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AUGUST 1959

SOME INSTABILITY PROBLEMS WITH RE-ENTRY SHAPES (U)

L. C. MacALLISTER

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(10) Leonard C. MacAllister

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BALLISTIC RESEARCH LABORATORIES

MEMORANDUM REPORT NO. 1224

LCMacAllister/djp
Aberdeen Proving Ground, Md.
August 1959

SOME INSTABILITY PROBLEMS WITH RE-ENTRY SHAPES (U)

(CONFIDENTIAL) ABSTRACT

Models of certain ICBM and IRBM nose-cone configurations have shown limit cycle yawing motions in low supersonic and high subsonic flight. For a given configuration the amplitudes of these limit cycles vary with Mach number, and possibly with Reynolds number. In general, the configurations exhibit limit cycles because of nonlinear damping moments, particularly in high subsonic flight.

This paper presents the more interesting of these phenomena as observed by model firings in the free flight spark ranges of Ballistic Research Laboratories. These phenomena are correlated, when possible, with variations in flow phenomena.

SYMBOLS

C_D - Drag Coefficient $\quad \dfrac{\text{Drag}}{\frac{\rho V^2}{2}\ \frac{\pi d^2}{4}}$

C_{L_α} - Lift Curve Slope $\quad \dfrac{\text{Lift}}{\frac{\rho V^2}{2}\ \frac{\pi d^2}{4}\ \alpha}$

C_{N_α} - Normal Force Slope $\quad \dfrac{\text{Normal Force}}{\frac{\rho V^2}{2}\ \frac{\pi d^2}{4}\ \alpha}$

C_{M_α} - Static Moment Slope $\quad \dfrac{\text{Static Moment}}{\frac{\rho V^2}{2}\ \frac{\pi d^3}{4}\ \alpha}$

C_{M_q} - Damping moment coefficient due to cross angular velocity $\quad \dfrac{M_{(q)}}{\frac{\rho V^2}{2}\ \frac{\pi d^2}{4}\ \left(\frac{qd}{2V}\right)}$

$C_{M_{\dot\alpha}}$ - Damping moment coefficient due to rate of change of yaw $\quad \dfrac{M_{(\dot\alpha)}}{\frac{\rho V^2}{2}\ \frac{\pi d^2}{4}\ \left(\frac{\dot\alpha d}{2V}\right)}$

M - Mach No.

ρ - Air density $\quad (\bar{\ }) $ - Conjugate

d - Diameter* $\quad (\ ')$ - $\dfrac{d}{d\,z}$

λ - $\beta + i\,\alpha$ (complex angle of yaw)

V - Missile velocity

q - Missile cross angular velocity

α^{-2} - $\dfrac{\alpha \quad 2\,dz}{dz}$

δ_t - Trim angle

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* The basic dimension for the sphere-cone is the maximum diameter while for the cylinder-flare the cylinder diameter is used.

INTRODUCTION

The components of ballistic missiles that re-enter the earth's atmosphere encounter several extreme conditions that tend to set apart the problems of these re-entry shapes from those of the conventional projectiles of the past. In particular, the re-entry shapes must survive extremely high temperatures for part of their trajectories, and must have adequate stability over a very wide range of Mach numbers (1). The critical design considerations that would permit a missile to survive high temperatures and hypersonic speeds frequently yield a missile that is ill suited to fly at transonic or subsonic speeds.

Almost all of the re-entry configurations tested at the Ballistic Research Laboratories have had, at small yaws, static or dynamic instability over at least one small band of Mach numbers between $M = 1.5$ and $M = 0.7$. In actual flight, however, most missiles can successfully traverse these regions by one of two methods. Either the time spent in the unstable region is too short for anything serious to develop; or, the moment system is nonlinear in such a way that, although the model is unstable at zero yaw, it stabilizes at some reasonable angle. This latter case is usually termed a "limit cycle" phenomenon (7). The model's yaw develops into a steady state circular, or near circular, motion of relatively fixed amplitude.

Generally, the test of a re-entry shape performed at the Ballistic Research Laboratories is aimed at the solution of some specific problem. And unfortunately, because of the development schedule, there is seldom time to obtain a complete picture of the aerodynamic behavior of the missile. In at least two cases, however, the large volume of data, or the sharp definition of the behavior, was sufficient to permit an adequate description of the aerodynamic properties of the model and of its limit cycle behavior.

The two shapes tested are shown in Figure 1. The first is a fairly pointed sphere-cone; the second, a blunted cylinder with a stabilizing skirt. The data for these models exhibited an unusual similarity for such dissimilar shapes. In addition, the data indicated that the moment system was more complex than generally formulated.

This report is concerned with the aerodynamic behavior of these two shapes, the similarities in their behavior, and the implications of the observed motions with regard to the aerodynamic moment system.

TEST

It is not pertinent to burden the reader with the details of the many individual tests that led to the data presented here, but it is necessary that some of the features of free flight range testing be covered since they bear on the nature of these data (2,3).

Basically the range test records the yawing motion and the transverse motion of the center of mass of the model as it flies through the range. The motions are recorded at discrete points as functions of distance along the trajectory. The resultant data are fitted to infer the aerodynamic forces and moments which acted on the model in flight to produce the observed motion. Two methods are generally available. The first, the classic one, is to obtain a closed solution for the differential equation of motion based on constant aerodynamic derivatives, and to fit the solution to the observed motions by a method of first approximation and successive differential corrections. This method utilizes a digital computer (4). The second method is to presume the proper differential equation and attempt to fit the observed motions by repeated trial integrations on an analogue computer (5).

The digital procedure is, of course, dependent on the underlying assumptions made in the solution. The basic computing procedure is more or less without error, however, and digital computers are fast and relatively tireless, so that a large number of iterations can be employed. Frequently fairly good fits, in the numerical sense, can be obtained after many iterations although the variation of the fitting parameters indicates that the theory's assumptions have been violated. In certain of these cases, when the force and moment derivatives are quadratic functions of yaw amplitude alone, it has been shown (6) that the output of the digital fit can be properly interpreted in terms of the true moment variation. Hence, under these conditions, it is feasible and proper to utilize the linearized fitting system on nonlinear data.

The advantage of the analogue technique lies in the fact that various and quite complicated forces and moments can be postulated in the differential equation in an attempt to fit an observed motion. Three major difficulties are, however, attendant on the procedure. In general, only one or two forces or moments can be permitted to be quite nonlinear at a time, or the error build-up from the nonlinear computing elements in the machine becomes prohibitive. The analogue procedure also requires that an operator visually determine the relation between the integral curve and the data points and judge which parameters to change to improve the fit. The last difficulty is that with nonlinear computing elements in the system the repeatability of runs is not precise.

The data presented are generally from the digital fitting procedures, although some of the yawing motions shown are attempts to fit some of the more complex motions by analogue techniques.

DISCUSSION OF RESULTS

Since the predominant interest in tests of this nature is the static and dynamic stability of the models, only those aerodynamic factors having a strong bearing on these properties will be presented. The aerodynamic derivatives of primary importance in the stability of missiles are the static moment slope, C_{M_α}, and the derivatives that enter into the linearized dynamic stability conditions for a nonspinning missile: the normal force slope, C_{N_α}, the damping derivatives, $C_{M_q} + C_{M_{\dot{\alpha}}}$, and C_D, the drag coefficient.

In the case of wind tunnel tests, C_{L_α} or C_{N_α}, and CP_N are generally presented. In the case of range tests there is a hierarchy of accuracy of determination of the following order; $C_{M_{\alpha_{CG}}}$ (1%), the damping exponent* (10%), and C_{N_α} (10%). Hence, for static stability, C_{M_α} will be considered; and for dynamic stability, since total damping of a model is not necessarily descriptive, C_{N_α} and $C_{M_q} + C_{M_{\dot{\alpha}}}$. Unfortunately both these terms appear in the

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* The damping exponent is proportional to $\left[C_{N_\alpha} - 2\,C_D - k_2^{-2}(C_{M_q} + C_{M_{\dot{\alpha}}})\right]$, where k_2 is the transverse radius of gyration.

total damping exponent and are separated out only by an independent determination of C_{N_α}*. Hence, $C_{M_q} + C_{M_{\dot\alpha}}$ inherits the error of the damping exponent and the error of the normal force slope.

Aerodynamic data: sphere-cone.

The variation of C_{M_α} with Mach number is given in Fig. 2. A zero yaw variation and the trend for a yaw amplitude of about three degrees are shown. The behavior is generally as follows: for the smallest yaw data there is a decrease in stability as Mach number increases from 0.5 to 0.8, a sharper decrease to a minimum at M = 1.15, and then the stability margin increases with increasing Mach number. The variations with yaw are large; however, the indicated value of C_{M_α} for zero yaw at M = 0.6 is -0.25, while for a yaw amplitude of about three degrees it is -0.15, a sharp decrease. This effect is shown in Figure 3, which contains the C_{M_α} versus yaw squared data for Mach numbers less than 0.8, and for M = 1.2 where there were sufficient data. The stability margin changes very rapidly with increasing yaw amplitude up to a level that represents about five degrees of true yaw. The trend is destabilizing. Above this level there is a weaker destabilizing trend with increasing yaw. Within the data scatter both trends appear linear with squared yaw. The transition appears sudden, with no clearly defined transitional curve between the two linear vaiations.

The variation of the normal force derivative, C_{N_α}, with Mach number and yaw appeared negligible, a value on the order of 2 being maintained.

The damping derivatives are given as a function of Mach number in Figure 4. For small yaws, there are violent variations with Mach number, transonically, and with yaw level (Figure 5). At a Mach number of about 1.2 and for Mach numbers of less than 0.8, $(C_{M_q} + C_{M_{\dot\alpha}})$ is destabilizing at zero yaw (values of yaw on the order of three to four degrees appeared adequate to yield a neutral value generally). It should be re-noted that the basic data reduction procedure postulates that no appreciable change of the derivatives occurs within

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* The value of C_D is also required but since it is determined to approximately 0.1% and is generally small it is not relevant to this qualitative discussion and will not be further considered.

a given test flight. In view of the indicated variations of $C_{M_q} + C_{M_{\dot{\alpha}}}$, this cannot be true in all cases and hence the derivatives, as determined, can hardly be considered as true point values as a function of yaw and Mach number.

A dependance on yaw is fairly well determined only for $M \doteq 1.2$ and for $M < 0.8$, and has the same general character at both speeds. $C_{M_q} + C_{M_{\dot{\alpha}}}$ is destabilizing at zero yaw and changes rapidly (in a stabilizing direction) with increase in yaw level for small yaws. At large yaws the stabilizing change of the derivatives continues, but is much milder.

The nonlinear characteristics of the damping properties lead to a condition where the yawing motion of the model is damped at some amplitudes of yaw* and divergent at others. The divergence occurs at small amplitudes and the damping at larger ones. The models seem to seek a neutrally damped condition between the two. The general motion, starting from small yaw, can be described as follows: any small yawing motion that results from the initial launching conditions diverges fairly rapidly and finally ends up in a nearly circular motion of fixed amplitude limits (Figure 6).

For the various models that were nearly homologous, and hence should have the same amplitude of yaw for zero damping, a plot (Figure 7) was made of the indicated line of zero damping as a function of yaw and Mach number. At the higher Mach numbers, and smaller stable yaws, the demarcation line between models that had slightly divergent exponents and those that had slightly damping exponents was quite clearly determined. At the lower speeds, with higher equilibrium yaws, there were fewer data points near the neutral state, hence there is more uncertainty as to the precise level. As a result the equilibrium level is shown as a band indicating the approximate degree of the uncertainty.

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* Amplitude of yaw may not be the only important factor.

Aerodynamic data: cylinder-flare

Although the test series on this shape was not as extensive as that on the sphere-cone, the properties were so definite that a relatively clear picture of the missile's aerodynamics was obtained. In point of fact, several minor variations of shape were tested but the gross similarity of the data was so great, as compared to the differences, that we shall consider a hypothetical model whose properties are the mean of those of the tested variations. As a result of limited data in the present case only the subsonic aerodynamic properties as a function of yaw amplitude will be discussed.

The static moment derivative, C_{M_α} *, is presented in Figure 8. The highest stability margin is at zero yaw level; this decreases with increased yaw until an amplitude representing about four degrees of true yaw is reached; thereafter the rate of change decreases markedly although the exact slope is not well determined.

Within a rather poor determination, there appeared to be no serious variation of C_{N_α} with yaw or Mach number, a value of about $C_{N_\alpha} = 7$ was observed.

The scatter of data for the damping derivatives, $C_{M_q} + C_{M_{\dot{\alpha}}}$, Figure 9, is considerable. This is in part due to considering all the model variations together. It seems clear that there is a very marked change in value from zero yaw to a value that is equivalent to about two degrees of true yaw; the damping being negative at zero yaw and improving with increasing yaw level. Above this level the sharp stabilizing trend ceases and the values appear to be essentially constant. The above situation appears to hold at all subsonic speeds except near $M = 0.9$. In this latter region the crossover to damping tendencies does not occur until considerably larger yaws, about 6 degrees.

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* It should be noted that the characteristic dimensions used for this shape are cylinder area and diameter.

These damping properties result in a limit cycle behavior with the amplitude characteristics shown in Figure 10. A general level of about three degrees of stable yaw is indicated for the lower speeds; while near Mach 0.9 amplitudes of about eight degrees seem probable. Above a Mach number of one no limit cycle of this nature was observed.

Past experience with blunt nosed models of this type, having dynamic instability, has indicated that there is frequently a correlation with flow separation. The flow shadowgraphs of these models were extensively examined in an attempt to correlate any of the observed flow differences with the observed changes in the aerodynamic behavior. There were definite changes in flow pattern with yaw level; and, in one instance, with Mach number. These are best shown in Figures 11, 12, 13 and 14. At the lower speeds, and small yaws, the stabilizing flare section oscillates in the separated flow region created by the blunt nose without affecting the external flow configuration of the separated flow. At yaw levels of about three degrees the oscillating flare definitely begins to influence the external flow shape although it does not penetrate into the outer flow itself. At about five degrees of yaw the flow generally attaches to the windward side of the model but remains separated on the lee. There is some evidence that as the yaw level increases, before general attachment, the flow remains attached for a very short, but increasing, distance around the nose.

Since an increase in the destabilizing effect of the nose, without a corresponding increase in the stabilizing effect of the flare section of the model, is definitely destabilizing; the static stability trend is, qualitatively, quite reasonable. When attachment occurs and the special purchase of the nose is obviated, the reversal of this trend is also reasonable. The indication of the flare's influence on the external flow at about three degrees also correlates nicely, if less understandably, with changes in the damping properties. In the Mach number region near 0.9 there are local shock formations on the separated flow and the separated region is much wider than it is at lower speeds (Figure 14). Similar flow changes occur with changing yaw level but larger yaws are required to produce the same changes; up to about ten degrees of yaw are required to attach the flow on the windward side, for instance. This too correlates nicely with the change in amplitude of the limit cycle behavior in this Mach range.

SIMILARITIES IN AERODYNAMIC PROPERTIES

Examination of the results of these two independent programs produced some rather odd similarities; especially in view of the gross shape differences. Figure 15 shows the C_{M_α} curves for both shapes as a function of yaw level. Naturally the exact level of the stability parameter is not too pertinent, since it varies with center of mass changes. The similarity in shape of the two curves is striking, however. Both are maximum at zero yaw and decrease in absolute value as yaw increases up to about five degrees; thereafter, the rate of change decreases suddenly. Within the somewhat poorer determination of the cylinder-flare shape, the two curves are superimposable.

The damping derivatives for the two types of models as a function of yaw level, are given together in Figure 16. The location of the center of mass can influence the exact level, but here again the similarity of the variation is marked. Maximum destabilizing values occur at zero yaw level and the effect decreases rapidly with increased yaw level up to an amplitude of about three degrees.

Since flow phenomena correlated with aerodynamic variations in the case of the cylinder-flare model, the flow pictures of the sphere-cone shape were re-examined in detail. The results can be stated briefly. The sphere-cone shape is very resistant to separation, angles of yaw way beyond the current range of interest, 20 to 30 degrees, were encountered without flow separation on the lee (Figure 17). It appears possible that first, flow separation phenomena are the basis for the aerodynamic properties of the cylinder-flare but other unrelated phenomena produce coincidentally similar traits for the sphere-cone; or, second, the variation of the aerodynamic properties of both models are basic to the subsonic flow itself and separation on the cylinder-flare shape converts it to an aerodynamic shape similar to the sphere-cone.

COMPLEX NATURE OF THE DAMPING MOMENT

Despite the rather good correlation of the damping moment with yaw parameters, the actual nature of the yawing motion as viewed in the polar yaw plot (Figure 6) was disturbing. If the aerodynamic moment derivatives are a function of yaw alone and there is no spin, then it can be shown (7) that the only admissible limit cycle motion is a planar one. The observed motions, however, were usually nearly circular.

It was clear from the nature of the yawing motions and from the fit of the unrestricted* digital reductions, that the terms related to spin effects in the fitting equation were the ones most important in matching the anomalies of the yawing motion. This, despite the fact that the models were basically nonspinning. The use of the spin terms implies that a force normal to the plane of yaw exists, or that the motion is unstable in the planar model. For the model with separated flow, the possibility of asymmetric effects, as the flare crosses from the separated to the outer flow region and back, is easy to postulate and seems reasonable to presume. This is not the case for the cone-sphere model, however.

In reviewing his earlier work in the light of the present data, C. H. Murphy has shown that terms which are not functions of yaw amplitude alone are also admissible in the analysis. These results have been recently published (8) and only the nature of the added terms will be discussed here.

If the complex yaw equation for a nonspinning body of revolution is represented by:

$$\lambda'' + H\lambda' - M\lambda = 0 \qquad (\lambda = \beta + i\alpha)$$

and

$$H = \text{Constant}$$

$$M = \text{Constant}$$

then, in this linear case, no limit cycle is possible.

If, however,

$$H = H_0 + H_1 \lambda\bar{\lambda} + H_2 \lambda' \bar{\lambda}$$

$$M = M_0 + M_1 \lambda\bar{\lambda} + M_2 \lambda \overline{\lambda'}$$

limit cycles can exist with proper combinations of the terms. If only the first two terms in H and M are permitted, only a planar limit cycle is possible. The use of the remaining terms does, however, permit limit cycles of a circular nature. Figures 18 and 19 show a measured yawing motion and attempts to fit it on an analogue computer with various parameters in the differential equation. Figure 18 shows an attempt for which $H_2 = M_2 = 0$. Only the initial parts of the measured and computed motions have the same nature. Inclusion of the H_2 and M_2 terms, in Figure 19, produces a computed motion that is similar in character to the measured one. Unfortunately, as the bilinearity of the static and damping moment data show, it would be necessary to permit the coefficients of the differential equation to take on two different sets of values in order to attempt to fit the measured motion precisely. This would introduce so many variables that, while a fit might be made, there would be no reliable determination of the coefficients.

SUMMARY

Firing range measurements on sphere-cone and cylinder-flare models have indicated a similarity of the static and dynamic moment variations with yaw amplitude.

Models of both types exhibit a generally circular limit cycle yawing motion at subsonic speeds.

The circular character of the limit motion implies a complicated nonlinear variation of the aerodynamic moment while the similarities of properties for the two shapes suggest that a common aerodynamic basis might exist.

L.C. MacAllister

LEONARD C. MACALLISTER

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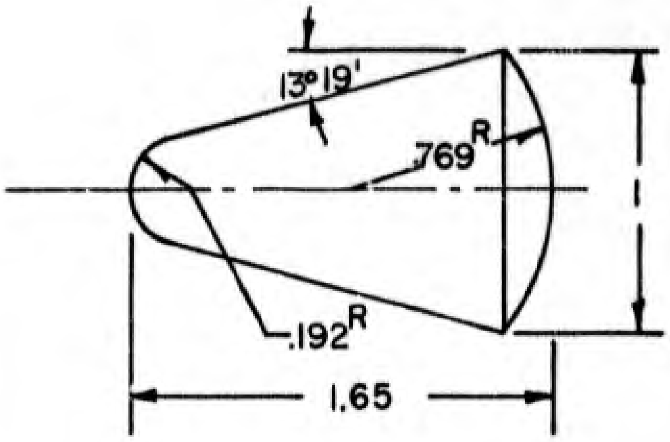
SPHERE-CONE



CYLINDER-FLARE

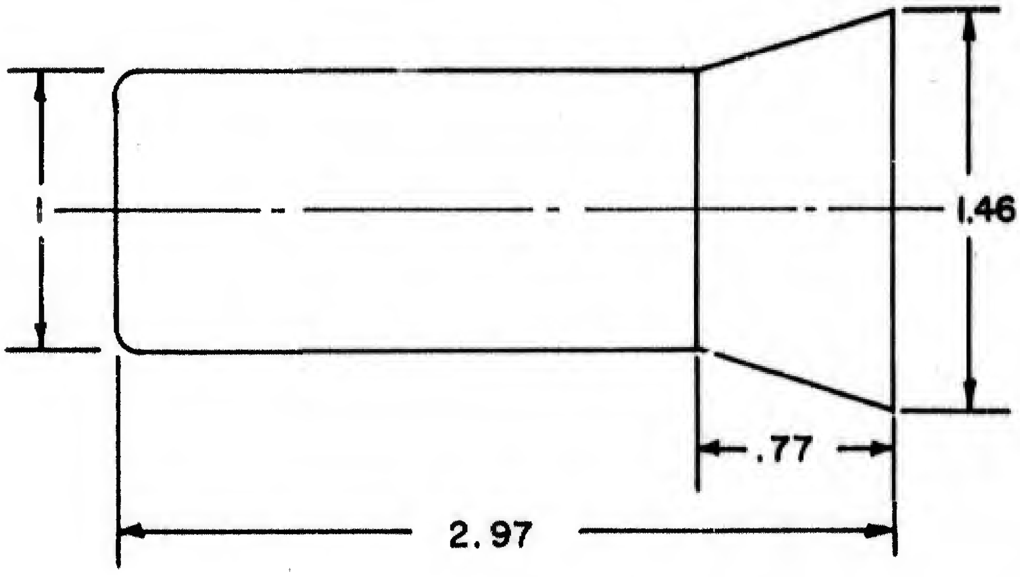


FIG. 1

STATIC MOMENT SLOPE vs MACH NUMBER

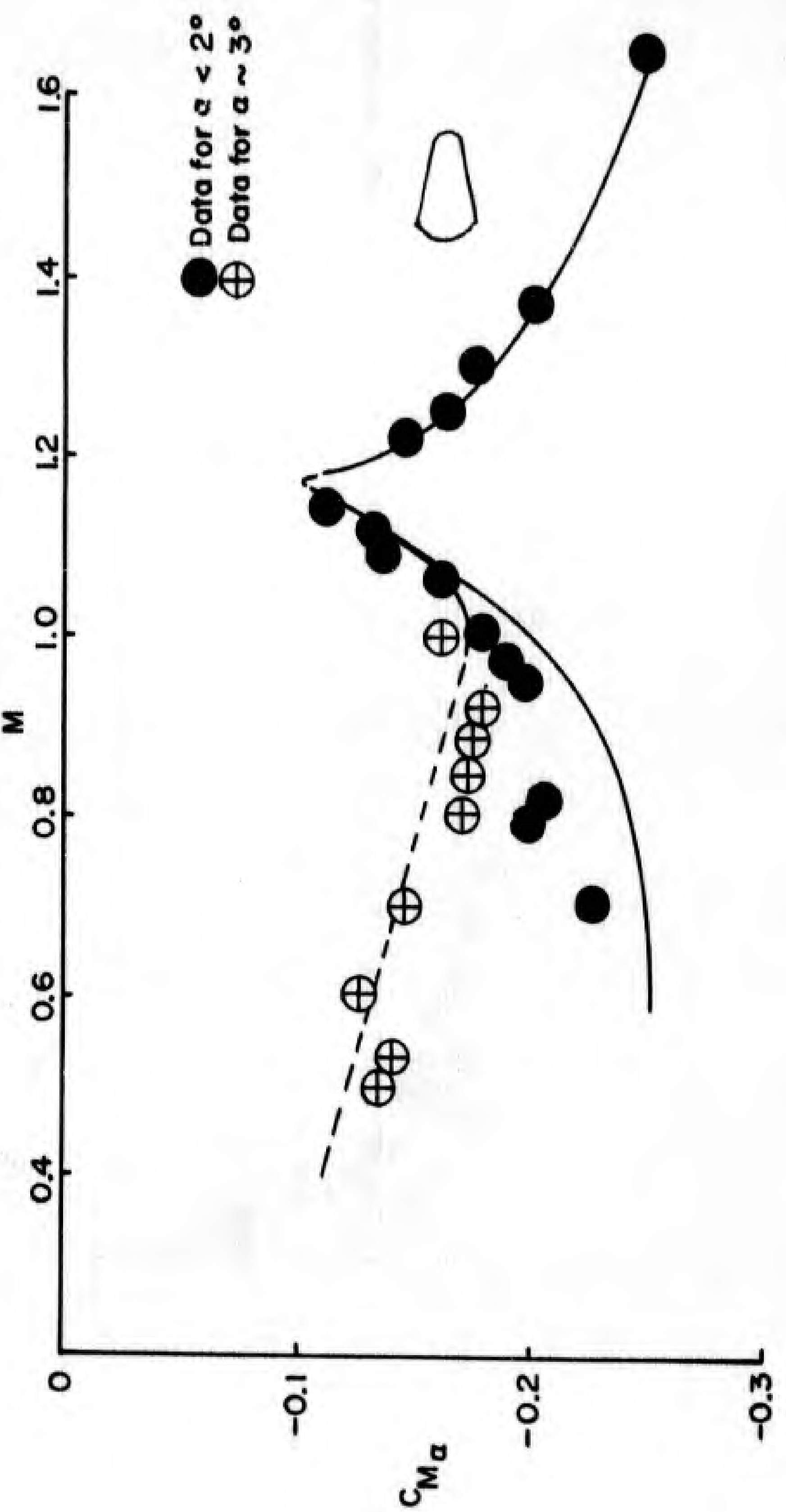


FIG. 2

STATIC MOMENT SLOPE vs YAW LEVEL

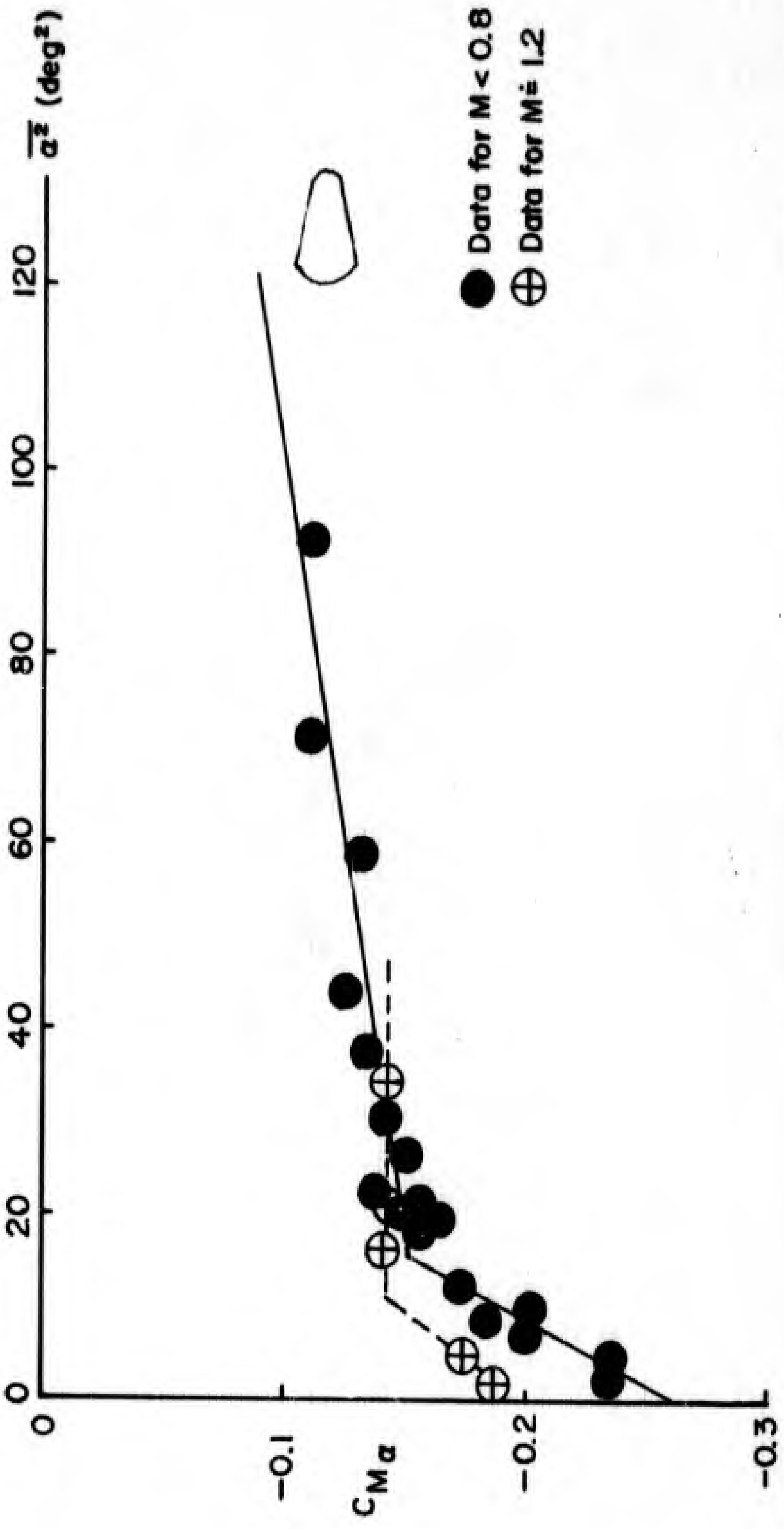


FIG. 3

DAMPING DERIVATIVES vs MACH NUMBER

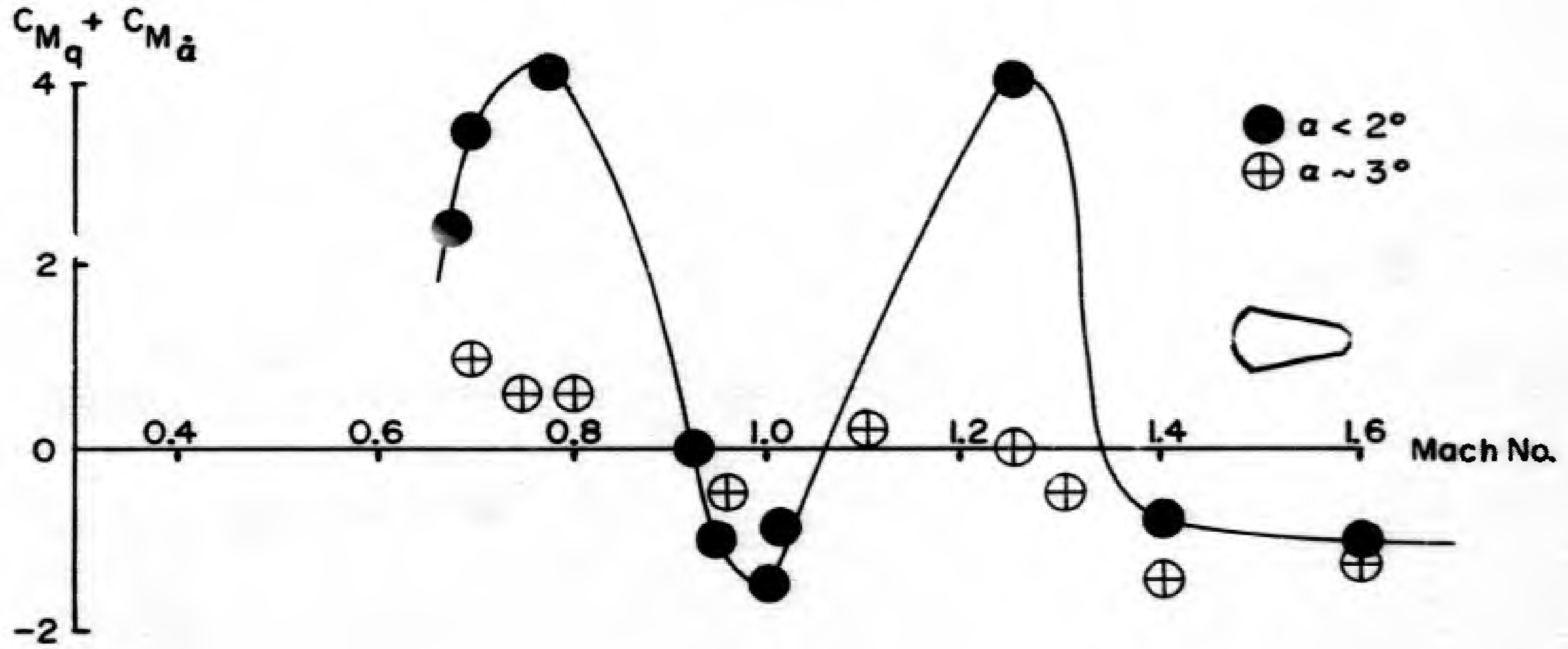
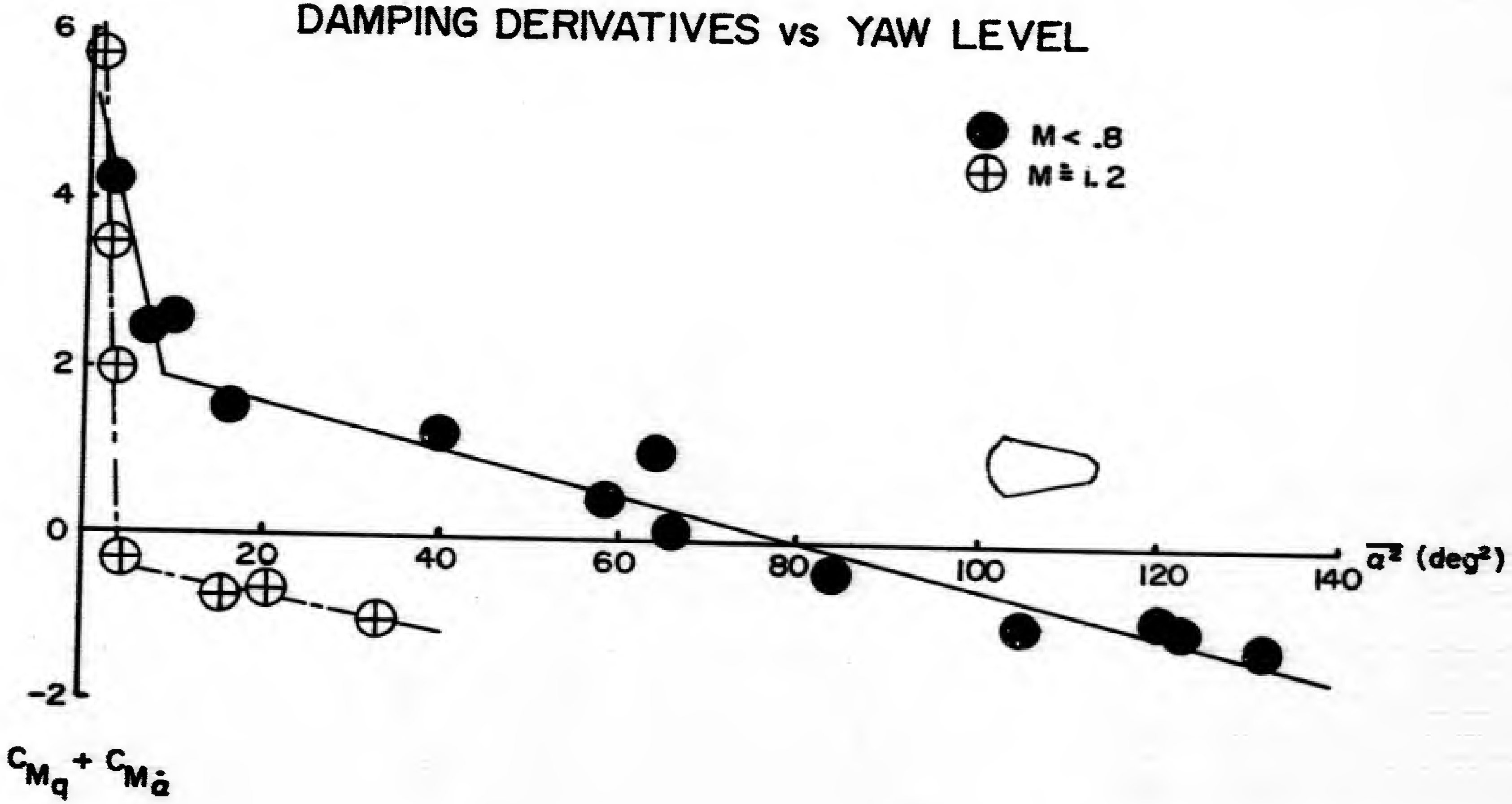


FIG. 4



DAMPING DERIVATIVES vs YAW LEVEL

FIG. 5

POLAR PLOT OF YAWING MOTION

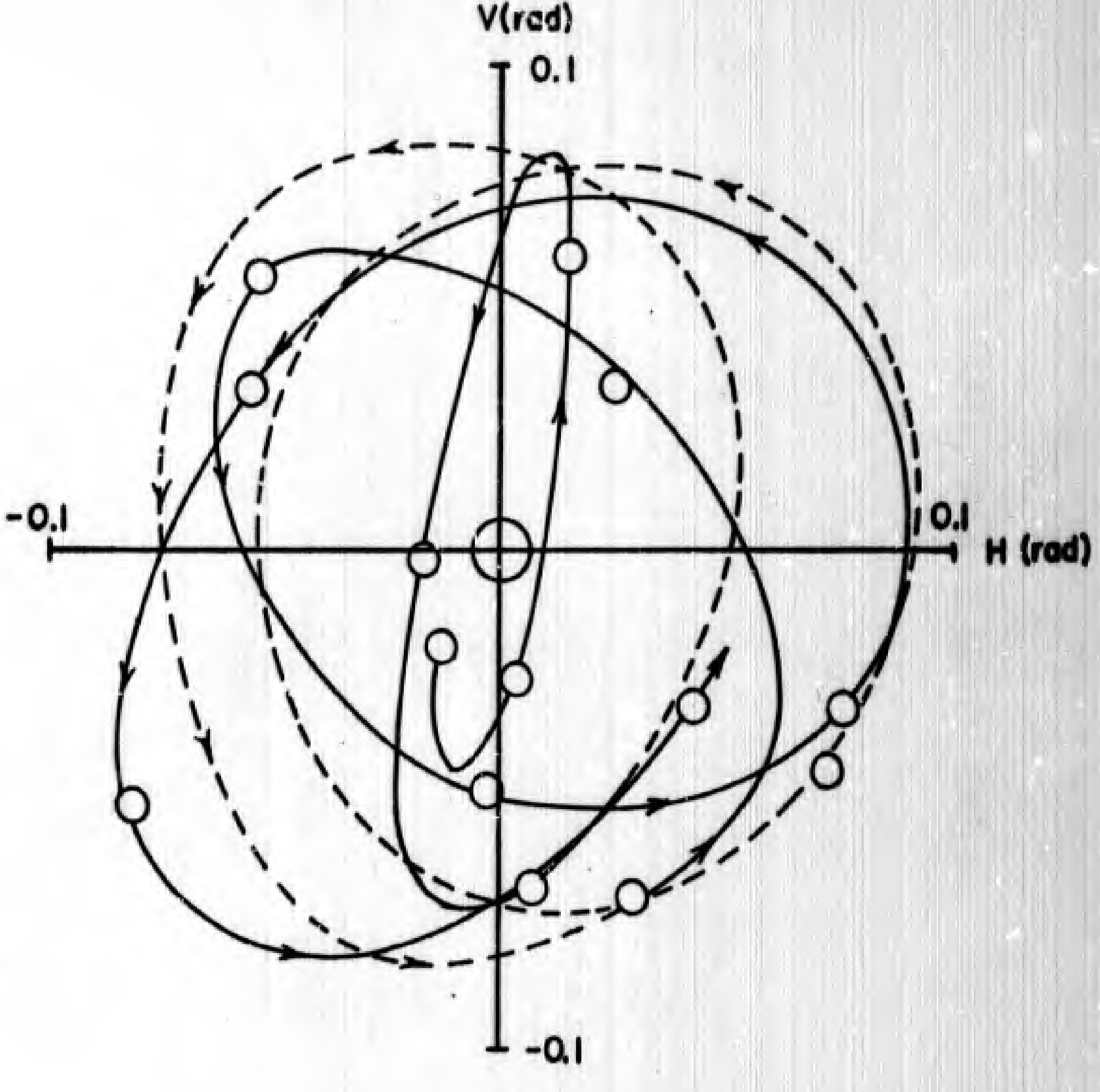


FIG. 6

LIMIT CYCLE AMPLITUDE

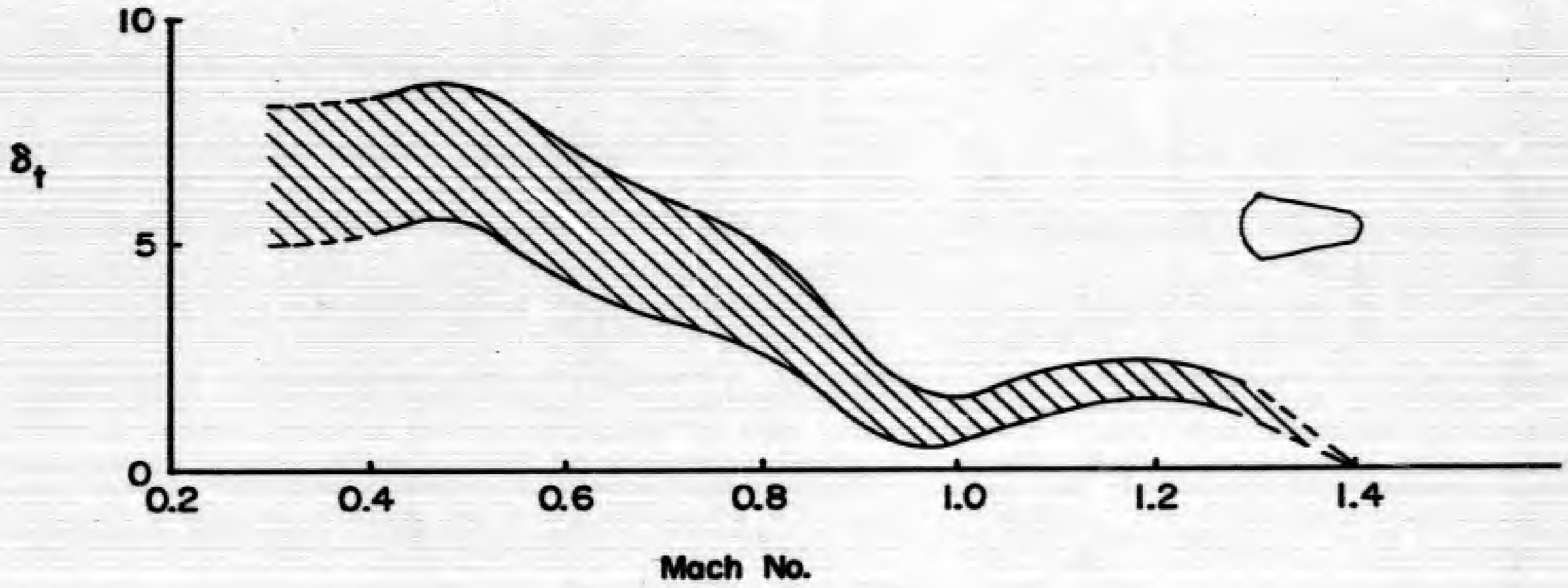


FIG. 7

STATIC MOMENT SLOPE vs YAW LEVEL

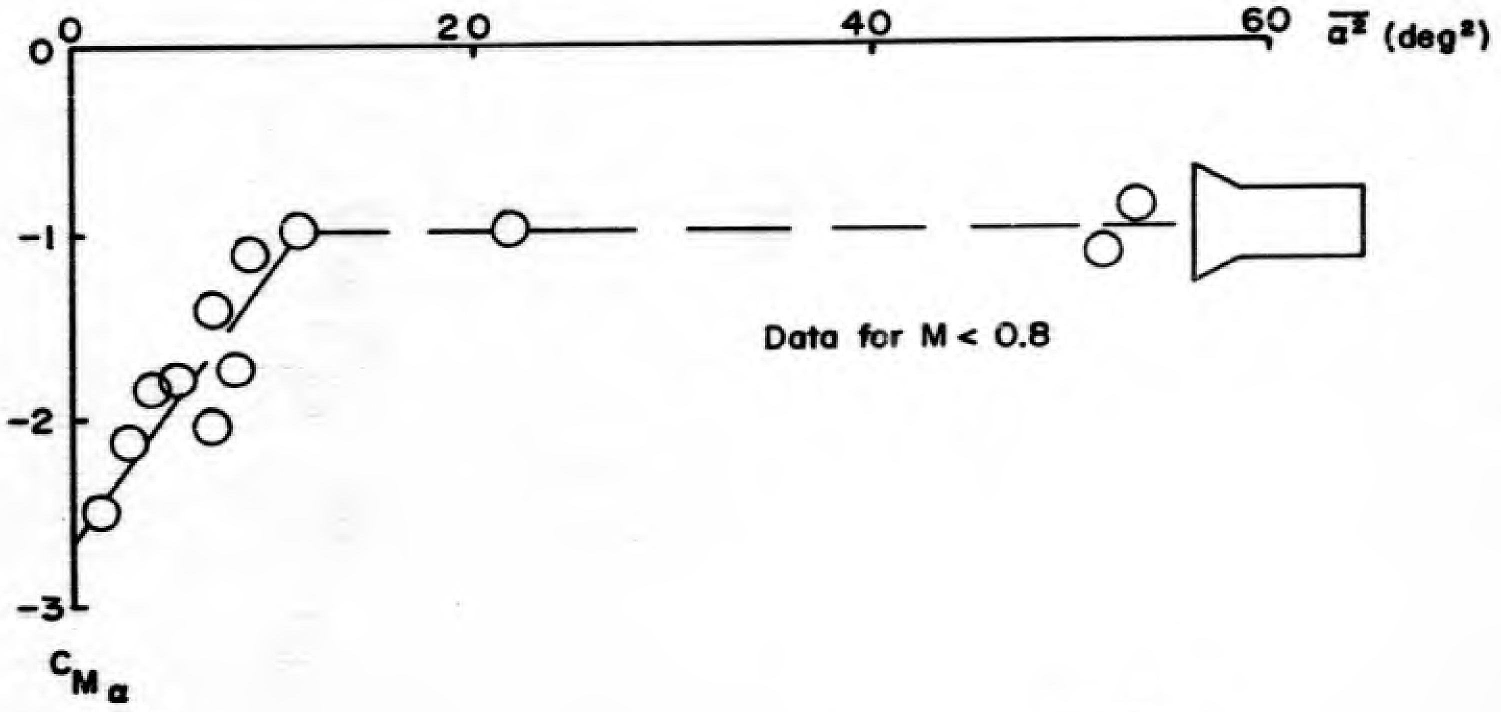


FIG. 8

DAMPING DERIVATIVES
vs
YAW LEVEL

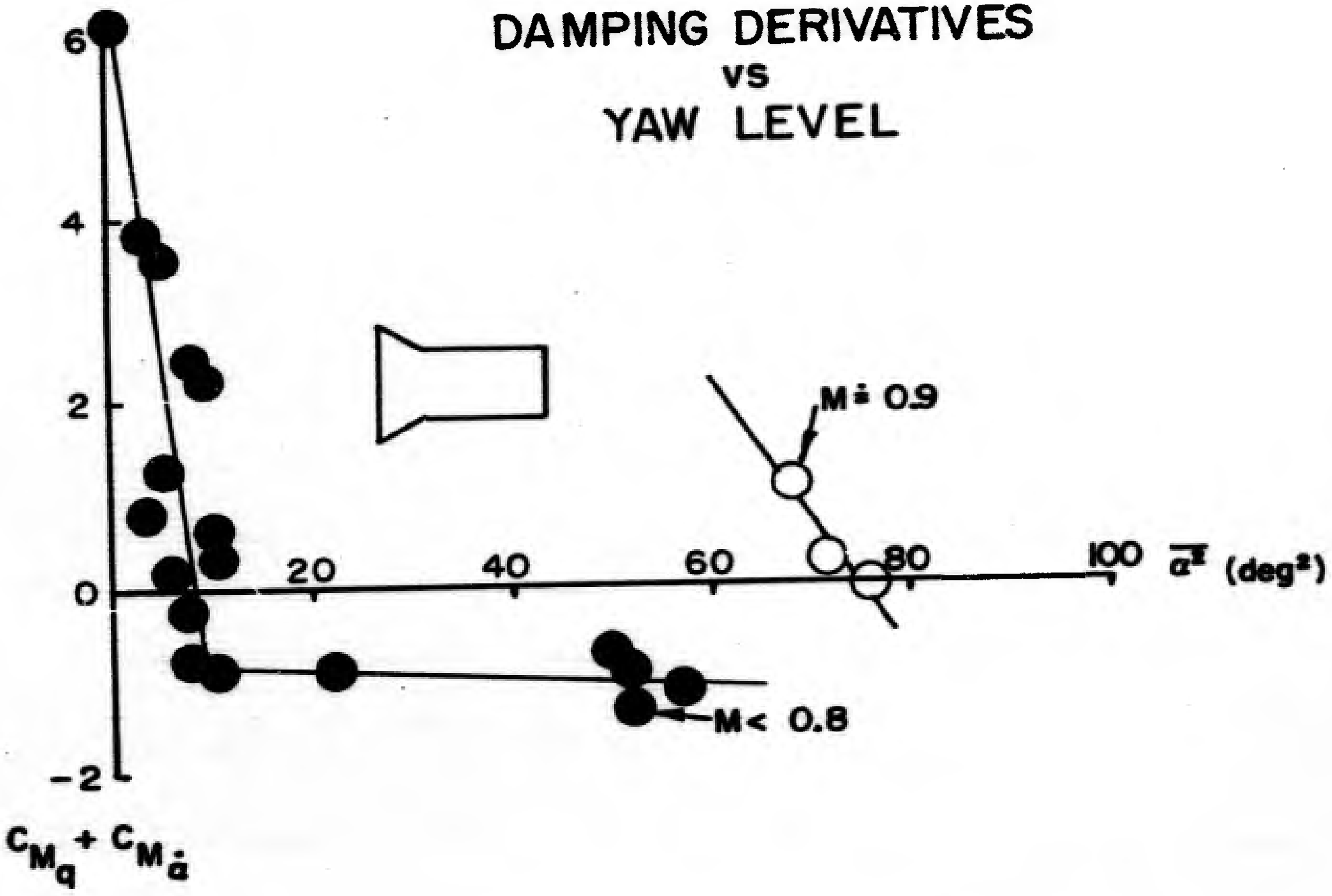


FIG. 9

LIMIT CYCLE AMPLITUDE

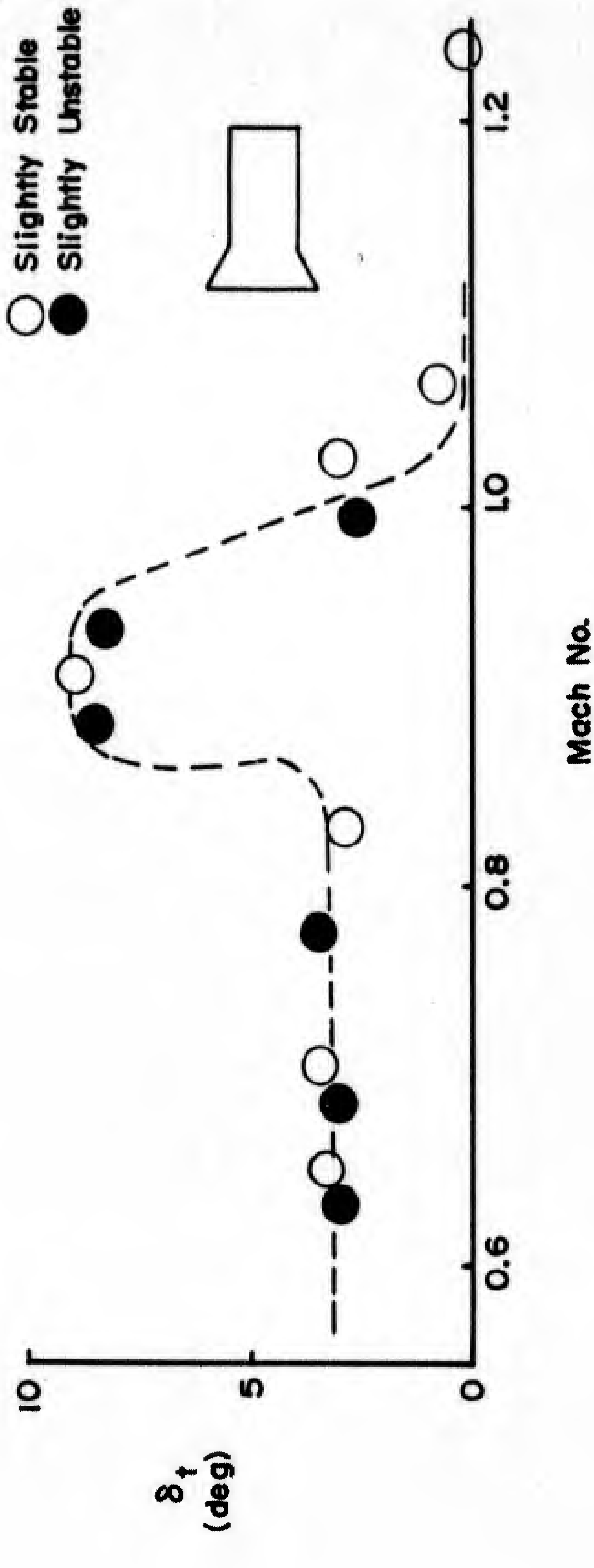


FIG. 10

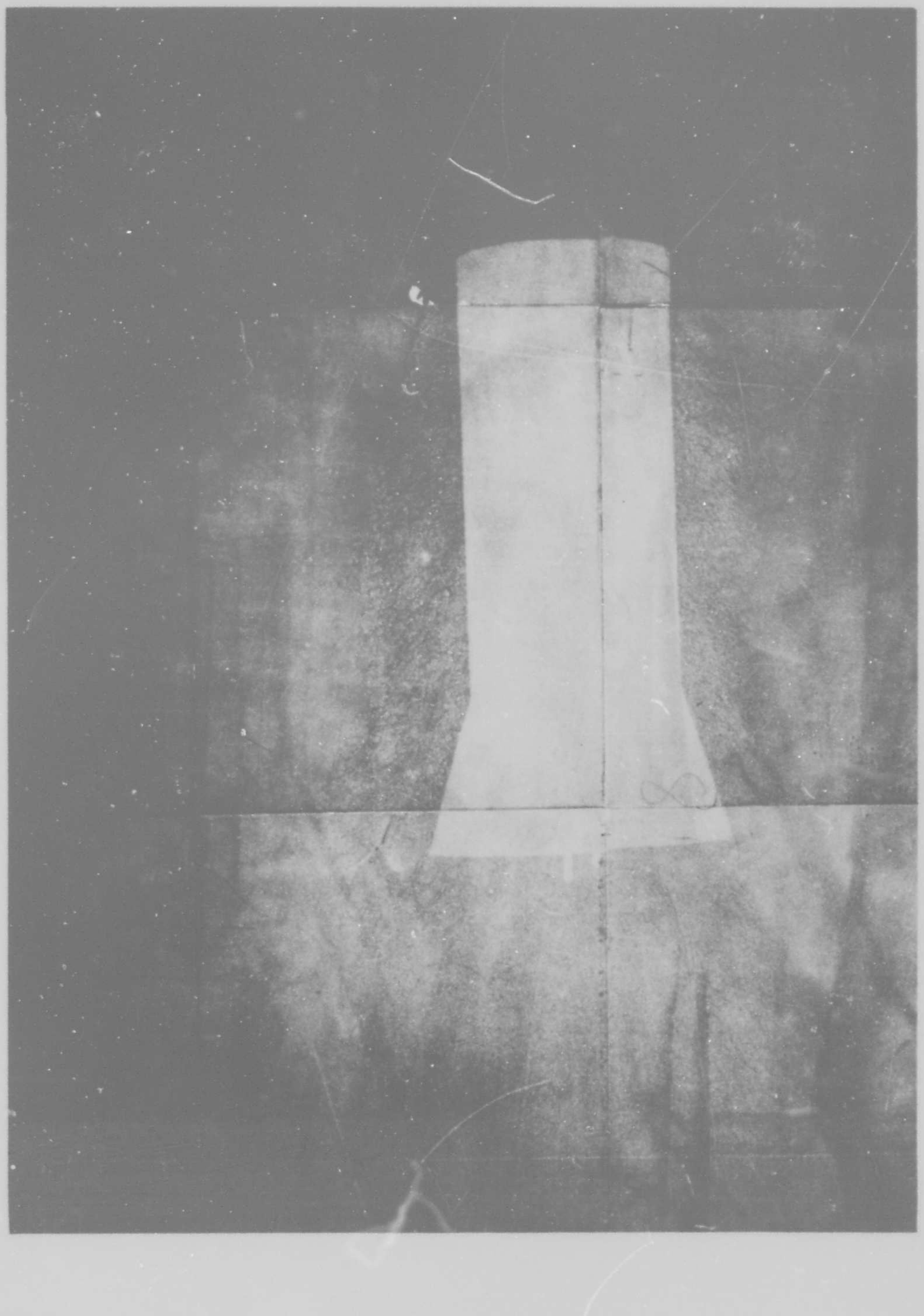


Figure 11 - Cylinder Flare
$M < 0.8$
$\alpha \sim 1^{\circ}$

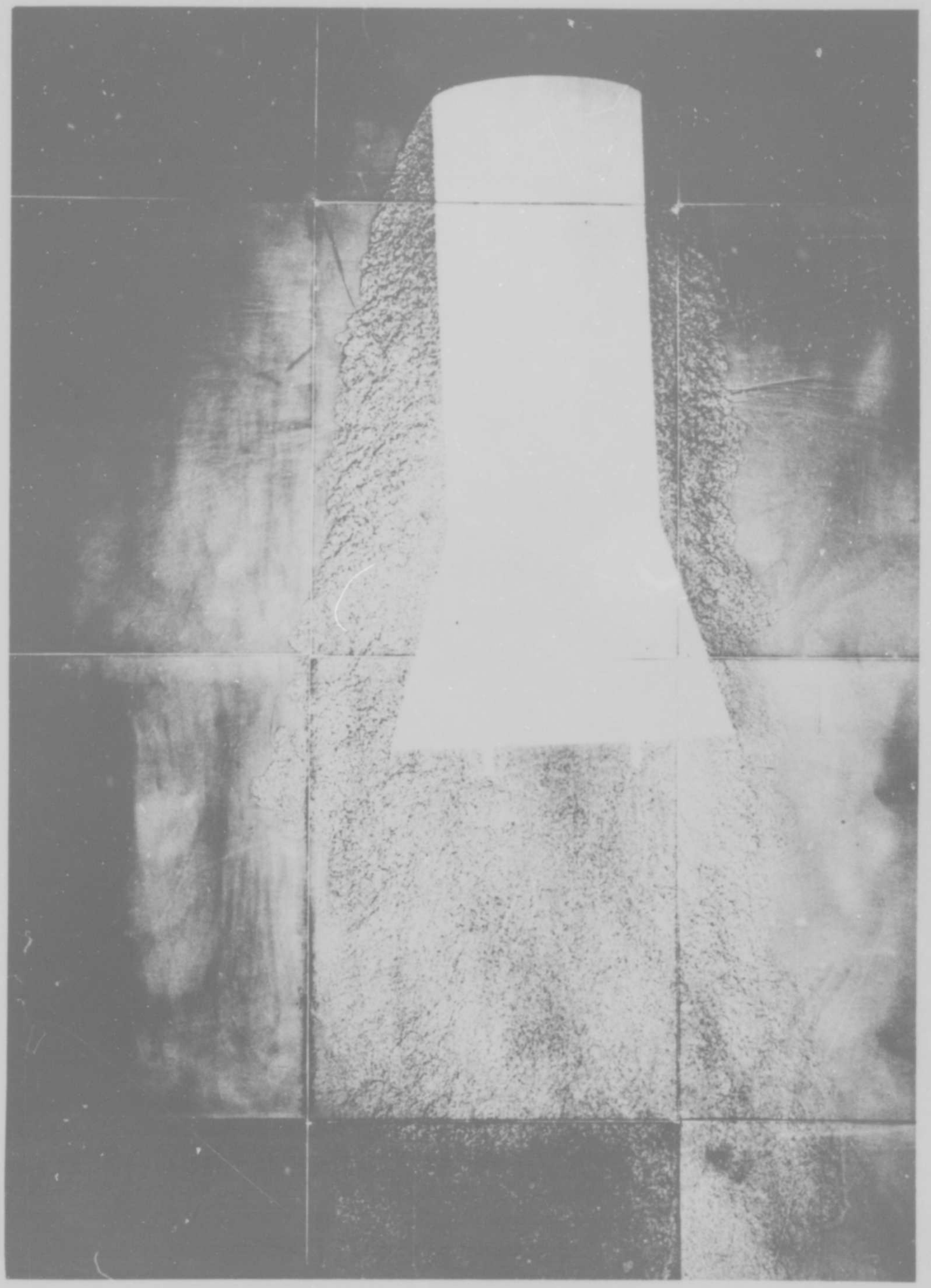


Figure 12 - Shadowgraph of Cylinder - Flare
$M < 0.8$
$\alpha \sim 3^{\circ}$

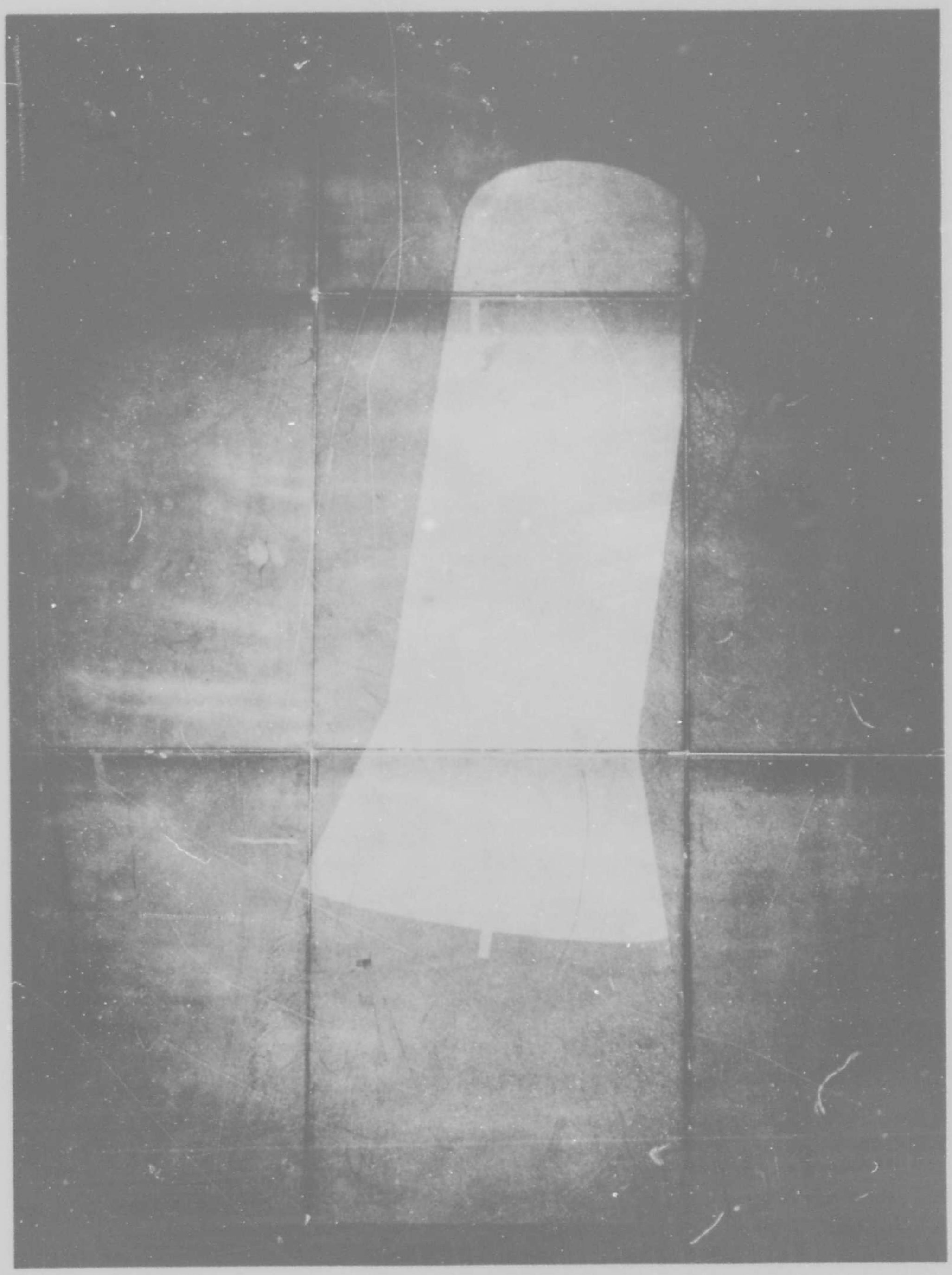


Figure 13 - Shadowgraph of Cylinder - Flare
$M < 0.8$
$\alpha \sim 5^\circ$

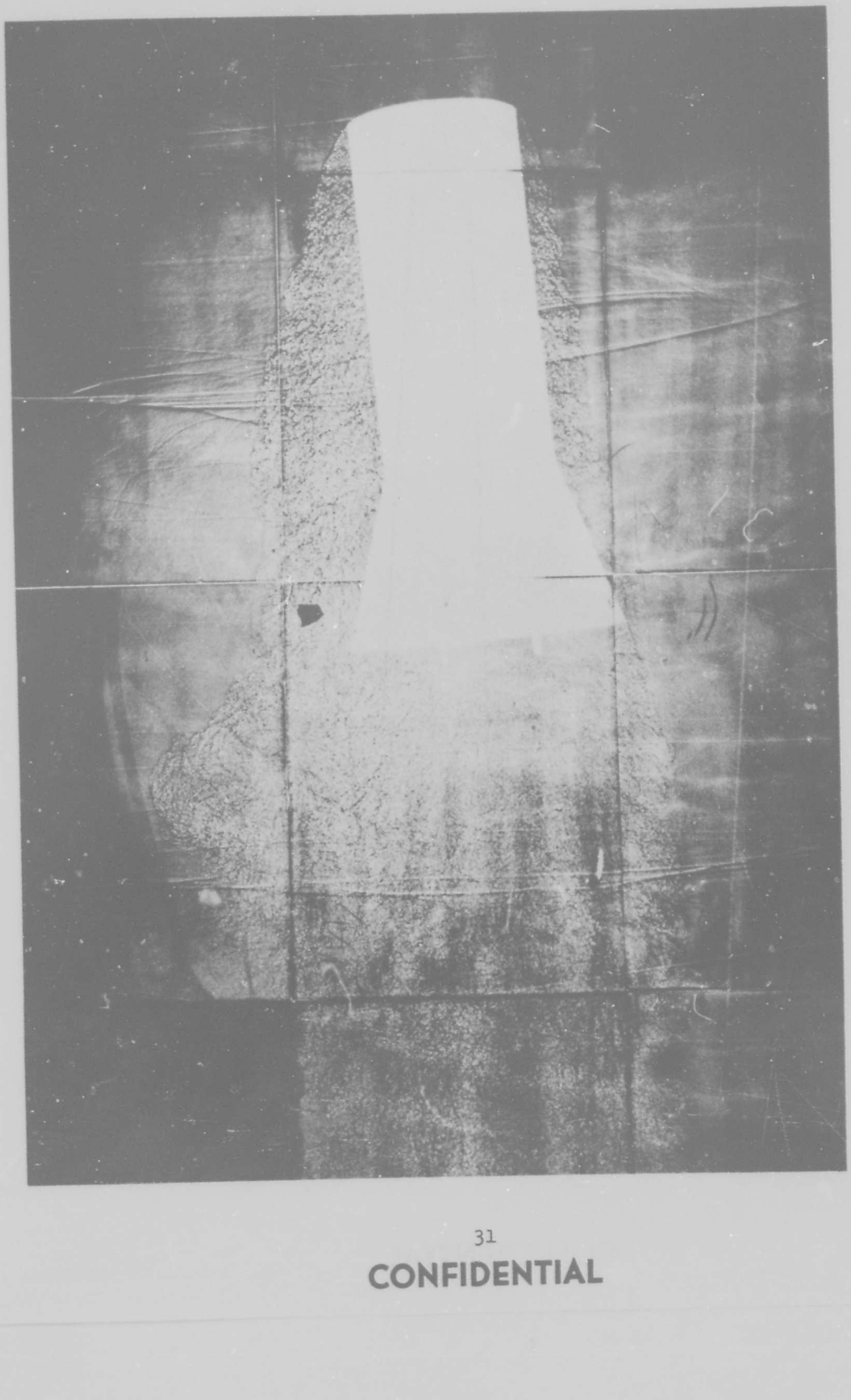


Figure 14 - Shadowgraph of Cylinder - Flare
$M \sim 0.9$
$\alpha \sim 5^\circ$

COMPARISON OF STATIC PROPERTIES

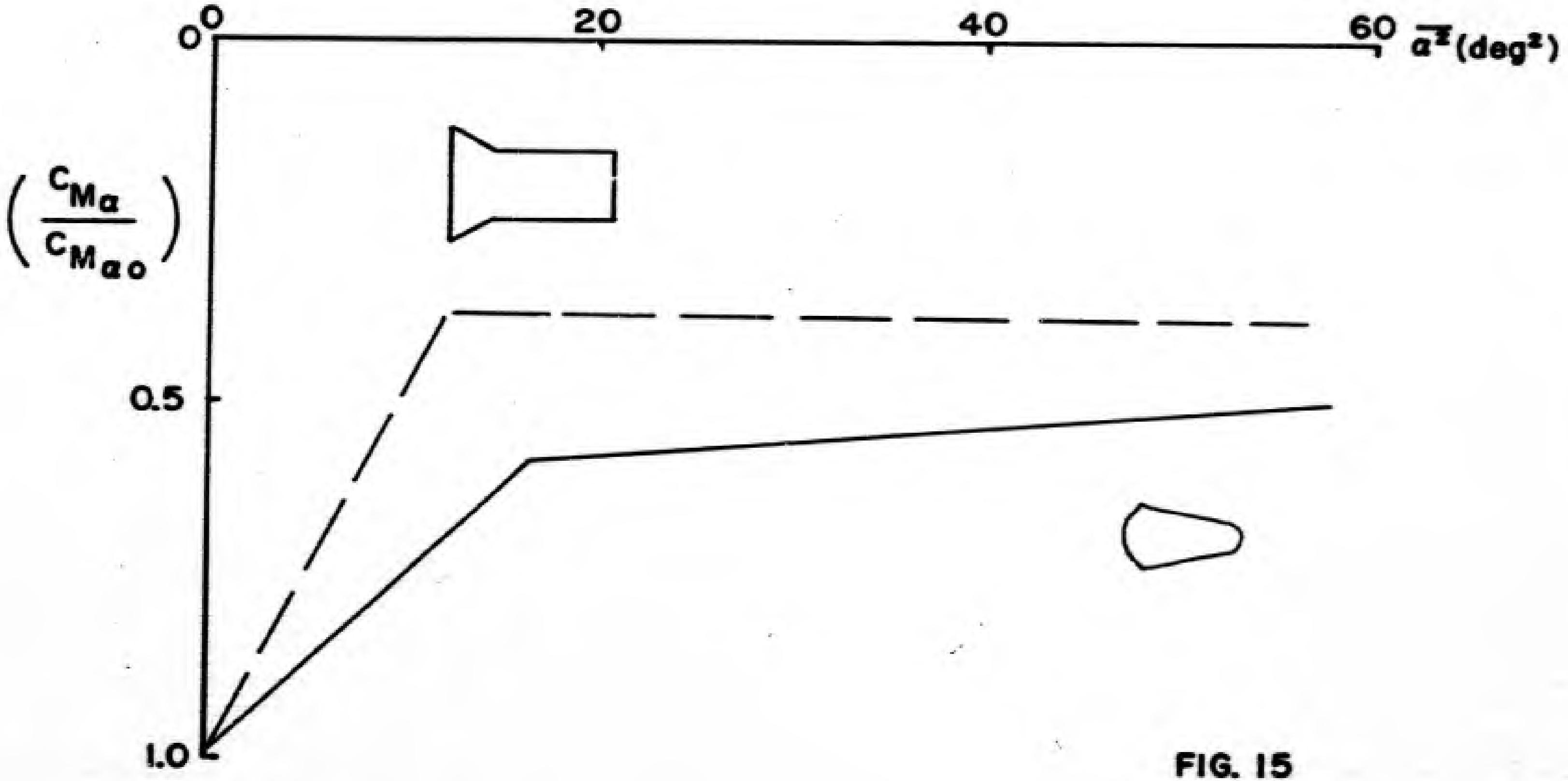


FIG. 15

COMPARISON OF DYNAMIC PROPERTIES

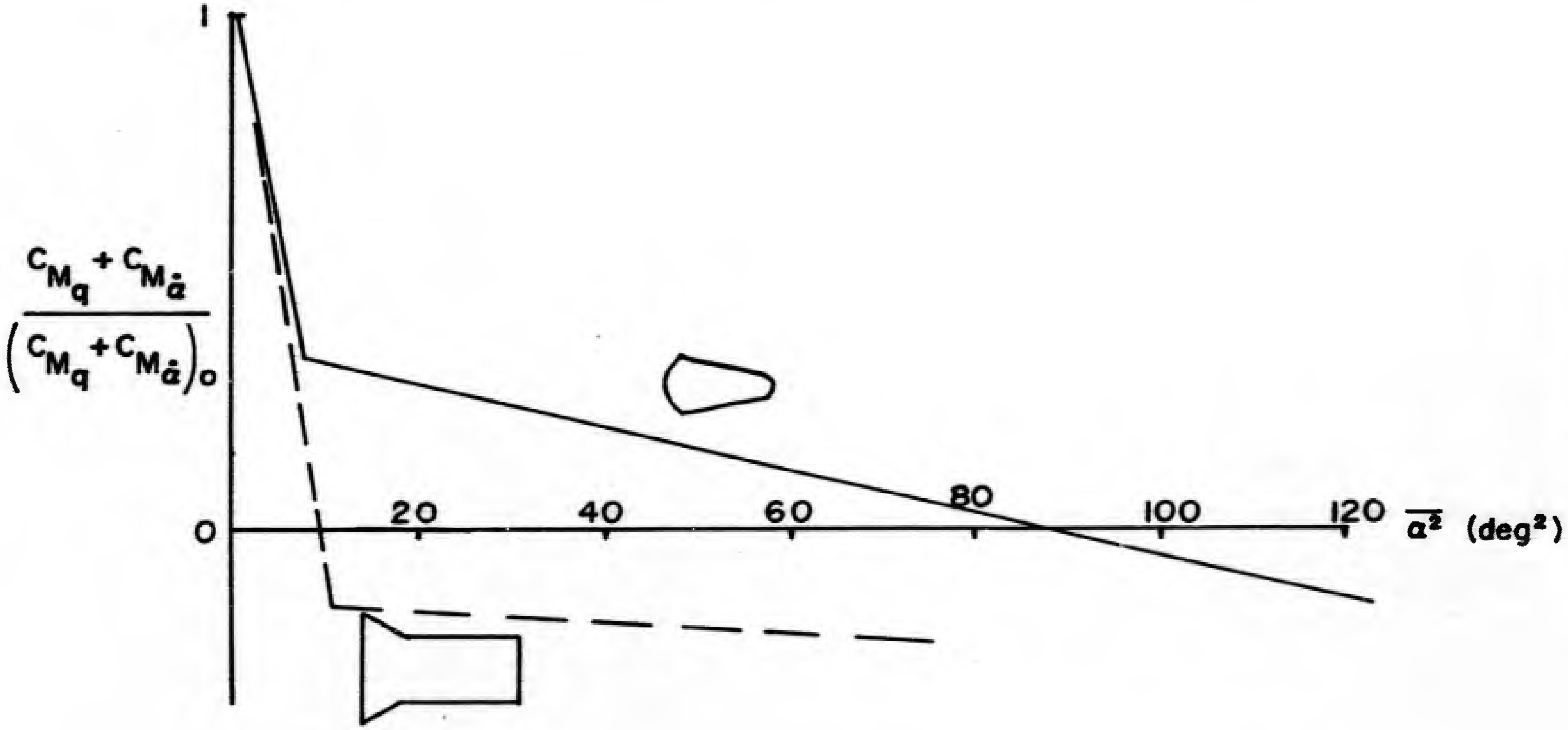


FIG. 16

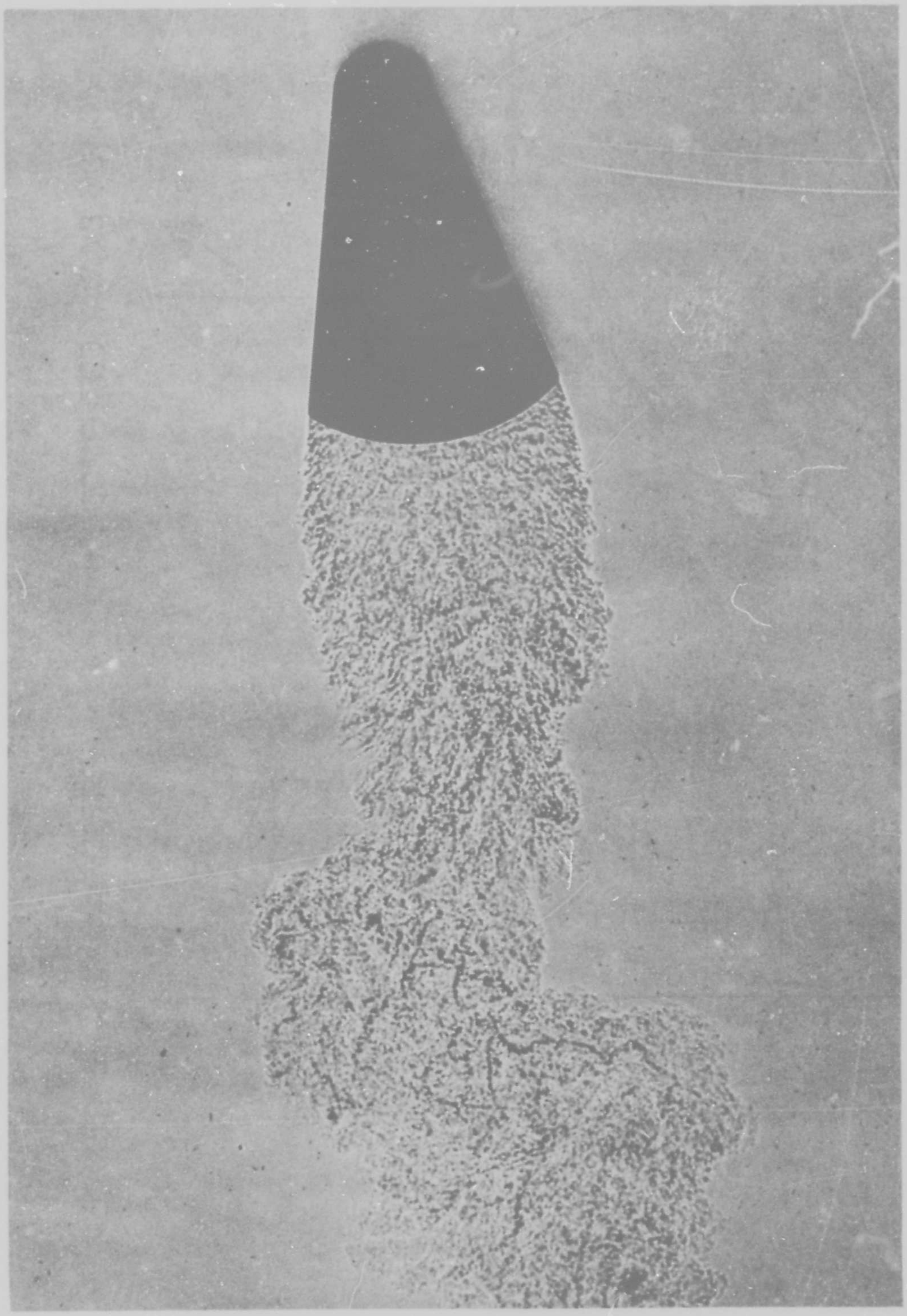


Figure 17 - Shadowgraph of Sphere - Cone
$M < 0.8$
$\alpha = 11^\circ$

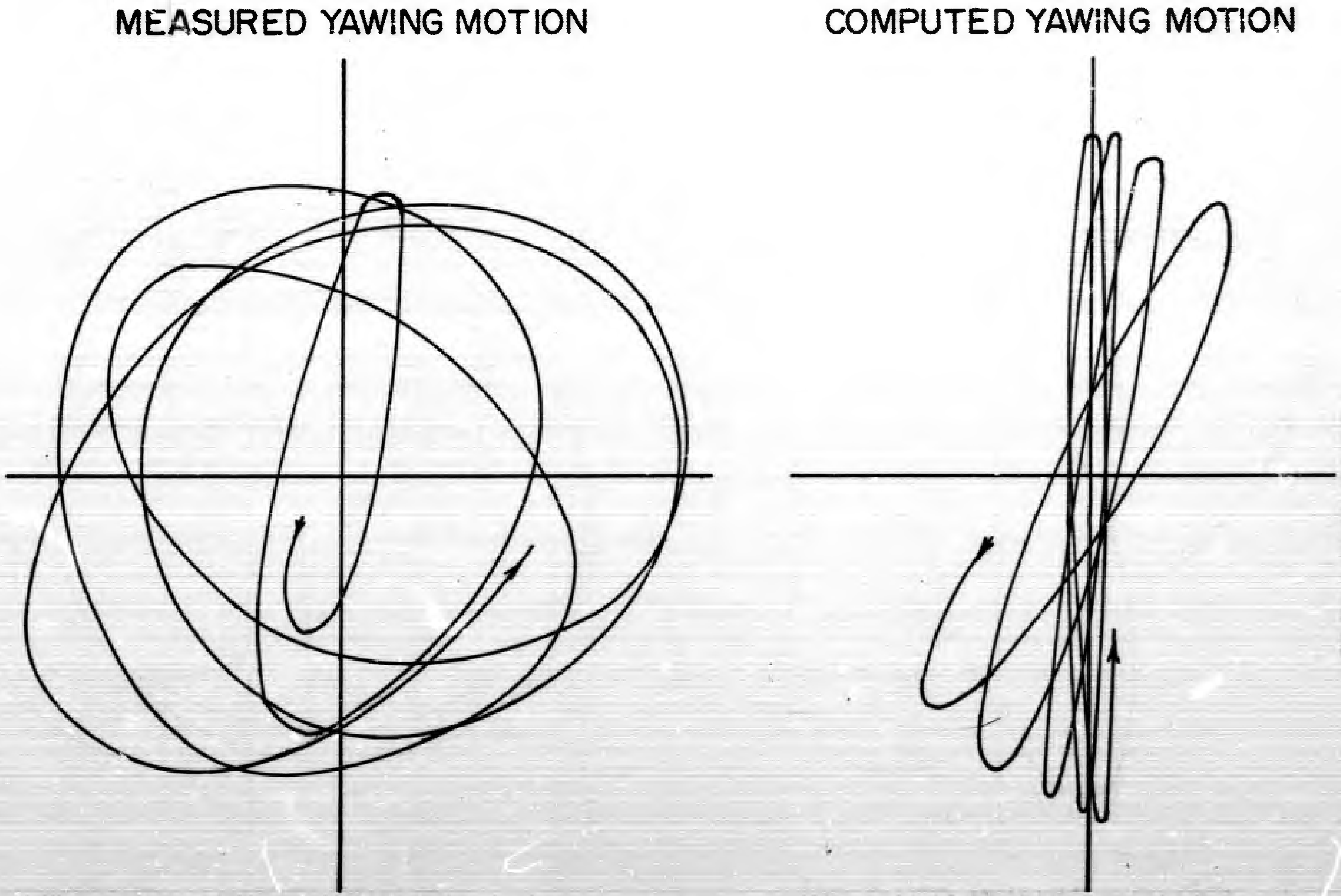
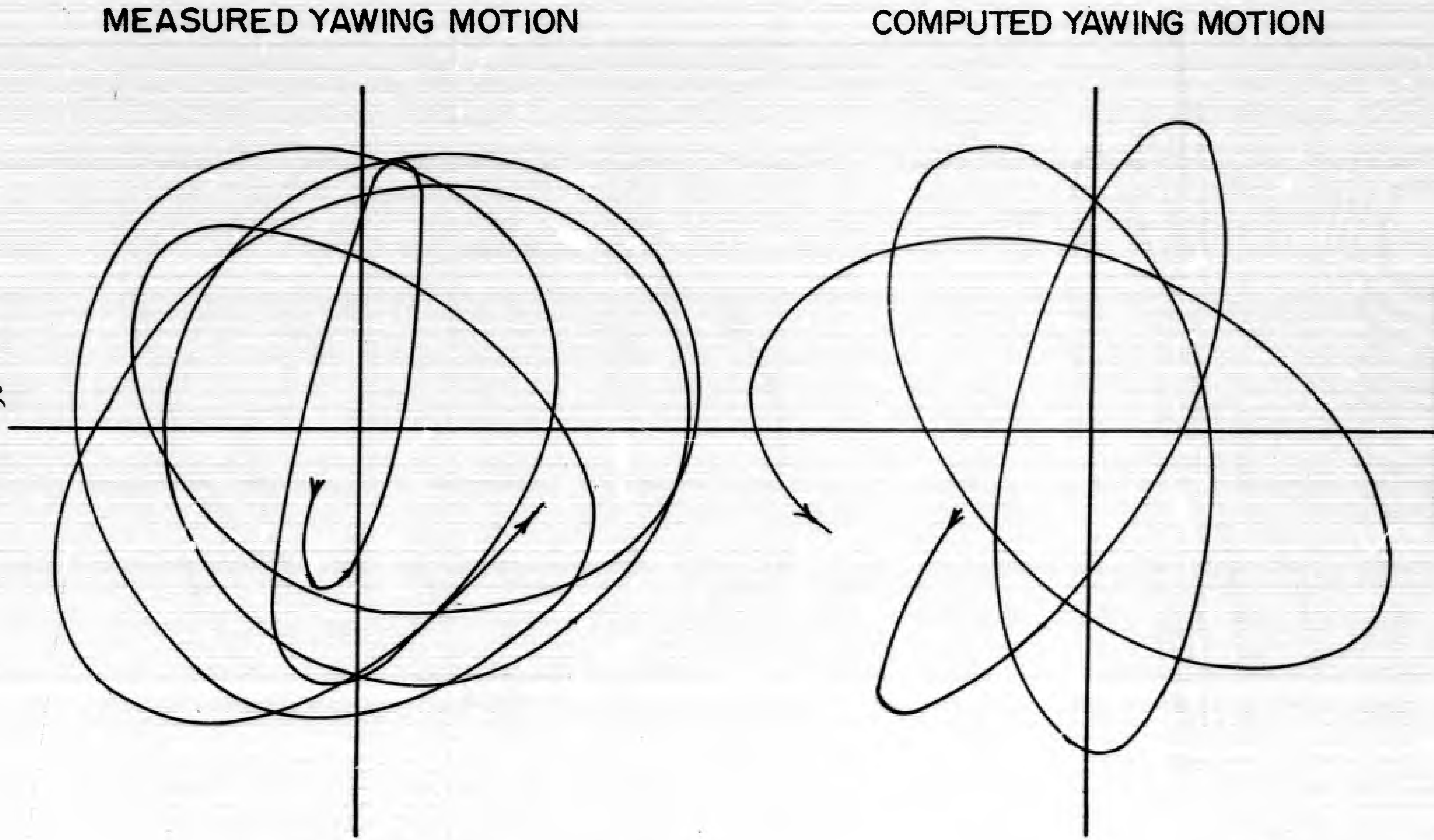


FIG. 18



MEASURED YAWING MOTION

COMPUTED YAWING MOTION

FIG. 19

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