	0.910	8.9	0.189	2.029	-1.00	4.784	23.4	-2.76		-0.0285	0.80	0.0011	0.050
		3.6	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0944	0.00	0.0020	0.000
T30169	0.917	3.6	0.194	2.064	-1.00	4.718	-12.2	-5.62		-0.0285	1.20	0.0010	0.107
		3.0	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0960	0.00	0.0029	0.000
T13820	0.924	7.6	0.205	1.934	-1.00	4.777	46.1	-5.18		-0.0285	1.20	0.0011	0.130
		4.2	2.000	7.000	0.00	-7.0	0.0	300.0	0.	0.0953	0.00	0.0043	0.000
T13813	0.924	51.1	0.211	2.149	-1.00	4.525	-15.2	1.33		-0.0285	0.00	0.0014	0.094
		10.8	2.000	0.000	0.00	0.0	0.0	0.0	0.	0.0945	0.00	0.0028	0.000
T30839	0.924	3.3	0.199	1.975	-1.00	4.573	46.7	-5.96		-0.0285	1.20	0.0010	0.112
		3.0	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0950	0.00	0.0024	0.000

Table 2. Single Fit - Six Degree of Freedom Results

6 DOF Summary Output
Shot Group Number: 1

Shot Number	Mach Number	DBSQ / ABARM	CX / CX2	CNa / CNa3	CYpa / CYpa3	Cma / Cma3	Cmq / Cmq2	Cnpa / Cnpa3	Cnpa5	Clp / IX/IY	CXM / CmaM	Probable Error X(m) / Y-Z(m)	Probable Error Angle(deg) / Roll(deg)
T30838	0.927	6.9	0.204	2.086	-1.00	4.590	30.7	-4.02		-0.0285	1.20	0.0009	0.060
		3.2	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0949	0.00	0.0018	0.000
T30837	0.928	19.8	0.212	2.145	-1.00	4.554	-8.1	-2.23		-0.0285	1.20	0.0010	0.074
		5.2	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0946	0.00	0.0021	0.000
T13823	0.933	197.0	0.158	2.352	-1.00	4.768	-13.6	-0.10		-0.0285	1.40	0.0026	0.141
		21.2	2.000	7.000	0.00	-7.0	0.0	0.0	0.	0.0940	0.00	0.0029	0.000
T13821	0.933	4.3	0.220	2.155	-1.00	4.369	-2.4	-4.85		-0.0285	1.40	0.0008	0.092
		2.7	2.000	7.000	0.00	-7.0	0.0	300.0	0.	0.0925	0.00	0.0033	0.000
T30102	0.953	7.1	0.232	2.291	-1.00	4.780	17.3	-3.07		-0.0280	1.40	0.0011	0.048
		3.3	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0950	0.00	0.0022	0.000
T30094	0.956	21.3	0.247	2.253	-1.00	4.630	-21.9	-2.14		-0.0280	1.40	0.0011	0.054
		6.2	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0949	0.00	0.0027	0.000
T30842	0.957	14.5	0.241	2.098	-1.00	4.427	-12.6	-2.72		-0.0280	1.40	0.0011	0.054
		4.7	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0946	0.00	0.0021	0.000
T30840	0.958	8.6	0.244	2.194	-1.00	4.407	1.5	-2.78		-0.0280	1.40	0.0011	0.061
		3.3	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0937	0.00	0.0025	0.000
T13812	0.962	13.5	0.267	2.096	-1.00	4.443	-14.2	-0.28		-0.0280	0.00	0.0011	0.073
		5.7	0.000	0.000	0.00	0.0	0.0	0.0	0.	0.0965	0.00	0.0025	0.000
T30098	0.962	1.6	0.247	2.046	-1.00	4.565	35.1	-7.22		-0.0280	1.40	0.0009	0.057
		2.1	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0957	0.00	0.0026	0.000
T30844	0.964	7.8	0.262	2.214	-1.00	4.377	-2.6	-2.31		-0.0280	1.40	0.0012	0.054
		3.0	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0933	0.00	0.0024	0.000
T30836	0.966	16.9	0.260	2.274	-1.00	4.472	-21.9	-2.41		-0.0280	1.40	0.0018	0.070
		4.9	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0945	0.00	0.0027	0.000
T30843	0.966	0.8	0.248	2.533	-1.00	4.122	-10.0	-6.04		-0.0280	1.40	0.0011	0.059
		1.1	2.000	0.000	0.00	0.0	0.0	300.0	0.	0.0990	0.00	0.0016	0.000
T30167	0.993	0.7	0.308	2.589	-1.00	4.384	-22.4	-2.11		-0.0275	1.50	0.0014	0.042
		1.2	3.000	0.000	0.00	0.0	0.0	0.0	0.	0.0948	0.00	0.0020	0.000
T30162	0.998	3.7	0.318	2.390	-1.00	4.588	-27.3	-1.05		-0.0275	1.50	0.0011	0.060
		2.3	3.000	0.000	0.00	0.0	0.0	0.0	0.	0.0942	0.00	0.0023	0.000

Table 2. Single Fit - Six Degree of Freedom Results

6 DOF Summary Output
Shot Group Number: 1

Shot Number	Mach Number	DBSQ ABARM	CX CX2	CNa CNa3	CYpa CYpa3	Cma Cma3	Cmq Cmq2	Cnpa Cnpa3	Cnpa5	Clp IX/IY	CXM CmaM	Probable Error X(m) Y-Z(m)	Probable Error Angle(deg) Roll(deg)
T30103	1.003	1.1	0.321	2.780	-1.00	4.434	-21.5	-2.29		-0.0275	1.50	0.0010	0.055
		1.4	3.000	0.000	0.00	0.0	0.0	0.0	0.	0.0944	0.00	0.0031	0.000
T30821	1.012	17.8	0.365	2.351	-1.00	4.716	-27.0	0.34		-0.0275	1.50	0.0011	0.063
		5.4	3.000	0.000	0.00	0.0	0.0	0.0	0.	0.0949	0.00	0.0020	0.000
T30095	1.015	10.9	0.354	2.409	-1.00	4.664	-28.6	0.11		-0.0275	1.50	0.0019	0.054
		4.2	3.000	0.000	0.00	0.0	0.0	0.0	0.	0.0949	0.00	0.0022	0.000
T30828	1.015	11.2	0.382	2.296	-1.00	4.673	-19.8	-0.16		-0.0275	1.50	0.0009	0.056
		4.2	0.000	0.000	0.00	0.0	0.0	0.0	0.	0.0943	0.00	0.0019	0.000
T14067	1.110	0.9	0.395	2.811	-1.00	4.614	-22.5	-0.09		-0.0260	-0.10	0.0009	0.089
		1.5	3.000	0.000	0.00	0.0	0.0	0.0	0.	0.0933	0.00	0.0028	0.000
T30139	1.261	0.3	0.368	2.400	-1.00	4.703	-32.0	0.71		-0.0260	-0.12	0.0009	0.057
		0.9	0.000	0.000	0.00	0.0	0.0	0.0	0.	0.0933	0.00	0.0030	0.000
T30144	1.286	0.6	0.362	2.648	-1.00	4.923	-42.9	1.42		-0.0260	0.00	0.0010	0.049
		1.0	0.000	0.000	0.00	0.0	0.0	0.0	0.	0.0943	0.00	0.0026	0.000
T30813	1.297	0.1	0.359	2.500	-1.00	4.950	-32.0	1.26		-0.0260	-0.12	0.0008	0.065
		0.4	4.000	0.000	0.00	0.0	0.0	0.0	0.	0.0931	0.00	0.0027	0.000
T14098	1.423	1.2	0.358	3.064	-1.00	4.874	-42.7	1.44		-0.0260	-0.12	0.0007	0.097
		1.9	0.000	0.000	0.00	0.0	0.0	0.0	0.	0.0927	0.00	0.0026	0.000
T30140	1.528	0.8	0.333	1.647	-1.00	4.932	-28.5	0.83		-0.0240	-0.10	0.0010	0.050
		1.3	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0949	0.00	0.0029	0.000
T30143	1.533	1.2	0.335	1.332	-1.00	4.909	-28.7	0.75		-0.0240	-0.10	0.0010	0.055
		1.5	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0950	0.00	0.0028	0.000
T30816	1.554	0.4	0.327	3.061	-1.00	4.768	-32.4	1.30		-0.0240	0.00	0.0011	0.074
		0.9	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0938	0.00	0.0026	0.000
T30819	1.557	1.5	0.335	2.172	-1.00	4.997	-38.7	0.99		-0.0240	-0.10	0.0011	0.048
		1.4	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0946	0.00	0.0020	0.000
T14100	1.578	1.1	0.335	2.408	-1.00	4.615	-35.1	0.95		-0.0240	-0.10	0.0010	0.072
		1.6	0.000	0.000	0.00	0.0	0.0	0.0	0.	0.0929	0.00	0.0030	0.000
T30141	1.844	2.7	0.303	2.457	-1.00	4.672	-38.5	1.07		-0.0230	0.00	0.0011	0.081
		2.1	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0941	0.00	0.0032	0.000

Table 2. Single Fit - Six Degree of Freedom Results

6 DOF Summary Output
Shot Group Number: 1

Shot Number	Mach Number	DBSQ / ABARM	CX / CX2	CNa / CNa3	CYpa / CYpa3	Cma / Cma3	Cmq / Cmq2	Cnpa / Cnpa3	Cnpa5	Clp / IX/IY	CXM / CmaM	Probable Error X(m) / Y-Z(m)	Probable Error Angle(deg) / Roll(deg)
T30142	1.863	1.1	0.296	2.400	-1.00	4.816	-38.9	1.13		-0.0230	0.00	0.0011	0.097
		1.3	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0948	0.00	0.0029	0.000
T30826	1.884	0.9	0.296	1.908	-1.00	4.906	-42.0	1.13		-0.0230	-0.10	0.0014	0.065
		1.2	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0957	0.00	0.0022	0.000
T14111	1.891	0.8	0.302	2.375	-1.00	4.714	-22.6	0.69		-0.0230	-0.10	0.0008	0.104
		1.4	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0939	0.00	0.0028	0.000
T30822	2.252	0.0	0.263	2.800	-1.00	4.559	-25.0	-1.65		-0.0230	0.00	0.0006	0.069
		0.2	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0930	0.00	0.0019	0.000
T30817	2.306	5.8	0.263	2.774	-1.00	4.525	-30.6	0.55		-0.0230	0.00	0.0009	0.101
		3.1	5.000	0.000	0.00	0.0	0.0	0.0	0.	0.0942	0.00	0.0024	0.000

Table 2. Single Fit - Six Degree of Freedom Results

6 DOF Summary Output
Shot Group Number: 3

Shot Numbers		Number	DBSQ ABARM	CX CX2 CX4	CNa CNa3 CNa5	CYpa CYpa3	Cma Cma3 Cma5	Cmq Cmq2 Cmq4	Cnpa Cnpa3 Cnpa5	Clp CXm CmaM	X(m) Y-Z(m)	Angle(deg) Roll(deg)
T14052	T14053	0.677	85.3	0.156	1.859	-1.60	4.257	-11.4		-0.0285	0.0014	0.1126
T14054	T14055		21.0	1.445	7.000	0.00	-3.000	0.0		0.0000	0.0029	0.0000
				0.00	0.00		0.0	0.		0.000		
T30832	T30091	0.756	5.5	0.153	1.992	-1.00	4.523	-4.3		-0.0285	0.0015	0.0542
T30099	T30090		5.8	1.800	7.000	0.00	-7.000	0.0		0.0000	0.0027	0.0000
				0.00	0.00		0.0	0.		0.000		
T30092	T30096	0.846	9.2	0.160	1.991	-1.00	4.752	-13.6		-0.0285	0.0011	0.0680
T30100			4.9	1.800	7.000	0.00	-7.000	0.0		0.2000	0.0029	0.0000
				0.00	0.00		0.0	0.		0.000		
T13815	T13822	0.866	36.7	0.162	1.828	-1.00	4.771	-17.1		-0.0285	0.0031	0.1168
T13816			14.9	2.026	7.000	0.00	-7.000	0.0		0.5500	0.0029	0.0000
				0.00	0.00		0.0	0.		-8.898		
T13822	T30101	0.867	31.7	0.163	1.961	-1.61	4.758	-16.9		-0.0285	0.0010	0.0976
T30097	T30093		14.9	1.800	7.000	0.00	-5.742	0.0		0.5500	0.0050	0.0000
				0.00	0.00		0.0	0.		0.000		
T30097	T30101	0.867	11.2	0.163	2.118	-1.00	4.786	-15.3		-0.0285	0.0010	0.0798
T30093	T30830		5.4	1.800	7.000	0.00	-7.000	0.0		0.5500	0.0049	0.0000
				0.00	0.00		0.0	0.		0.000		
T30164	T30168	0.897	15.9	0.176	1.880	-1.00	4.854	-10.8		-0.0285	0.0012	0.0814
T30170	T30171		8.2	3.157	7.000	0.00	-7.000	0.0		0.7000	0.0025	0.0000
T13814				0.00	0.00		0.0	0.		0.000		
T13819	T13818	0.902	34.8	0.193	1.884	-1.50	4.861	-9.1		-0.0285	0.0016	0.0959
T13814	T30170		13.6	1.532	8.000	0.00	-7.000	0.0		0.8000	0.0030	0.0000
				0.00	0.00		0.0	0.		0.000		
T30169	T13820	0.922	17.0	0.202	1.972	-1.00	4.717	-5.4		-0.0285	0.0017	0.1064
T13813	T30839		10.7	2.000	7.000	0.00	-7.000	0.0		1.2000	0.0031	0.0000
				0.00	0.00		0.0	0.		-6.401		
T13813	T13821	0.929	55.9	0.208	1.988	-1.07	4.595	-12.3		-0.0285	0.0015	0.0904
T13823	T30838		21.1	3.246	10.767	0.00	-4.748	0.0		1.3000	0.0026	0.0000
T30837				-26.50	0.00		0.0	0.		-1.721		
T30102	T30094	0.956	12.8	0.241	2.160	-1.00	4.588	-13.9		-0.0280	0.0016	0.0940
T30842	T30840		6.2	2.000	7.000	0.00	-5.000	0.0		1.5000	0.0025	0.0000
				0.00	0.00		0.0	0.		-19.895		

Table 3. Multiple Fit - Six Degree of Freedom Results

6 DOF Summary Output
Shot Group Number: 3

Shot Numbers		Number	DBSQ ABARM	CX CX2 CX4	CNa CNa3 CNa5	CYpa CYpa3	Cma Cma3 Cma5	Cmq Cmq2 Cmq4	Cnpa Cnpa3 Cnpa5	Clp CXm CmaH	X(m) Y-Z(m)	Angle(deg) Roll(deg)
T13812	T30098	0.964	8.4	0.255	2.168	-1.00	4.450	-20.5		-0.0280	0.0025	0.0829
T30844	T30836		5.8	2.000	7.000	0.00	-3.000	0.0		1.4000	0 0026	0.0000
T30843				0.00	0.00		0.0	0.		-1.307		
T30167	T30162	1.002	5.9	0.329	2.442	-1.00	4.631	-30.4	-1.49	-0.0275	0.0023	0.0636
T30103	T30821		5.4	3.000	0.000	0.00	0.000	0.0	245.75	2.9106	0.0025	0.0000
				0.00	0.00		0.0	0.	0.	6.631		
T14067	T30139	1.239	0.5	0.370	2.518	-1.00	4.768	-26.6	0.53	-0.0260	0.0018	0.0663
T30813	T30144		1.5	4.000	0.000	0.00	0.000	0.0	0.00	-0.1200	0.0028	0.0000
				0.00	0.00		0.0	0.	0.	1.624		
T30139	T30144	1.317	0.6	0.361	2.566	-1.00	4.817	-42.8	1.46	-0.0260	0.0017	0.0686
T30813	T14098		1.9	4.000	7.000	0.00	0.000	0.0	0.00	-0.1200	0.0028	0.0000
				0.00	0.00		0.0	0.	0.	0.000		
T30140	T30143	1.550	1.0	0.332	2.043	-1.00	4.883	-34.2	0.91	-0.0240	0.0014	0.0610
T30816	T30819		1.6	5.000	7.000	0.00	0.000	0.0	0.00	-0.1000	0.0028	0.0000
T14100				0.00	0.00		0.0	0.	0.	0.000		
T30141	T30142	1.871	1.4	0.299	2.367	-1.00	4.746	-31.6	0.89	-0.0230	0.0015	0.0876
T30826	T14111		2.1	5.000	0.000	0.00	0.000	0.0	0.00	-0.1000	0.0028	0.0000
				0.00	0.00		0.0	0.	0.	0.000		
T30141	T30142	2.066	2.5	0.281	2.569	-1.00	4.624	-35.0	0.88	-0.0230	0.0012	0.0859
T30822	T30817		3.2	5.000	0.000	0.00	0.000	0.0	0.00	-0.0860	0.0027	0.0000
				0.00	0.00		0.0	0.	0.	-0.420		
T30822	T30817	2.279	2.9	0.262	2.830	-1.00	4.535	-29.8	0.51	-0.0230	0.0009	0.0833
			3.1	5.000	0.000	0.00	0.000	0.0	0.00	-0.1000	0.0021	0.0000
				0.00	0.00		0.0	0.	0.	0.000		

Table 3. Multiple Fit - Six Degree of Freedom Results

M483.1 CG = 3.64 CALIBERS FROM NOSE

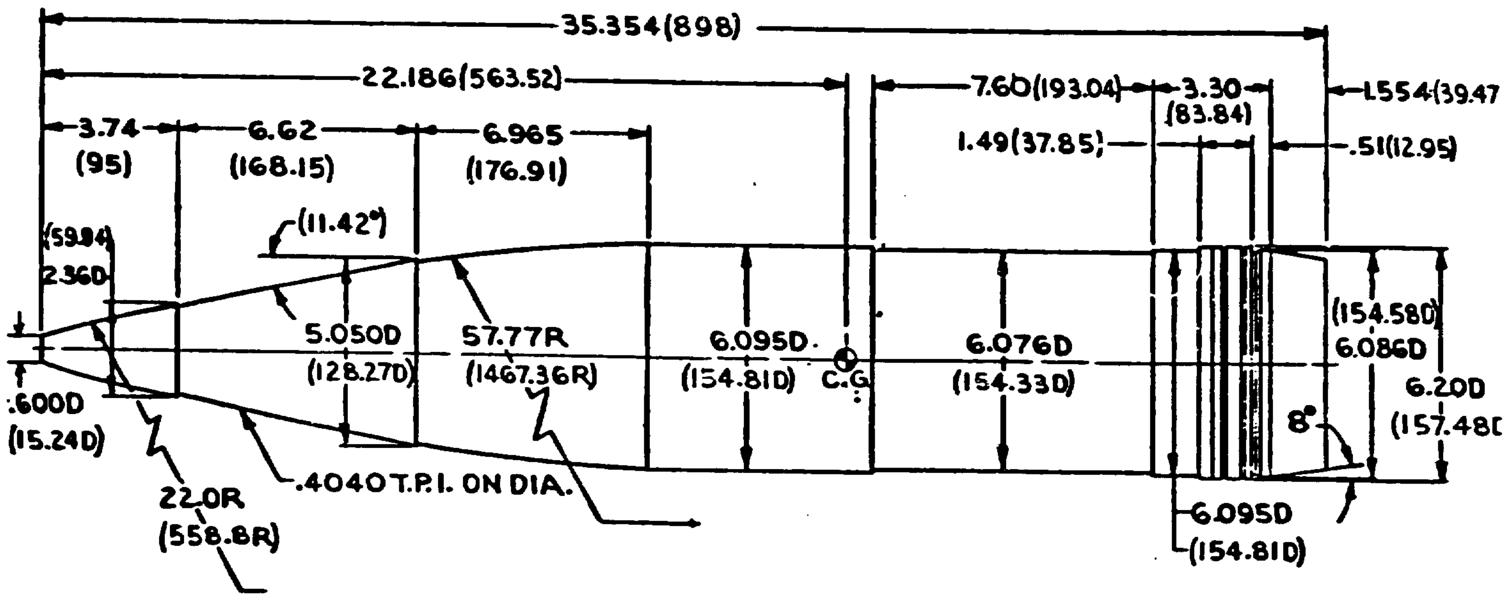
MAGNUS MOMENT VS. ANGLE OF ATTACK VS. MACH NUMBER

	MACH NUMBER									
AOA	0.50	0.75	0.87	0.90	0.93	0.96	1.00	1.25	1.50	3.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	-0.026	-0.026	-0.038	-0.065	-0.070	-0.050	-0.012	0.0046	0.0079	0.0079
1.0	-0.050	-0.050	-0.074	-0.120	-0.130	-0.100	-0.023	0.0092	0.0157	0.0157
2.0	-0.074	-0.074	-0.107	-0.160	-0.170	-0.140	-0.039	0.0185	0.0314	0.0314
3.0	-0.037	-0.037	-0.070	-0.100	-0.110	-0.090	-0.034	0.0277	0.0471	0.0471
4.0	0.015	0.015	0.007	0.005	-0.002	-0.010	-0.001	0.0370	0.0628	0.0628
5.0	0.057	0.057	0.090	0.085	0.085	0.035	0.040	0.0462	0.0784	0.0784
6.0	0.086	0.086	0.130	0.130	0.135	0.070	0.060	0.0554	0.0941	0.0941
7.0	0.105	0.105	0.140	0.155	0.165	0.090	0.070	0.0646	0.1097	0.1097
8.0	0.116	0.116	0.150	0.170	0.180	0.110	0.079	0.0738	0.1253	0.1253
10.0	0.132	0.132	0.150	0.160	0.180	0.120	0.097	0.0920	0.1563	0.1563
12.5	0.150	0.150	0.140	0.145	0.150	0.110	0.115	0.1147	0.1948	0.1948
15.0	0.160	0.160	0.120	0.120	0.120	0.105	0.135	0.1372	0.2329	0.2329

Table 4. Magnus Moment C_{n_p} vs Angle of Attack vs Mach Number

Mach No.	$C_{m\alpha}$	S_g 15C	S_g -40C
0.65	4.20	2.06	1.69
0.75	4.52	1.91	1.57
0.85	4.75	1.82	1.49
0.87	4.80	1.80	1.48
0.90	4.85	1.78	1.46
0.93	4.60	1.88	1.54
0.96	4.45	1.94	1.59
1.00	4.63	1.87	1.53
1.25	4.77	1.81	1.48
1.50	4.88	1.77	1.45
2.30	4.53	1.91	1.57

Table 5. Muzzle Gyroscopic Stability Factor



NOTE: Dimensions are in in. and mm.

Figure 1. Configuration for 155mm projectile, M483A1

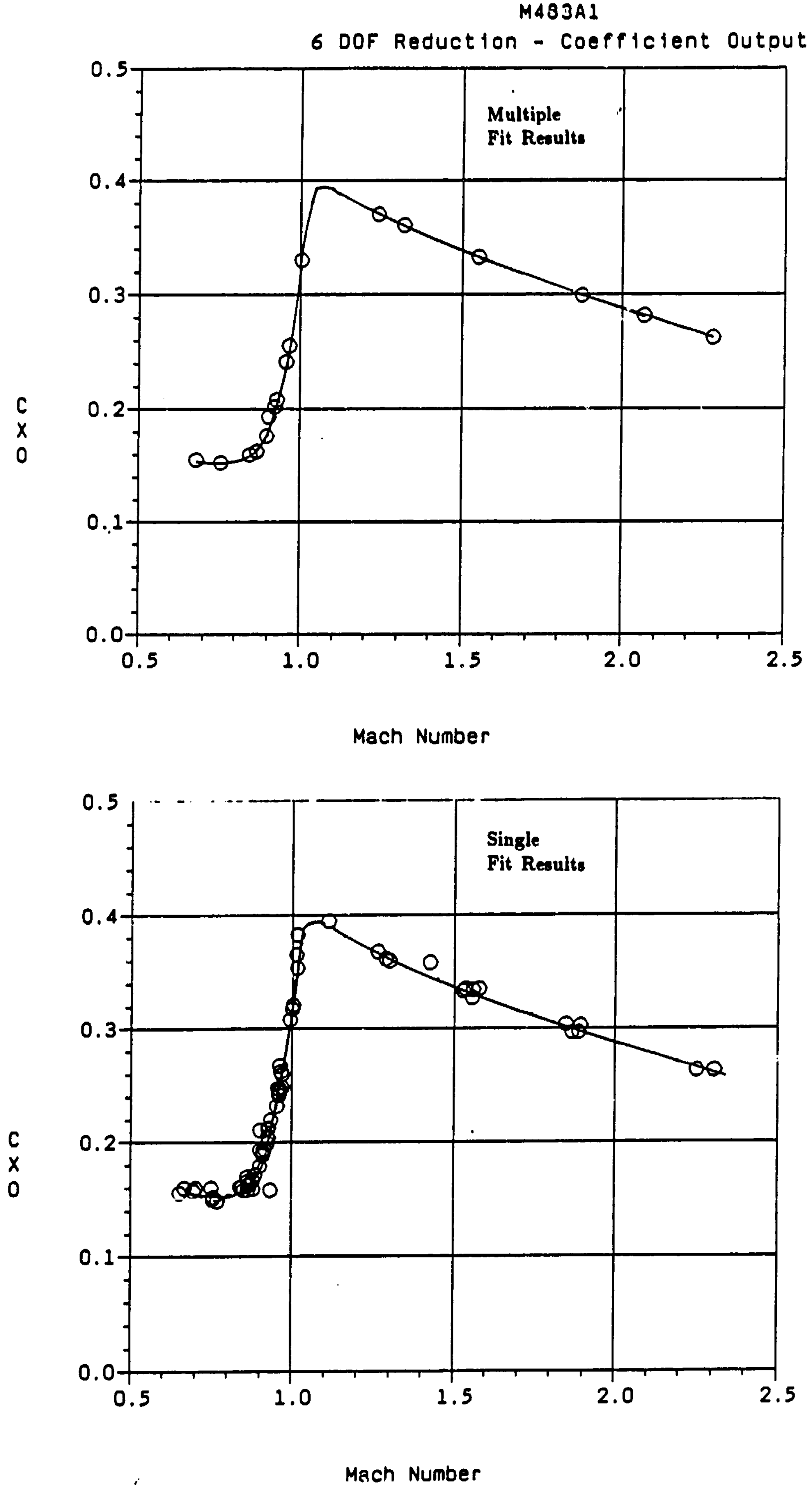
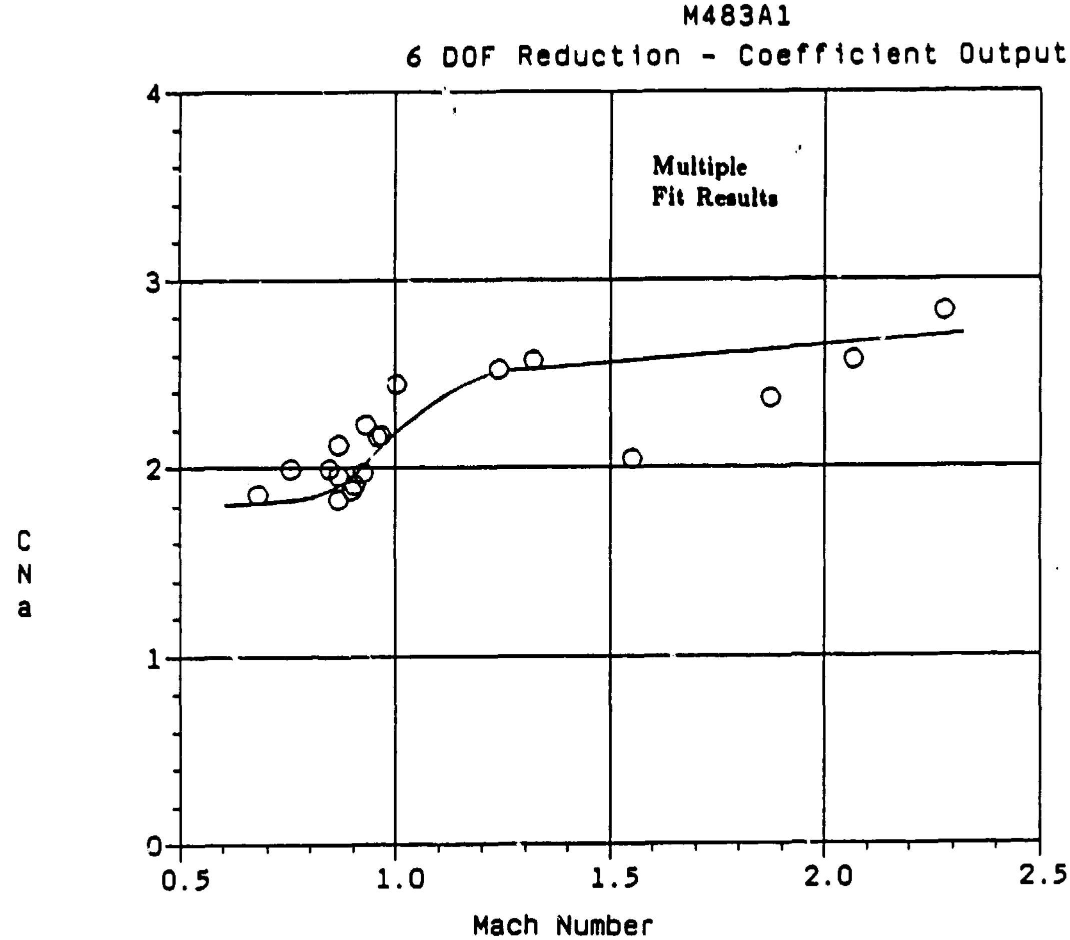


Figure 2. Axial Force Coefficient vs Mach Number



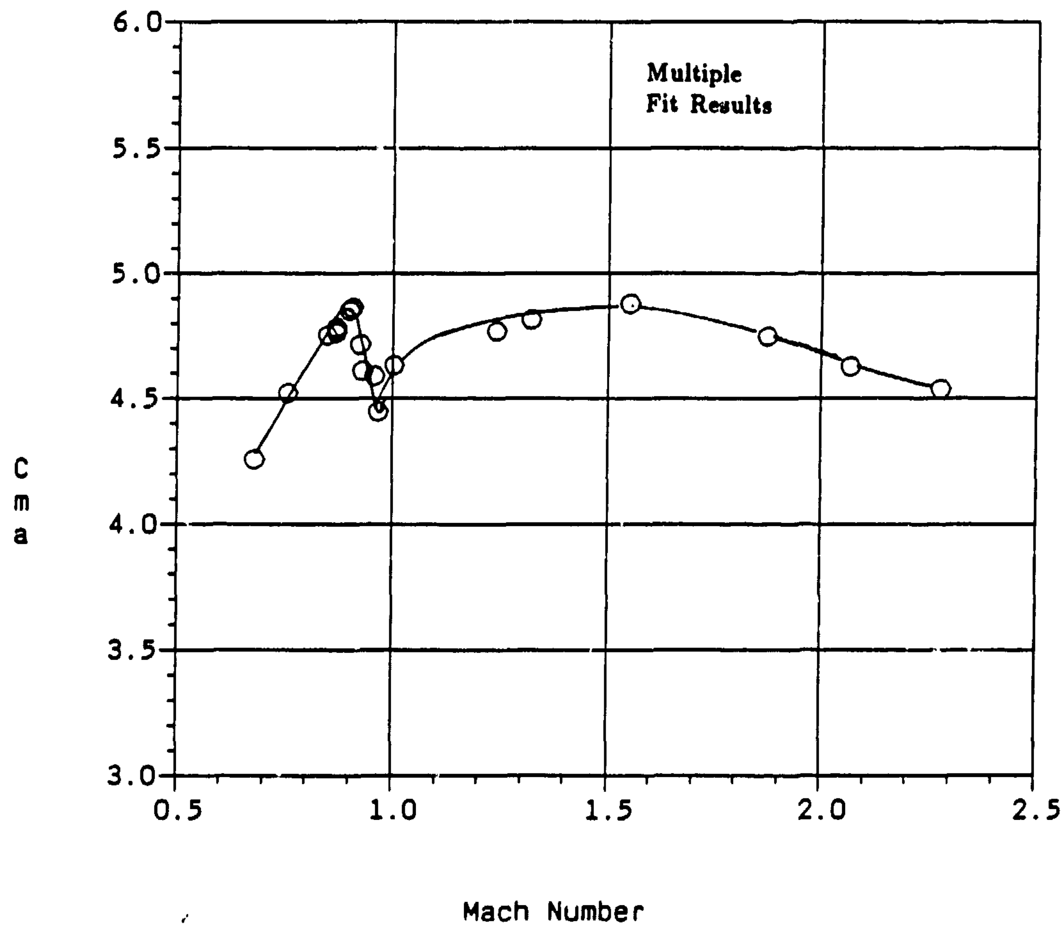


Figure 3. Normal Force and Pitching Moment Coefficients vs Mach Number

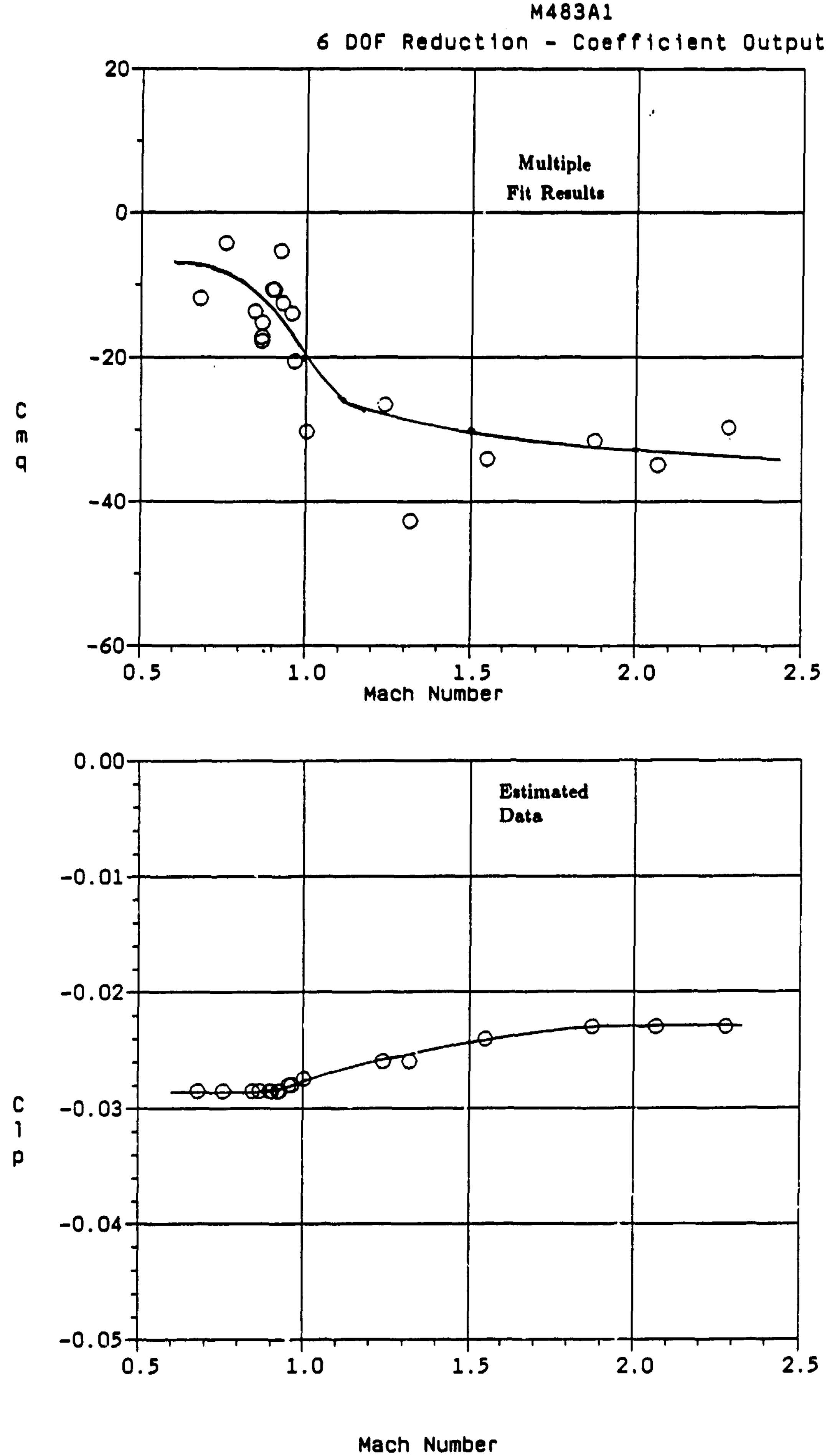


Figure 4. Pitch Damping and Spin Damping Coefficients vs Mach Number

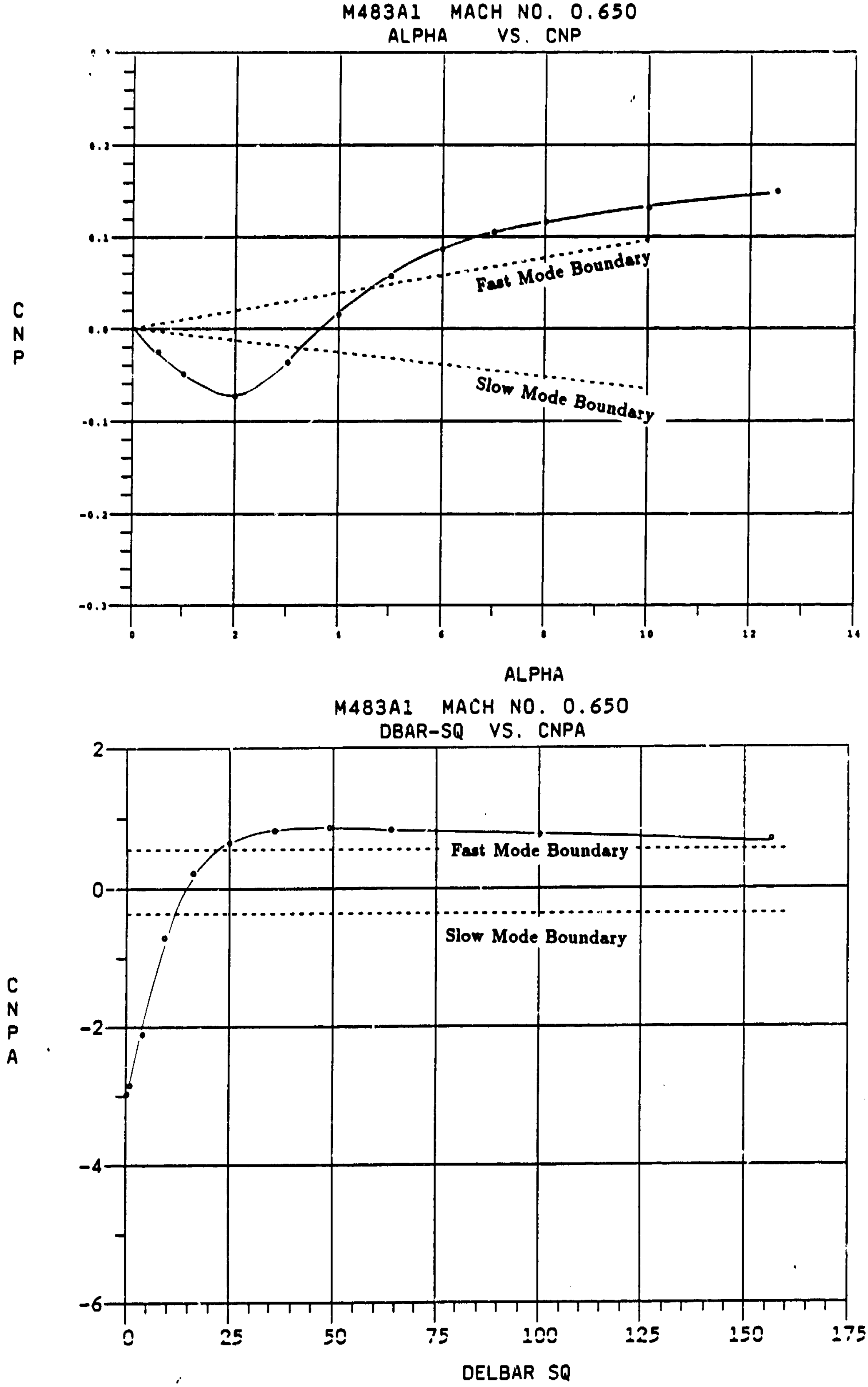


Figure 5. Magnus Moment Coefficients vs Angle of Attack at Mach No. 0.65

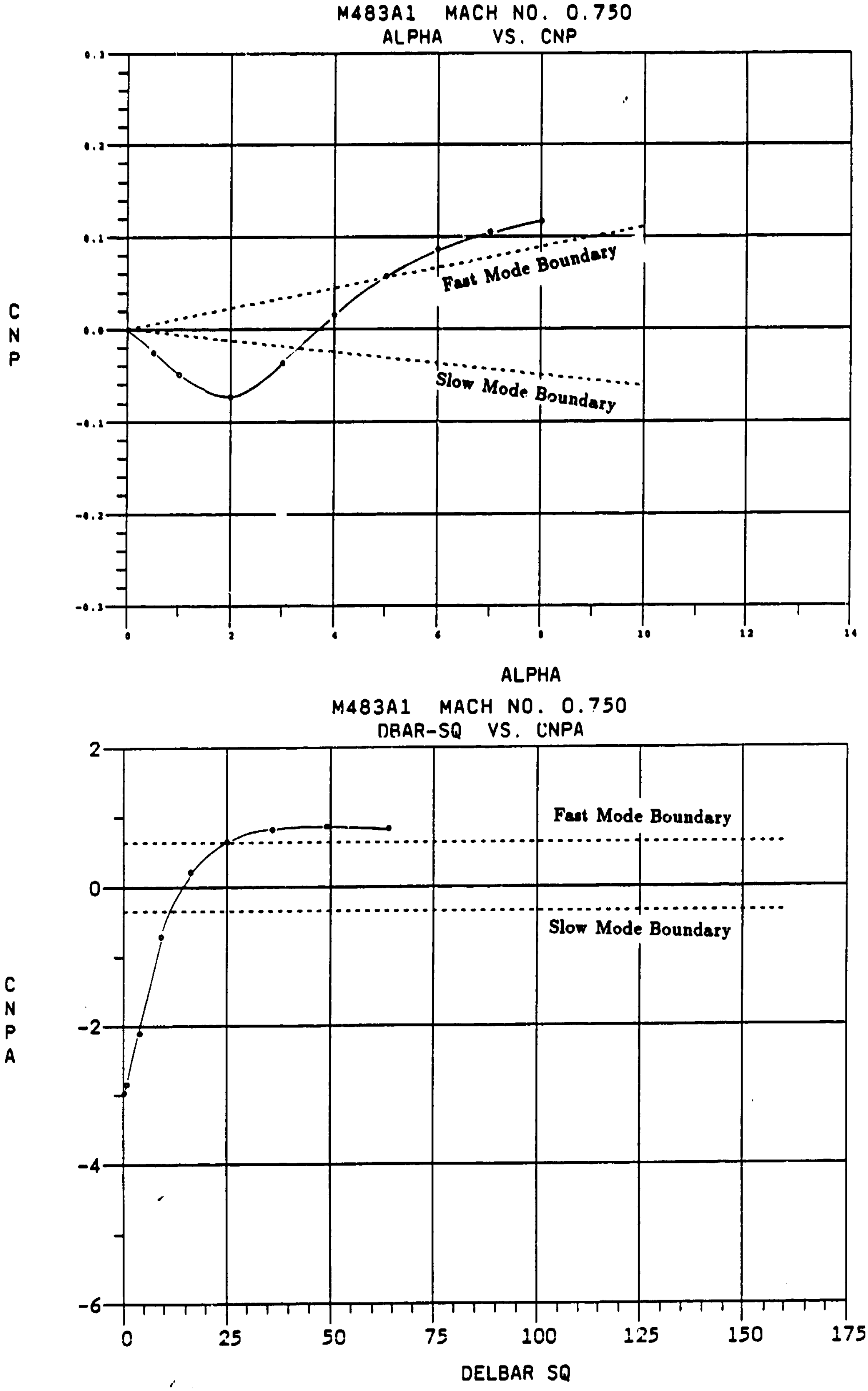


Figure 6. Magnus Moment Coefficients vs Angle of Attack at Mach No. 0.75

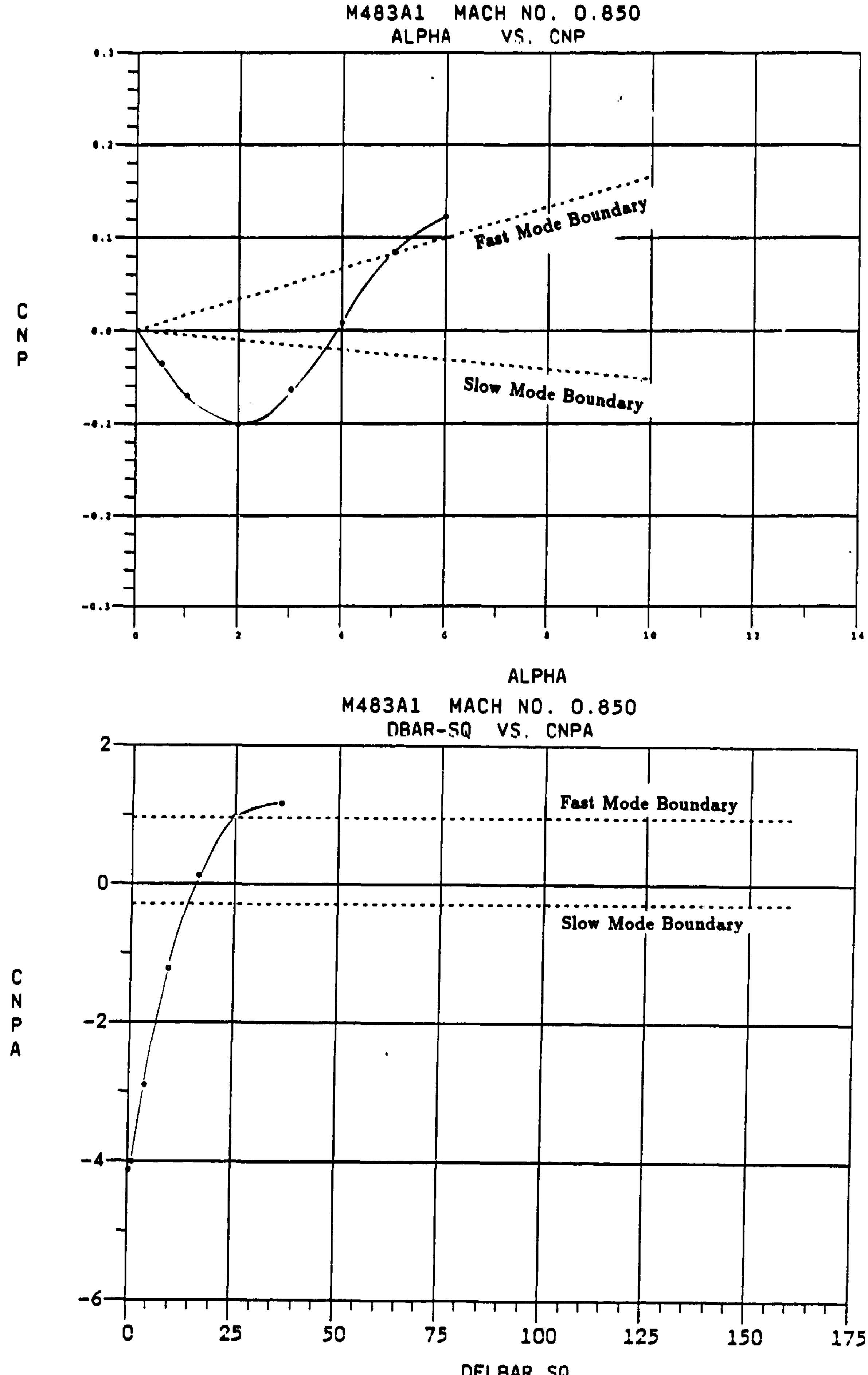


Figure 7. Magnus Moment Coefficients vs Angle of Attack at Mach No. 0.85

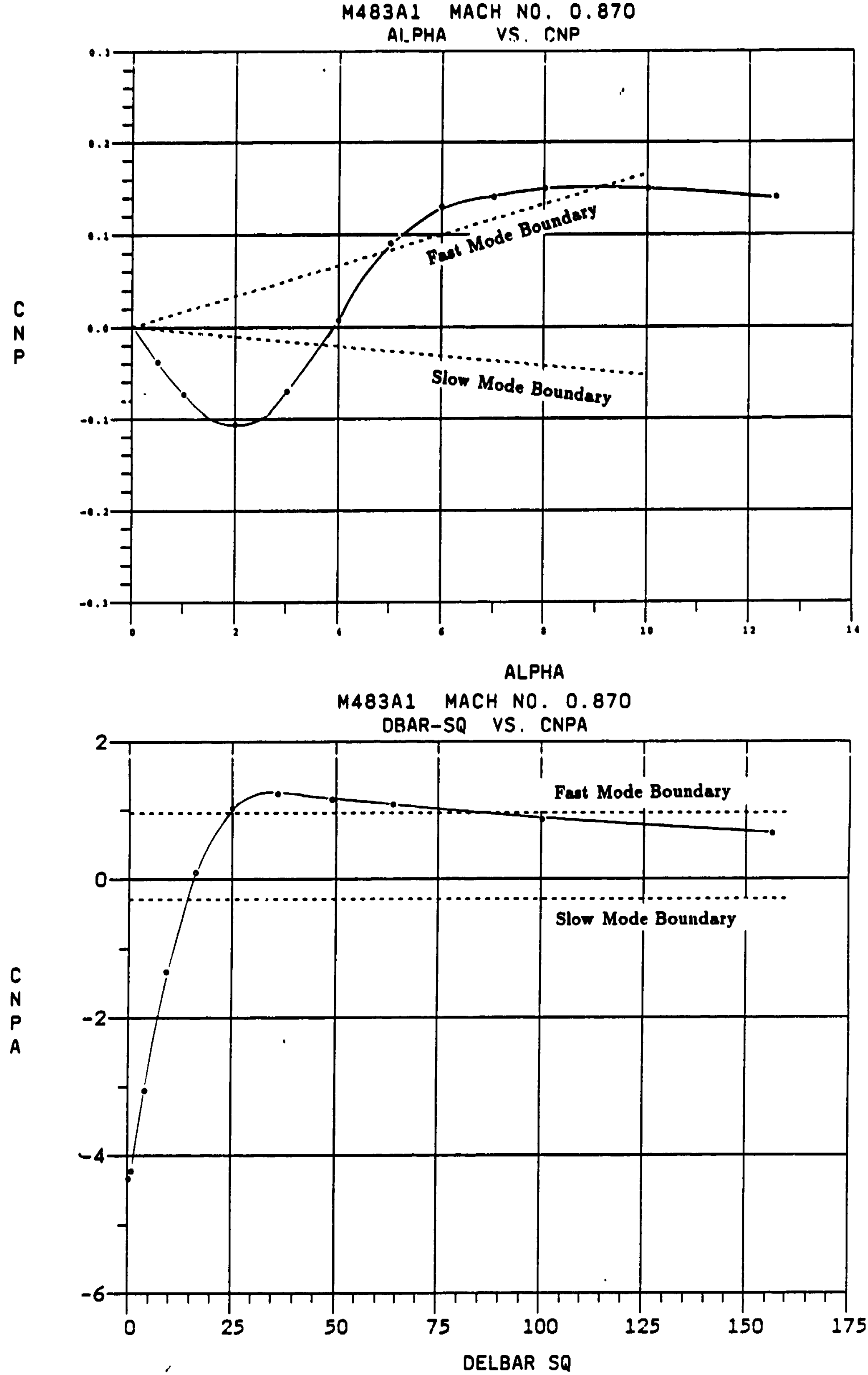


Figure 8. Magnus Moment Coefficients vs Angle of Attack at Mach No. 0.87

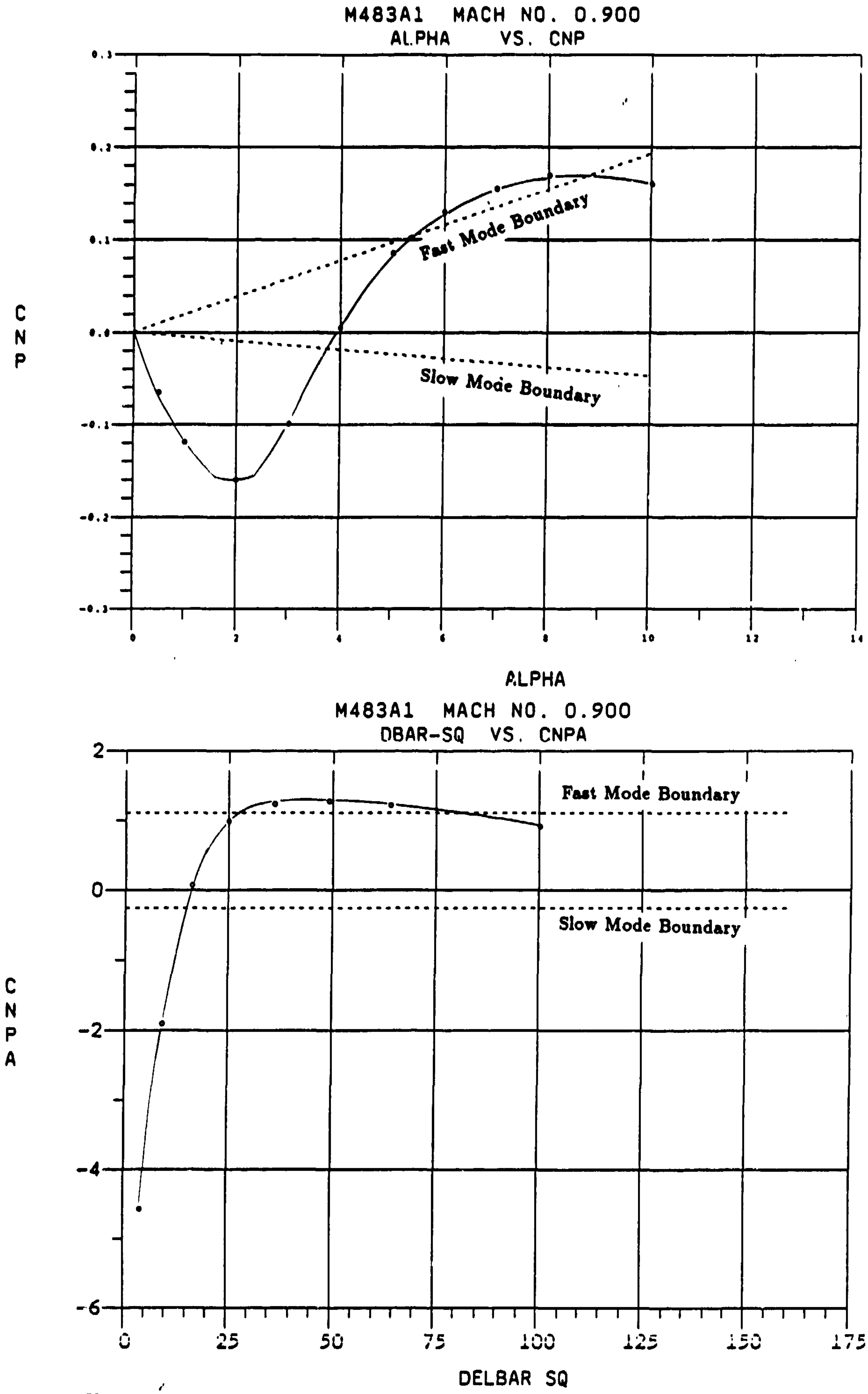


Figure 9. Magnus Moment Coefficients vs Angle of Attack at Mach No. 0.90

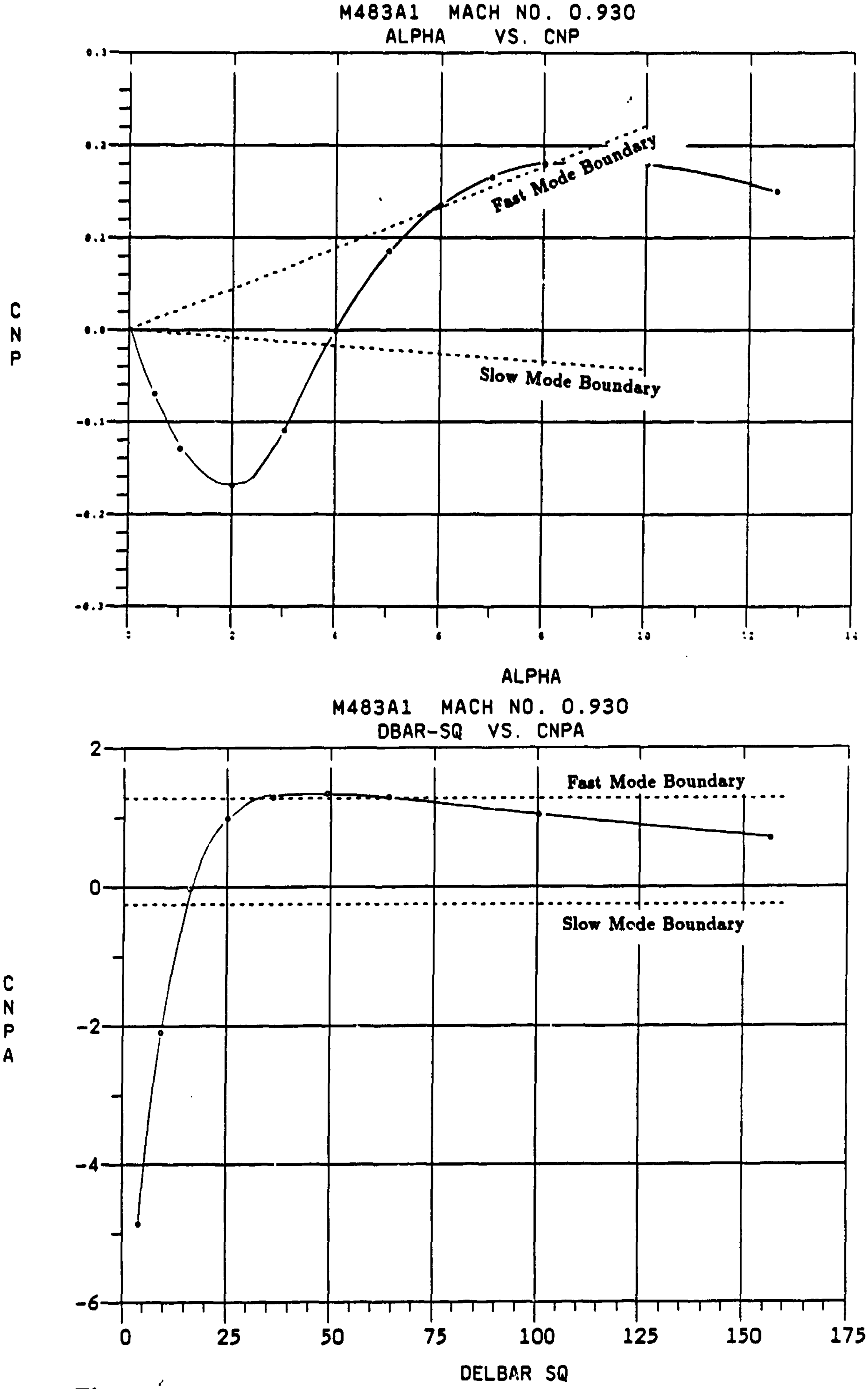


Figure 10. Magnus Moment Coefficients vs Angle of Attack at Mach No. 0.93

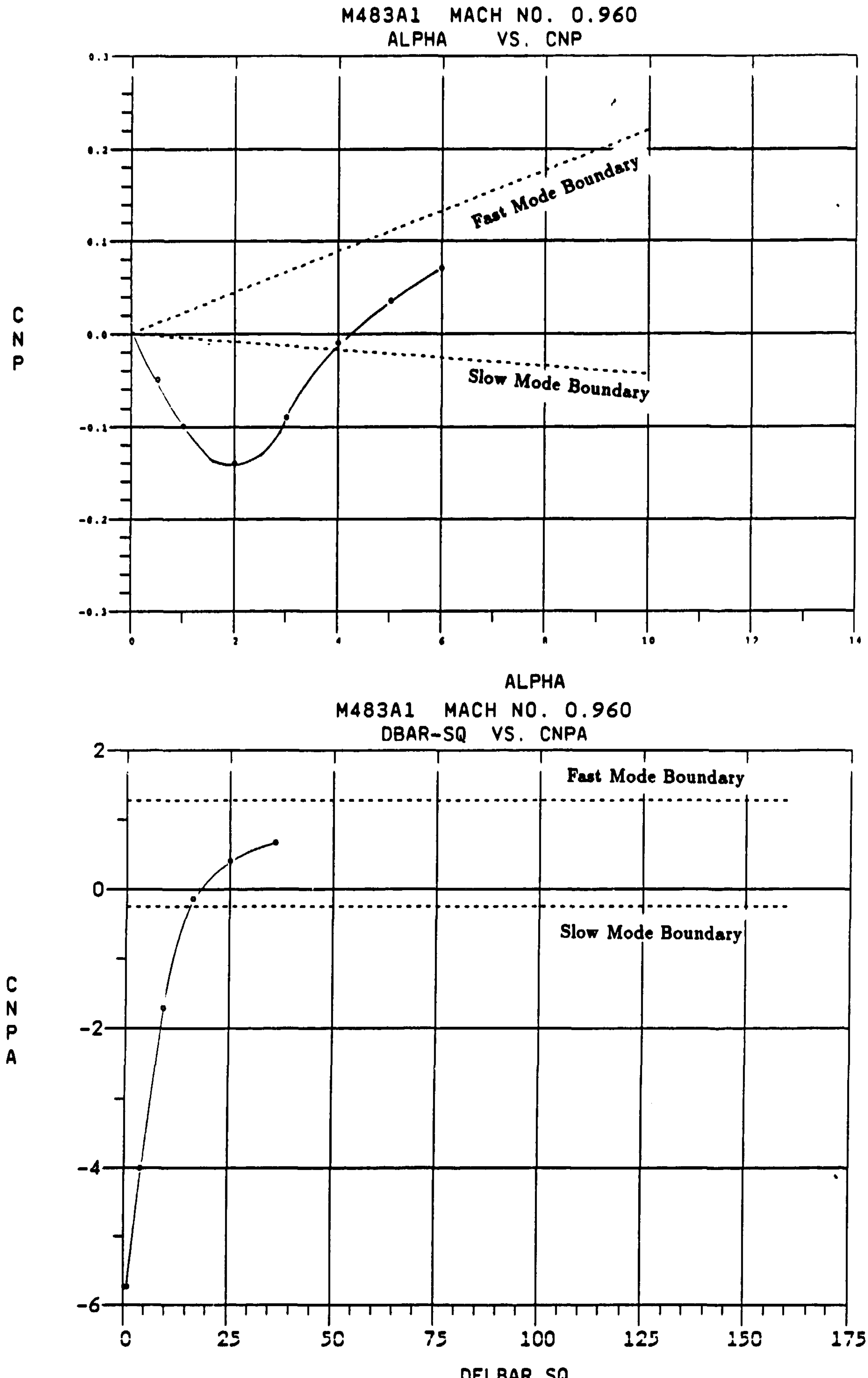
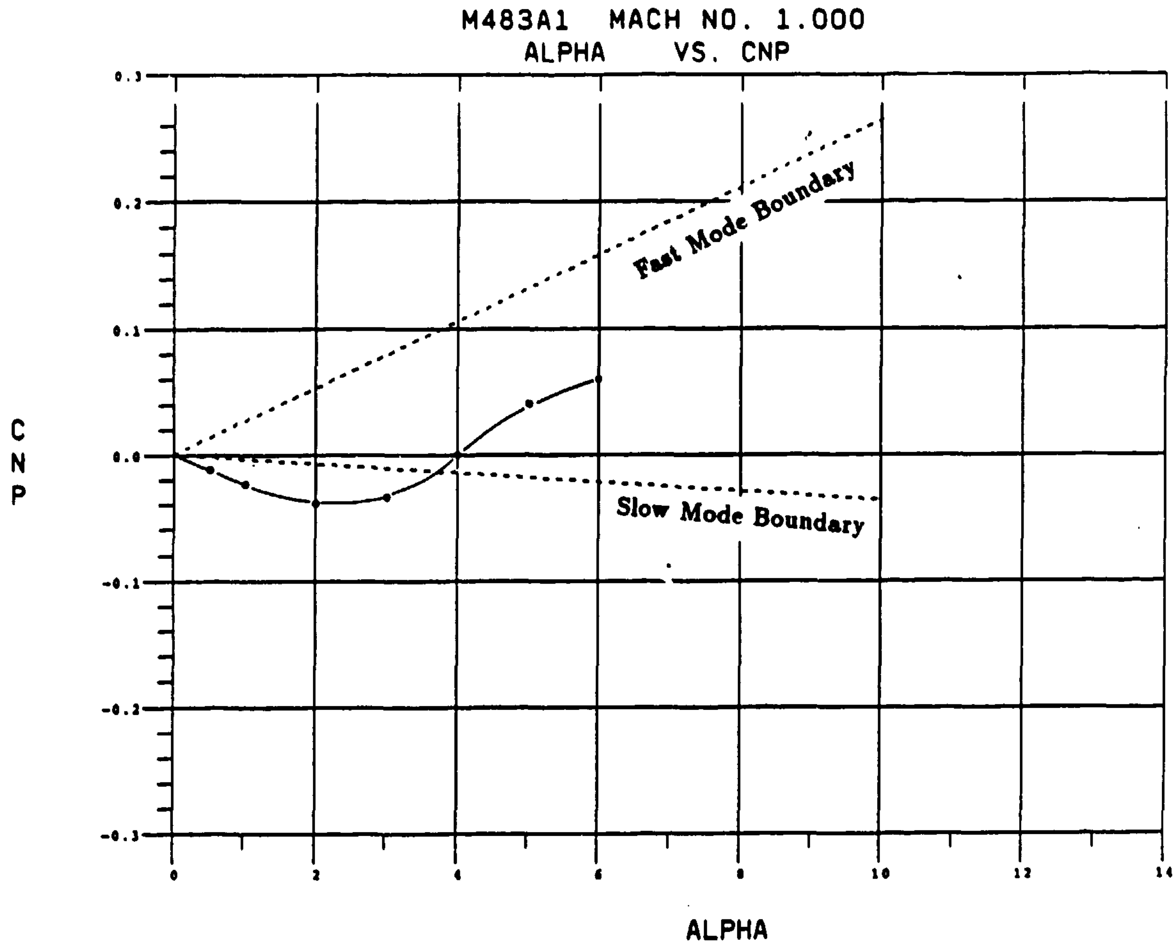


Figure 11. Magnus Moment Coefficients vs Angle of Attack at Mach No. 0.96



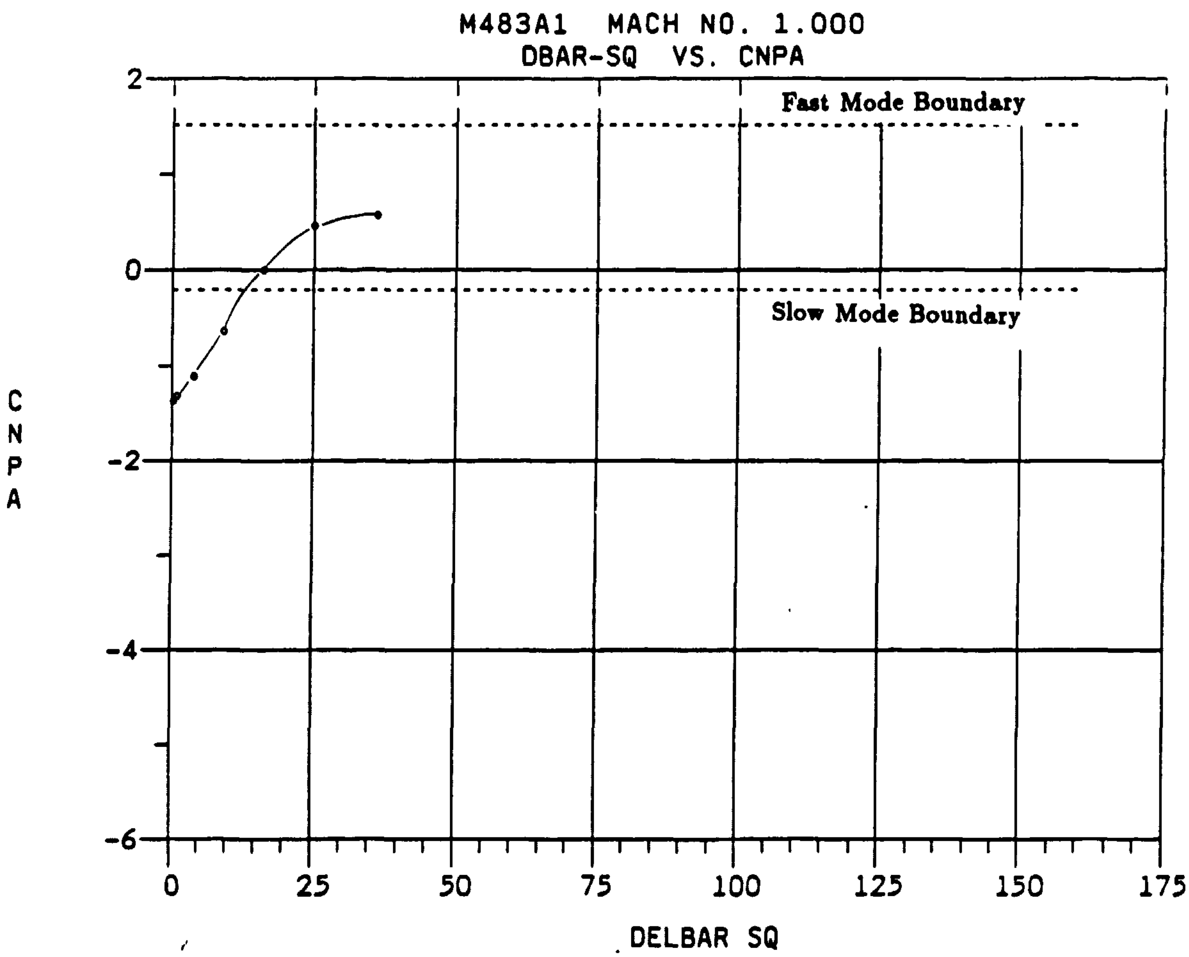
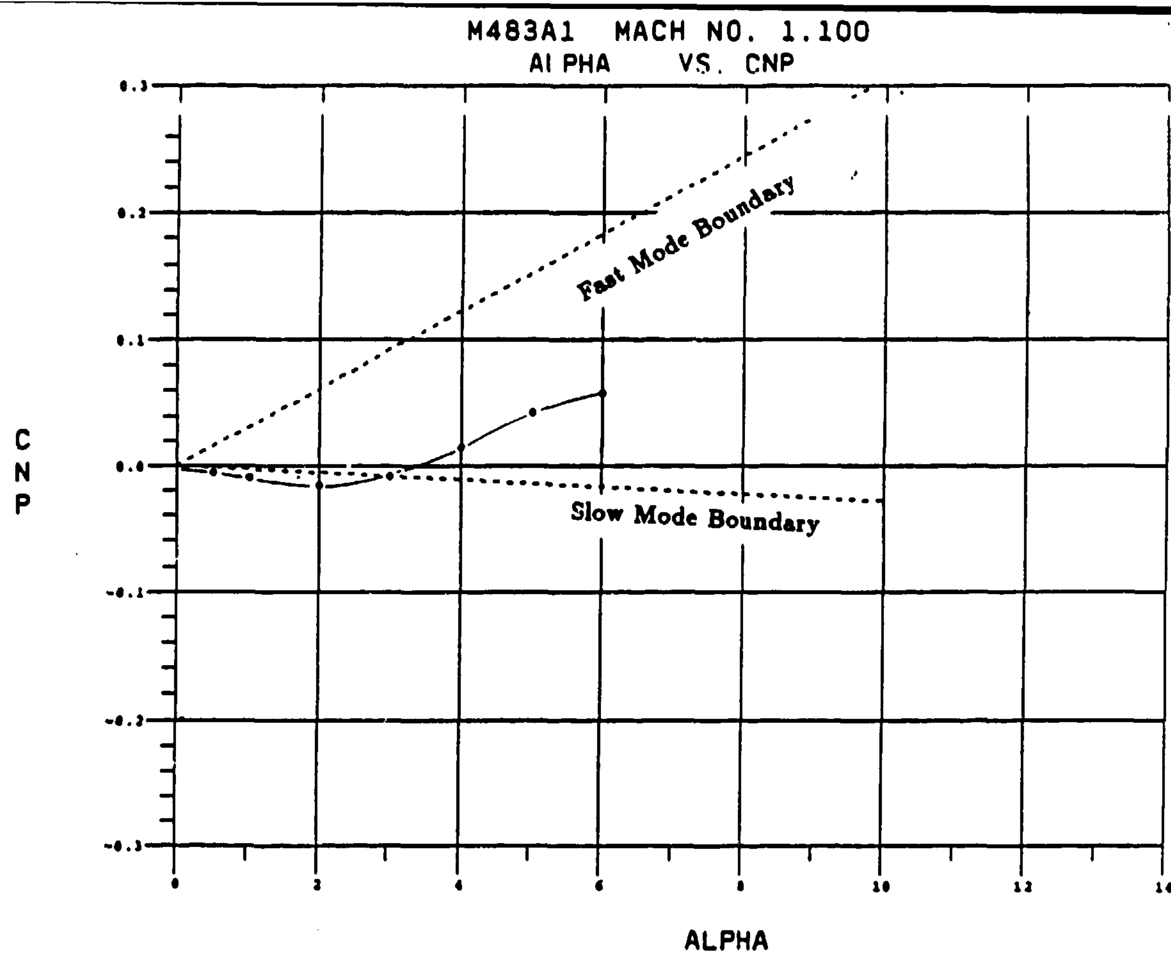


Figure 12. Magnus Moment Coefficients vs Angle of Attack at Mach No. 1.00



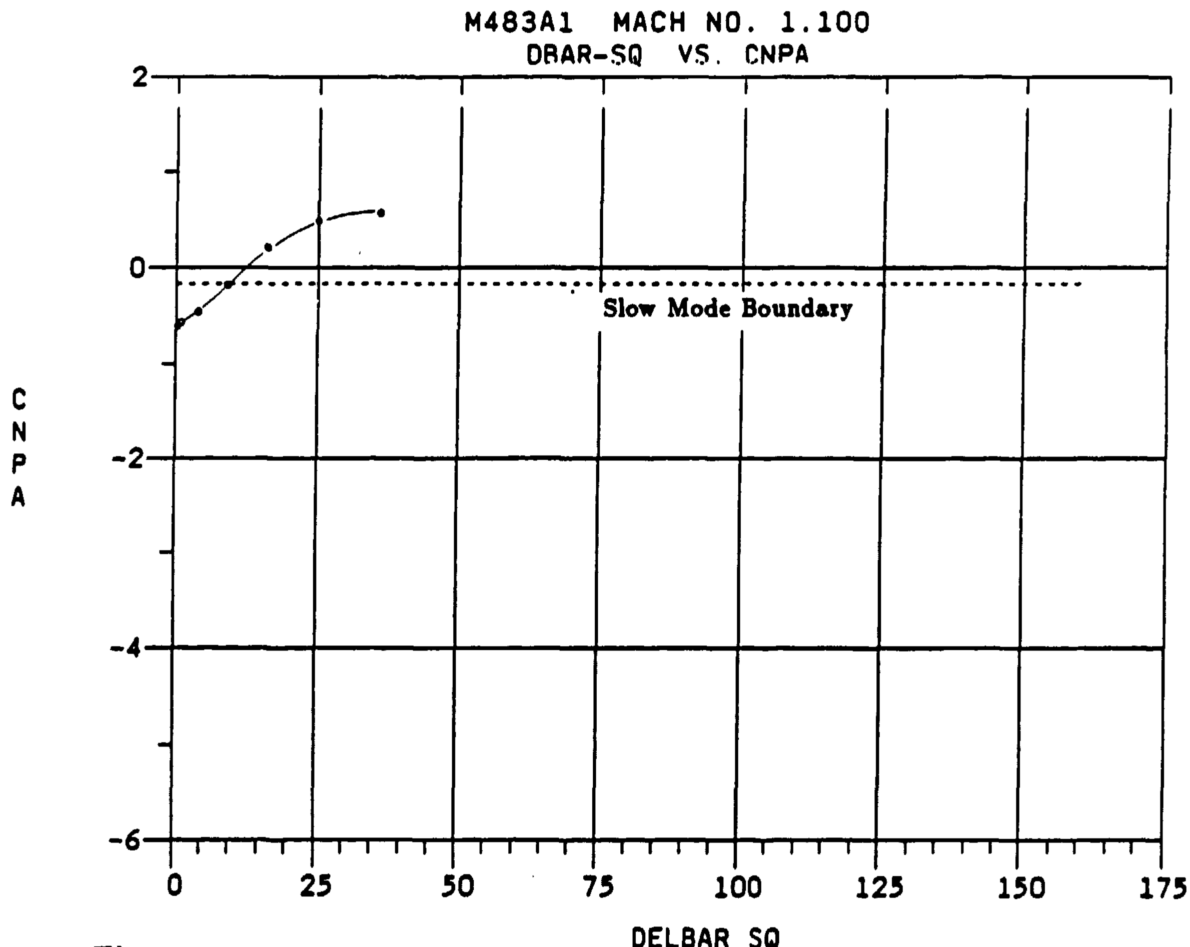


Figure 13. Magnus Moment Coefficients vs Angle of Attack at Mach No. 1.10

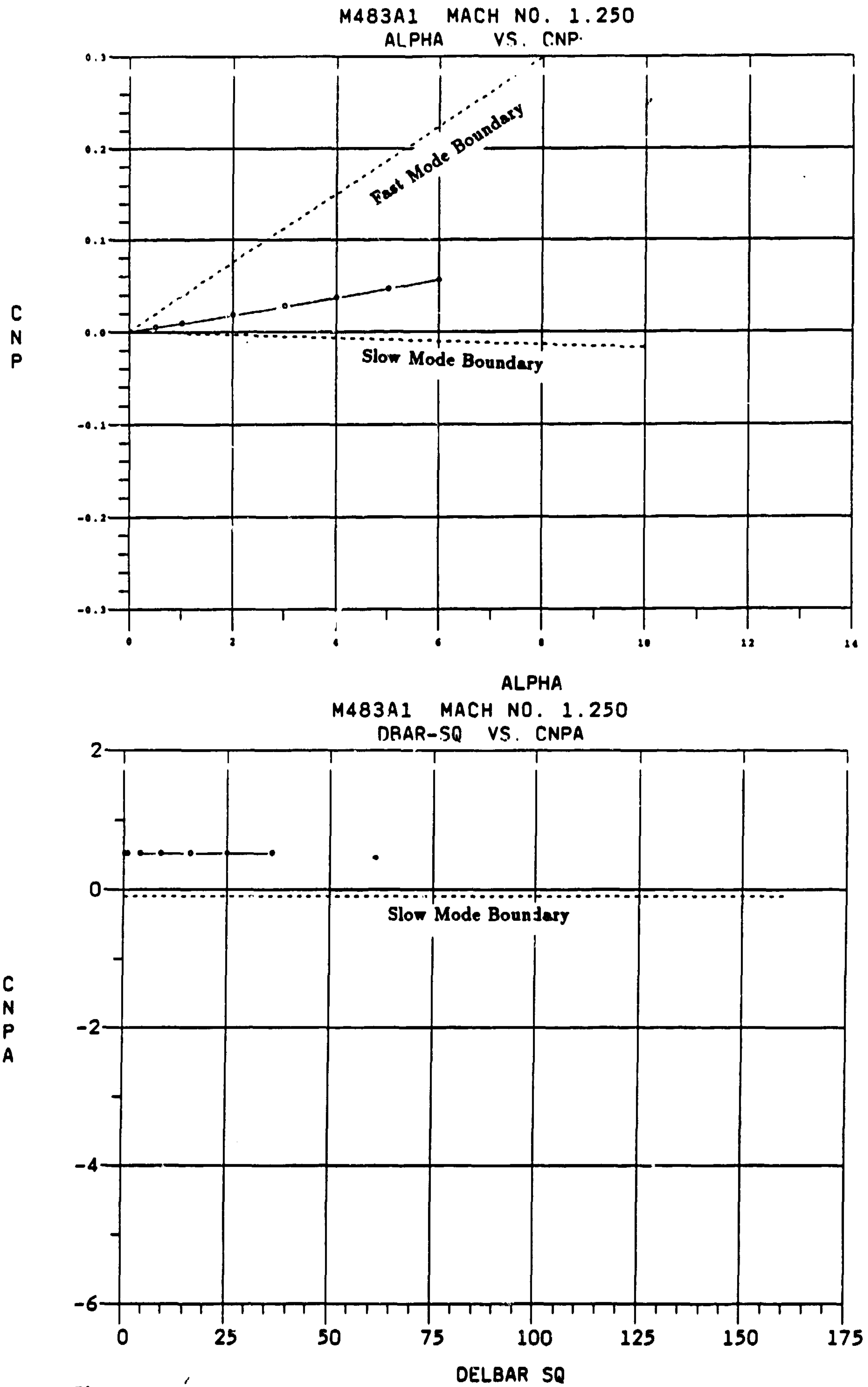


Figure 14. Magnus Moment Coefficients vs Angle of Attack at Mach No. 1.25

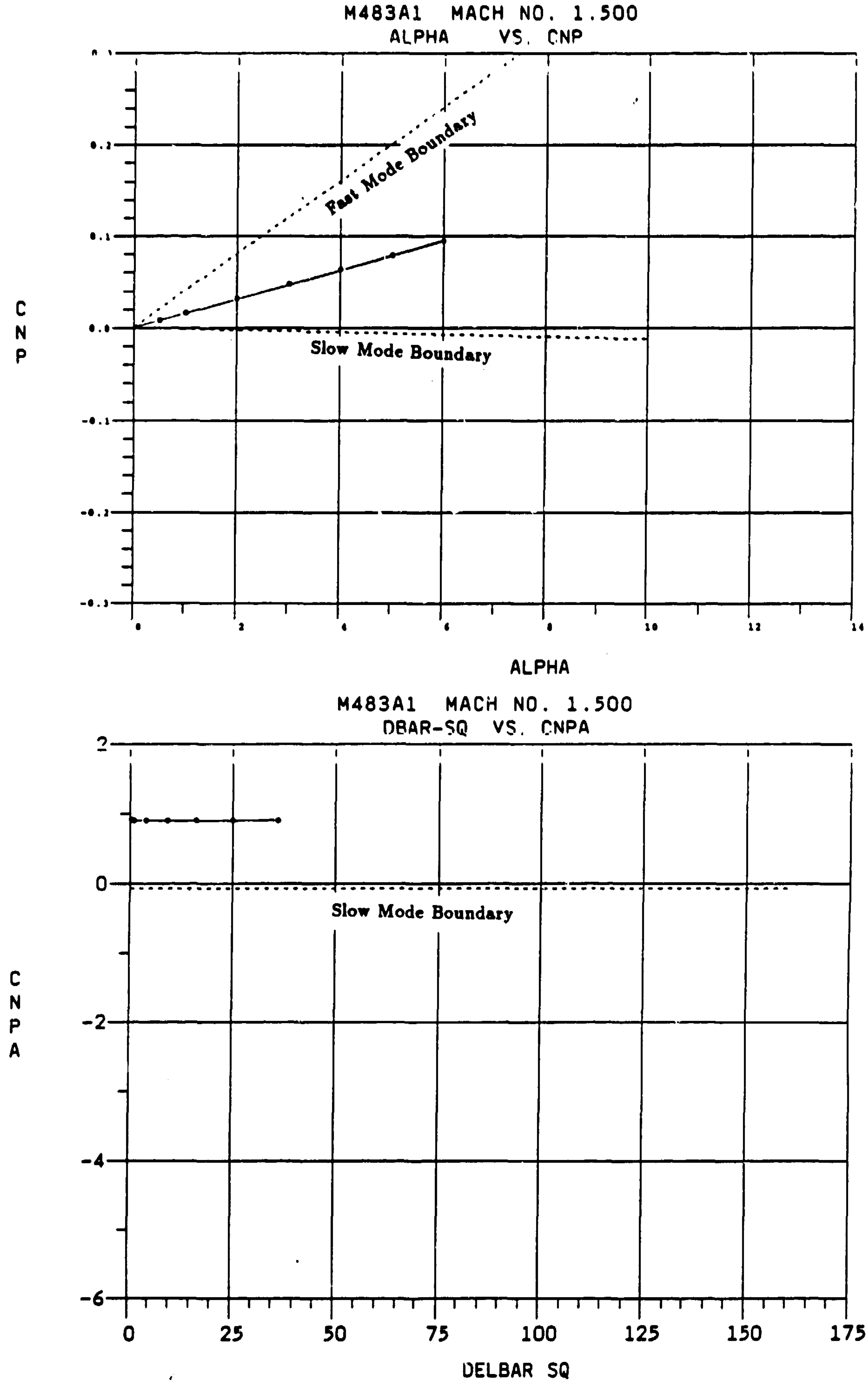


Figure 15. Magnus Moment Coefficients vs Angle of Attack at Mach No. 1.50

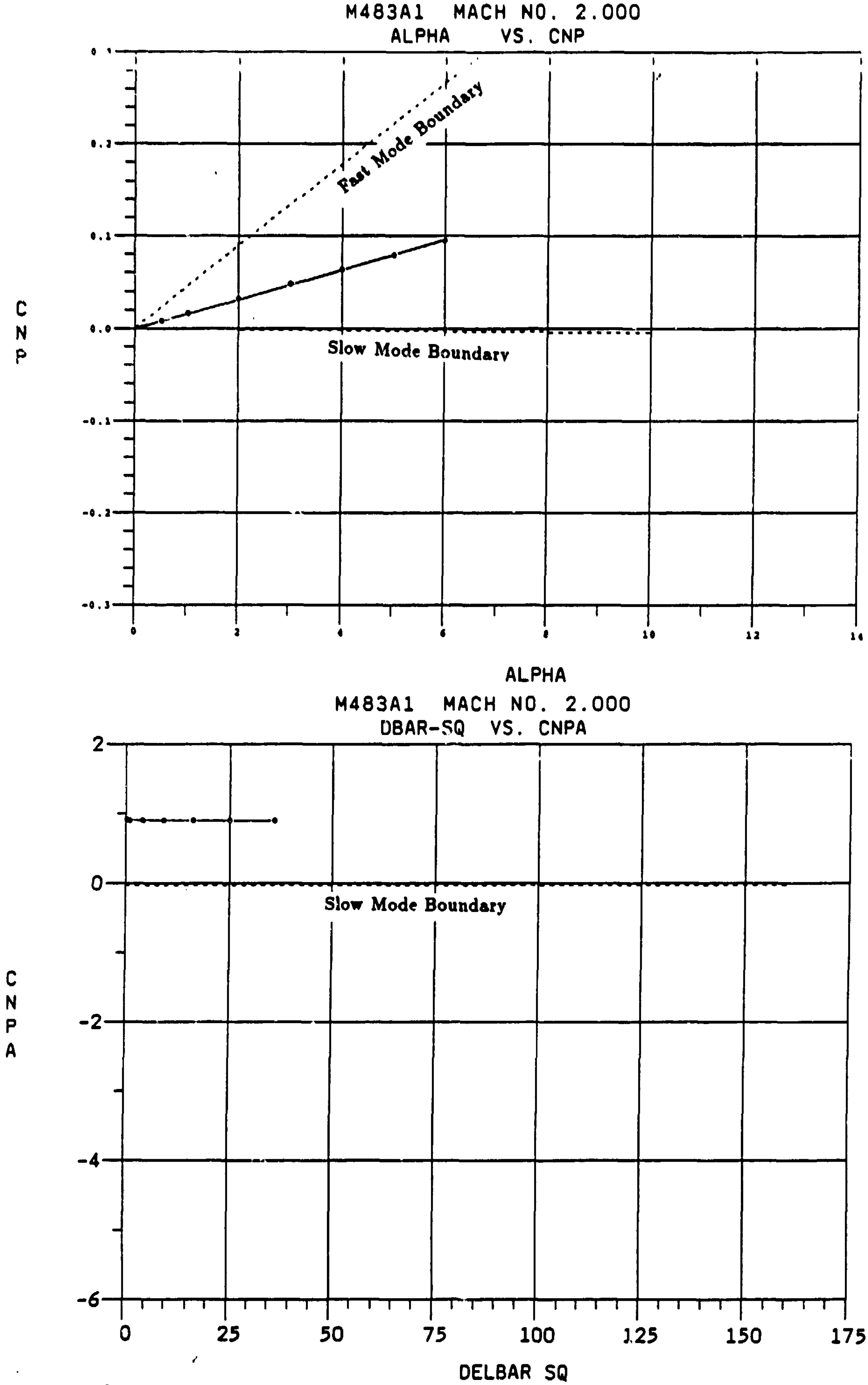


Figure 16. Magnus Moment Coefficients vs Angle of Attack at Mach No. 2.00

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List of Symbols

A	$\pi d^2/4$, reference area
C_X	$\|axial\ force\| / [(1/2)\rho A V^2]$
C_{Y_p}	$\pm\|Magnus\ force\|/[(1/2)\rho A V^2 (pd/2V))]$
C_N	$\pm\|normal\ force\| / [(1/2)\rho A V^2]$
CPN	center of pressure of the normal force (calibers from the nose)
C_{ℓ_p}	$\pm\|roll\ damping\ moment\| / [(1/2)\rho A d V^2 (pd/(2V))]$
C_{n_p}	$\pm\|Magnus\ moment\| / [(1/2)\rho A d V^2 (pd/(2V))]$
C_{m_q}	$\pm\|damping\ moment\ sum\| / [(1/2)\rho A d V^2 (qd/2V))]$
C_m	$\pm\|static\ moment\| / [(1/2)\rho A d V^2]$
d	reference length: the projectile diameter
I_x, I_y	the projectile's axial and transverse moments of inertia
m	projectile mass
M	Mach number
p, q, r	components of the projectile's angular velocity
S_g	The gyroscopic stability factor, gyroscopic instability occurring when $0 < S_g < 1$
t	time
u, v, w	projectile velocity components
V	projectile velocity
X, Y, Z	range coordinates, a right-handed system with X positive down-range Y positive left and Z positive upward.
$\bar{X}$	$\int V\, dt$, arclength along the trajectory
$\bar{\alpha}$	the total angle of attack, $\arccos(u/V)$

$\bar{\delta^2}$	mean-squared yaw: $\geq K_F^2 + K_S^2$
λ_F, λ_S	damping rates of the yaw fast and slow arms
ρ	air density

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