AMES 1958 TRIENNIAL INSPECTION

Supersonic Free-Flight Wind Tunnel Presentation

THE STABLE DESCENT OF MISSILES, SATELLITES, AND SPACE CRAFT THROUGH THE EARTH'S ATMOSPHERE

We are going to discuss some of the considerations for successful recovery of satellites and space craft and the successful entry of ballistic missiles into the atmosphere. We start from the assumption that the flight should be controlled and orderly rather than an uncontrolled tumbling of the reentering vehicle, and will illustrate these two possibilities with the aid of a water tank and some models. The first model (drop while talking) illustrates the kind of flight characteristics we want. The model undergoes some oscillation in attitude, but it remains nose-forward during the descent. The second model (drop) shows no particular preference as to attitude, falling sometimes nose-forward and sometimes nose-rearward. This descent is obviously unsatisfactory. Now what is the difference between these two models? Technically, it is called a difference in stability. The term as we shall use it here refers to the tendency of a model to fly nose-forward. A model that continues to depart from the nose-forward condition on being disturbed is said to be unstable.

Stability is an obviously desirable characteristic for hypersonic vehicles entering the atmosphere, just as it is for an automobile driven at high speed. If we wish to accomplish a controlled, maneuvering flight such as will be made by a manned satellite making a safe reentry into the atmosphere, stability is, in fact, necessary. In addition to retaining control over the vehicle, it is also necessary to avoid the high frequency tumbling and swerving of the vehicle which lead to an intolerably rough ride for the pilot. Another paramount consideration is to hold the vehicle attitude fixed so that the heat shield on the front face of the vehicle remains in the forward position where it can protect the vehicle from destruction by the heat generated by atmospheric friction.

Flight stability is therefore essential for recoverable space craft, satellites, and ballistic missiles. But what controls and determines whether a vehicle will be stable or not? This can be explained with the aid of the first chart. This chart depicts a body in flight, momentarily misaligned with respect to the flight direction, which is represented by these arrows indicating the direction of the oncoming wind. Now as a result of this misalignment, there is produced a component of aerodynamic force perpendicular to the axis of the missile. The aerodynamic force will in general tend to rotate the vehicle, and the point about which it rotates is the center of gravity, represented by this spot on the missile axis. The center of gravity is the point of balance of the vehicle--that is, it is the point which must be placed vertically above a knife edge in order for the model to balance on the knife edge. Now if, by design, the center of gravity is located ahead of the point of application of the aerodynamic force, as shown here for example, the vehicle will rotate in such a direction as to become aligned with the flight direction, and the vehicle is said to be stable. Note that when the direction of the misalignment is reversed, that is when the body nose points down instead of up, the direction of the aerodynamic force is also reversed, and the vehicle is therefore stable for all directions of misalignment. However, if the center of gravity is located behind the center of the aerodynamic forces (move c.g. sticker), the rotation is in the direction to cause tumbling and the vehicle is unstable.

With this picture of the basis for stability in mind, we can see that stability will be controlled by factors which control the size and location of the aerodynamic force--namely the body shape and the flight speed. It is also governed by the location of the center of gravity. The important influence of body shape will be illustrated with models in the water tank. The first model, a cone, does not have a stable position. The second model, a cone of larger nose angle, is stable nose forward and makes a very satisfactory descent. From this comparison, it is evident that a modest change in cone angle has in this case made the difference between instability and stability. To consider a somewhat more drastic change, we test a circular cylinder and find that it has rather unpredictable flight characteristics. Now these three models have been solid, homogeneous models with centers of gravity corresponding to this type of construction. We also have available (hold up model) a circular cylinder which has had the center of gravity moved forward by use of ballast weights near the nose. This model makes a definite nose-forward descent.

We have been illustrating these ideas in water instead of air. This technique is of some value for preliminary study of the characteristics of satellite and missile models. However, the models descend through the water tank at a low subsonic speed, and speed is one of the things which influences stability. That is, the characteristics of models falling slowly in water cannot be taken as equal to the characteristics of vehicles making supersonic and hypersonic descents through air. The NACA has devised test facilities which give information on the stability characteristics in the correct medium, air, at the hypersonic, supersonic, and transonic speeds which will occur during reentry. This demonstration is taking place in the test chamber of one of those facilities, called the supersonic free-flight wind tunnel. Effectively, it replaces the water in this tank with air, and is rotated to a horizontal position so that the flights occur in a generally level direction, but it is otherwise similar to the water tank. A scale model of the vehicle to be studied is set into high-speed flight by launching it from a gun, and from the motion of the model, we can determine the flight stability. The model is flown through the test section of a wind tunnel, through which there flows a supersonic airstream in a direction opposite to that of the oncoming model. In this way, the speed of the model relative to the air is made very high. In fact, this facility is one of the highest speed facilities now in use, anywhere in the world. It has been used to make tests in air at Mach numbers up to 17, which is the equivalent of 13,000 miles per hour, and for this reason, it has been valuable in providing basic research information for the design of this country's ballistic missiles. It is now being used for additional testing of ballistic missiles and is being applied to the problem of the safe recovery of satellites, as well as to a great variety of problems of stability and other fundamental aspects of high speed aerodynamics. It should be emphasized that the air speed and density are uniform through the length of the test region. Thus, the results indicate what will happen at fixed speed and altitude. This is in contrast to the atmosphere-entry simulator, being shown today, wherein the model speed and air density vary along the test length to represent their variation with altitude.

The facility is just behind this light tight partition on your right, and cannot be conveniently viewed by a group of this size.. However, we have a closed circuit TV system set up which we will use to show the wind tunnel. The camera is now on the supersonic nozzle used to accelerate the airstream up to test velocity, and is now panning down the length of the test section toward the direction of the diffuser which is where the model launching gun is located. We are going to demonstrate operation of this equipment, and will begin with a high-speed motion picture of a model being launched. (Start movie) The particular model shown is a model of the X-15 research airplane being launched from a 57 mm smooth bore gun. This movie slows down the actual event in the ratio of 300/1. The objects which can be seen trailing behind the model are pieces of a plastic sabot used to adapt and align the model to the gun. This illustrates how the models are set in flight. Prior to this, however, the wind tunnel air flow will normally have been established. We will therefore proceed to run through the entire test sequence, beginning with the air flow and terminating with the firing of a model. You will see on the TV monitor the operator setting the pressure at the desired level. You will hear the roar of the air flowing through the channel at 1400 miles per hour, one hundred and forty pounds per second. After the instruments and fire control sequence are set in operation, you will hear the firing of the model from a 1-3/4 inch smooth bore gun. The model is a right circular cylinder similar to one used in the water tank. The powder charge is about 1/3 pound and the resulting Mach number is near 10. We will now have the demonstration.

WIND TUNNEL DEMONSTRATION
ENDING WITH CAMERA SET ON POTTER TIMERS

The duration of this flight test was about 4/1000 of a second. During this time, a photographic record of the flight was made, consisting of 18 pictures. In addition, the time intervals for the model to fly from each photographic station to the next station were recorded by an electronic chronograph accurate to one ten-millionth of a second. The TV monitor shows the bank of lights which present the time intervals recorded.

The pictures of the model are of the type shown in this slide which shows a cone in flight at a Mach number of 16.5. Certain characteristic features of the flow field such as the bow shock wave and an expansion line at the body base are visible which is useful for understanding the kind of flow which occurs. For measuring stability, however, it is the pitching and yawing motions that take our attention. We have a sequence of 9 of these pictures, recorded at 3-foot intervals along the flight path which we will now show in consecutive order. In each picture, a reference line, shown here, has been superimposed on the model to indicate the direction of the model axis. This line is parallel to the permanent reference line normally used for this purpose which is visible at the top of the picture. In this first picture, the model axis is misaligned downward; in the second picture, it has recovered up to and slightly past zero misalignment. Now (3rd picture) it is near maximum amplitude in the upward direction, and in the fourth station, it is recovering toward zero again. We can see that stability exists in this flight. To determine its quantitative value, we measure the angles recorded in flight and make a graphical presentation of the kind shown in this chart. The angle is recorded in relation to the distance traveled. The distance to undergo one complete oscillation is indicated on the chart, and is a quantitative measure of the degree of stability. If the stability were increased by forward movement of the center of gravity, the distance required to perform one oscillation would be diminished. From the determination of wave length, the stability is quantitatively defined.

As an example of the application of these techniques to particular problems, we will describe an investigation completed in the spring of this year. The purpose was to compare the stability characteristics of two blunt bodies, both of which were indicated by earlier research to be satisfactory from the heating standpoint for hypersonic entry into the atmosphere. For reasons of military security, these models will not be shown. The two models had satisfactory and nearly equal stability in the sense we have described. The characteristics of one of the models are shown by chart 2 which shows values of the stability coefficient from five test facilities at this Laboratory. This group of facilities supplement each other to give the stability over a wide speed range. Note that of necessity the test techniques employed in all these facilities differ, particularly between the flight and wind-tunnel facilities, and that the models ranged in size from 1.5-inch diameter to 18-inch diameter. Nevertheless, in terms of the dimensionless coefficient of stability, the results form a consistent set. We are encouraged to believe that they will therefore have precise application to the full-scale missiles which they are intended to represent. Values plotted above the axis indicate a stable condition. Notice that this model as tested is stable throughout the speed range.

As mentioned above, the two models under study were essentially equal in respect to the kind of stability we have been discussing. This is termed static stability. Both models tended to return to a nose-forward attitude when disturbed. However, they were not equal in another important sense; in respect to what is termed dynamic stability. This concept will be illustrated by use of two models in the water tank. Notice that the first model, when dropped with initial misalignment, not only recovers nose forward, but that the resulting oscillation damps and disappears. The model is said to be dynamically stable. The second model, when dropped with very small disturbance, gradually gains amplitude and sometimes overturns. It is said to be dynamically unstable. To get another look at this interesting motion, we repeat the drop. Now these two different characteristics can be represented graphically as shown on this chart. At the top of the chart, we show an oscillation diminishing with distance traveled, representative of dynamic stability, while at the bottom of the chart there is shown an oscillation growing with distance flown, indicating dynamic instability. The diminishing type of oscillation is, of course, the desired one. Research has shown that the tendency for a dynamically unstable vehicle to build up oscillation is opposed during the early part of atmosphere entry by the rapid increase of air density during descent. During the latter part of the descent, however, the dynamic instability can take over and cause destructive oscillations. In the case of severe dynamic instability, the build up in amplitude can occur even during earlier parts of the descent. Hence, it was an objective of our research to compare the dynamic as well as the static characteristics of the two models.

The flight tests revealed one of the models to be dynamically unstable, and the other to be dynamically stable. This is indicated on chart 4. The degree of dynamic stability is plotted against the amplitude of oscillation. Values above the axis indicate damping; values below the axis, a diverging oscillation. These measurements showed that for both models the dynamic stability depended on the amplitude of oscillation. The second model became less unstable as the amplitude increased and appeared to be headed toward the stable region at slightly higher amplitude. This would imply what is called a "limit cycle" type of motion, which is characterized by a steady increase in the oscillation amplitude up to a limiting value which is that amplitude at which the change from dynamic instability to dynamic stability occurs. This type of motion also can occur in the water tank as illustrated by this model. This study reveals the flight characteristics of the bodies tested to be somewhat more complicated than one would initially suspect. However, it is clearly necessary to take these factors into account in order to anticipate correctly the behavior of the entering vehicle.

This example illustrates the role played by the NACA Laboratories in the development of new areas of aeronautics. In studying the stability characteristics of missiles and satellites making hypersonic entries into the earth's atmosphere, we come up against many technical problems. These problems must be solved to accomplish successful entries. We have illustrated the stability concept by water-tank experiments. We have shown a facility for determining the stability characteristics by flight tests at hypersonic speeds. Work of the kind we discussed has been carried out in relation to intercontinental missiles and is currently being extended to include the safe recovery of satellites. It will be carried forward to provide basic information needed for the successful design of a variety of manned satellites and space craft. We hope that this presentation has been of interest to you. Thank you for your attention.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., July 9, 1958

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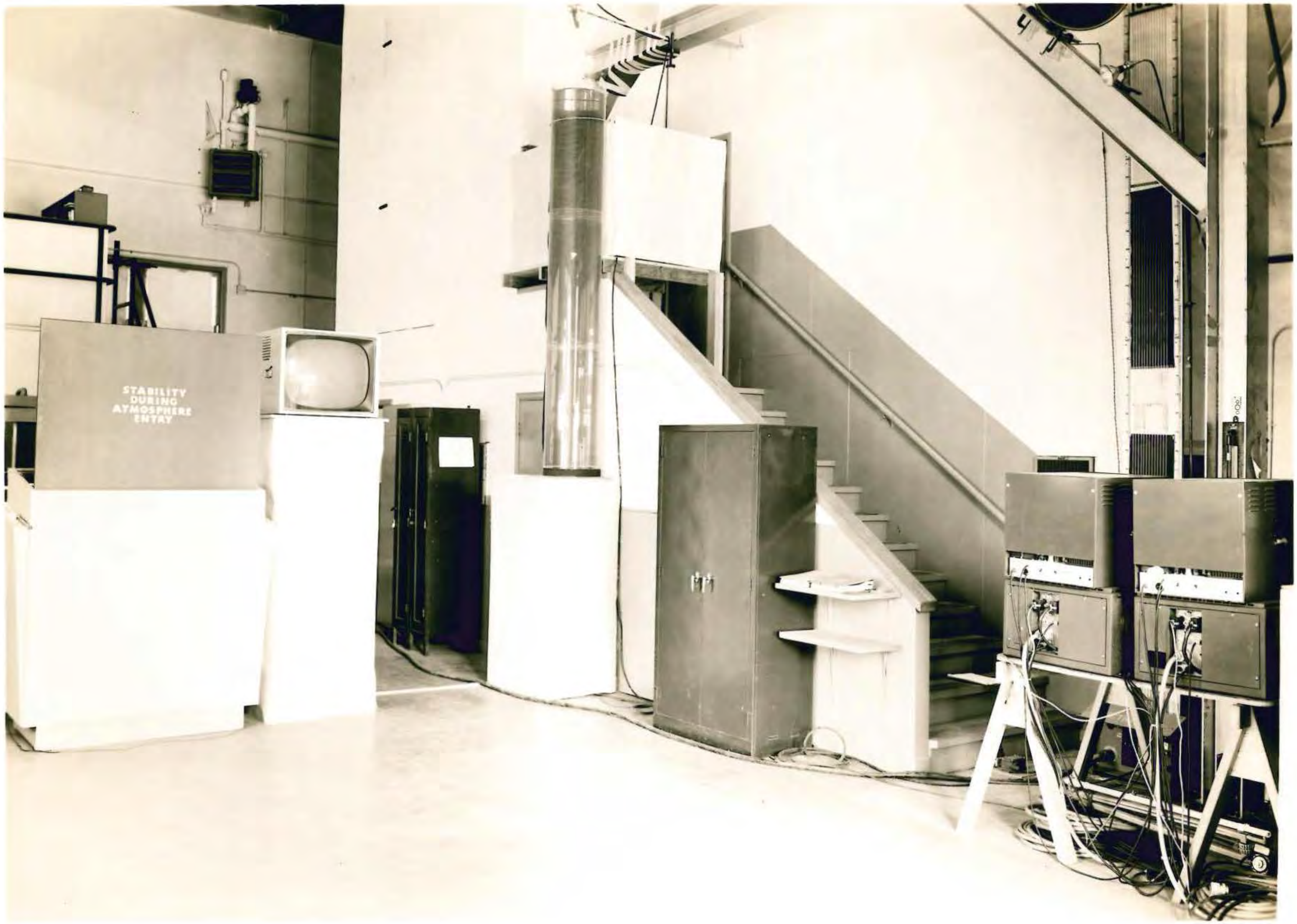

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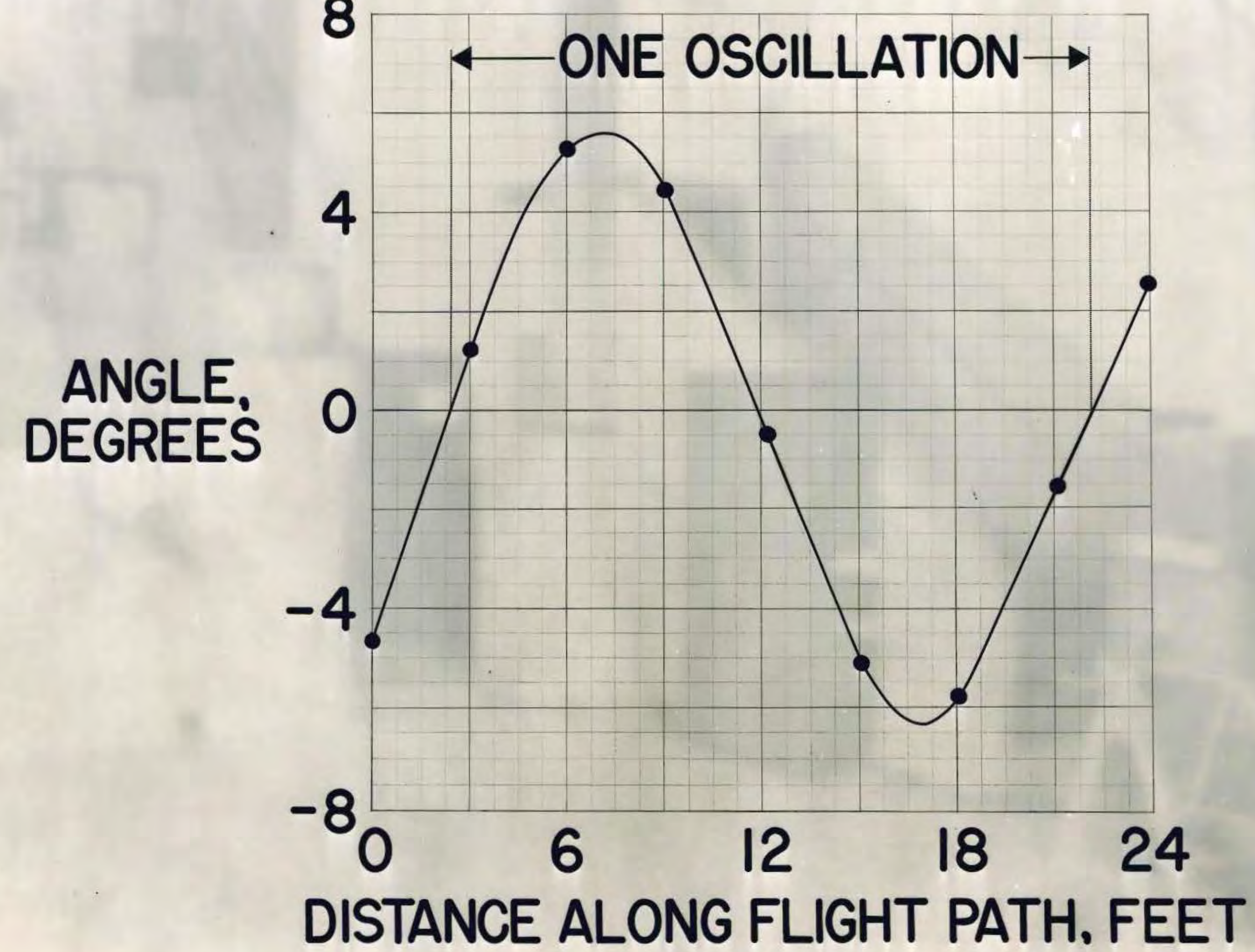
ANGULAR MOTION OF A MODEL IN FLIGHT



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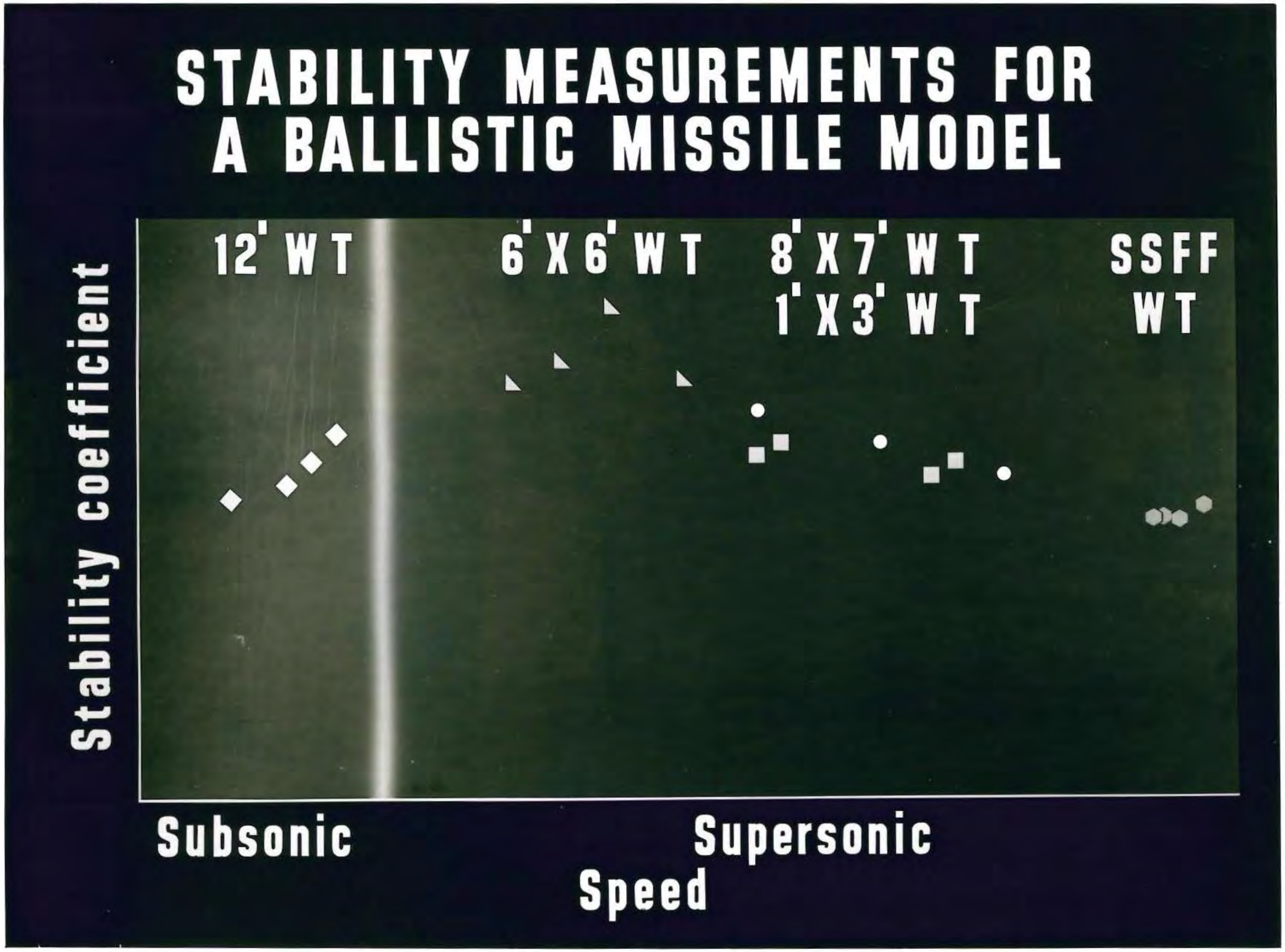
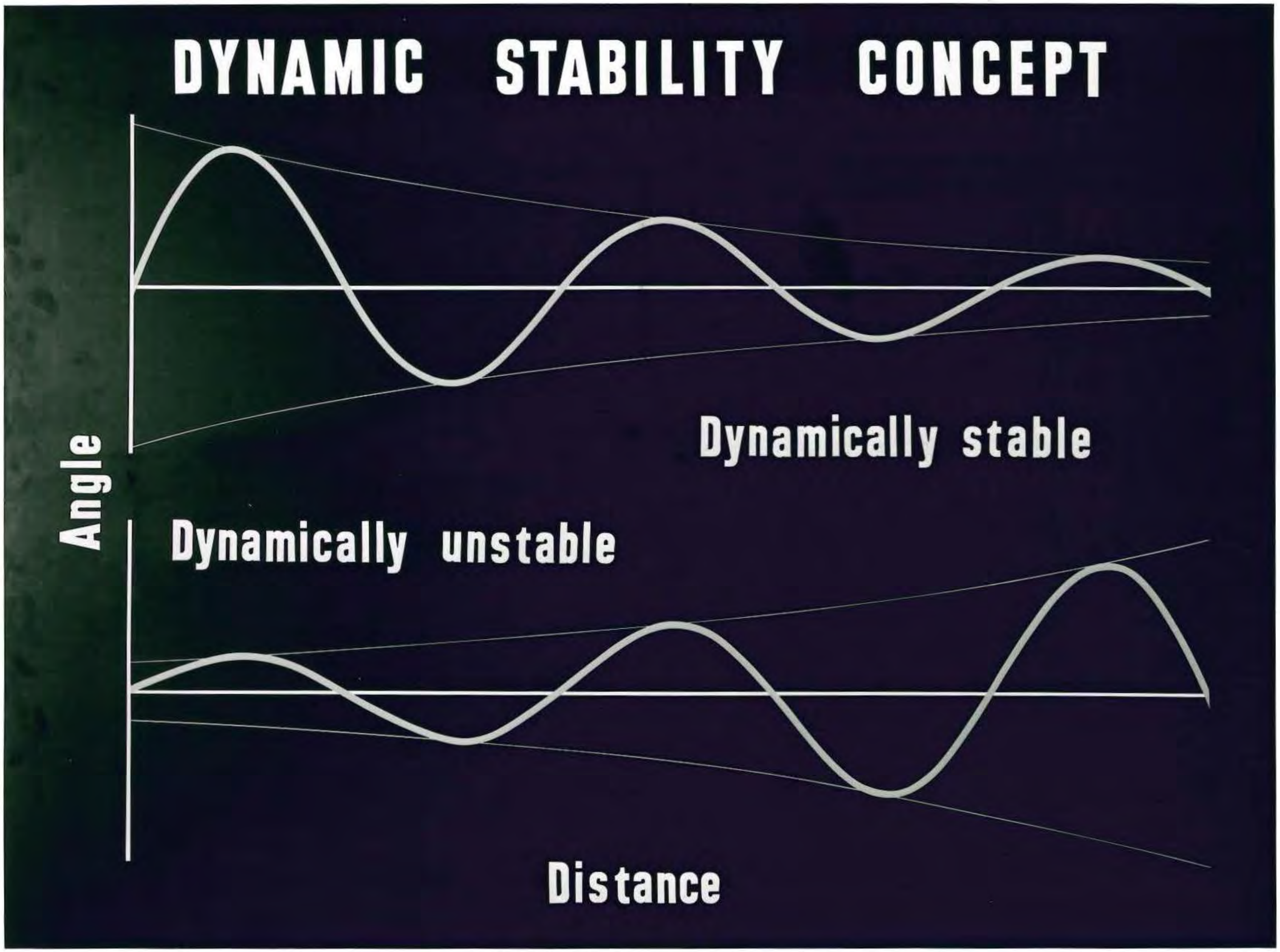

STABILITY MEASUREMENTS FOR
A BALLISTIC MISSILE MODEL
12' W T
6' X 6' W T
8' X 7' W T
1' X 3' W T
SSFF
WT
Stability coefficient
Subsonic
Supersonic
Speed



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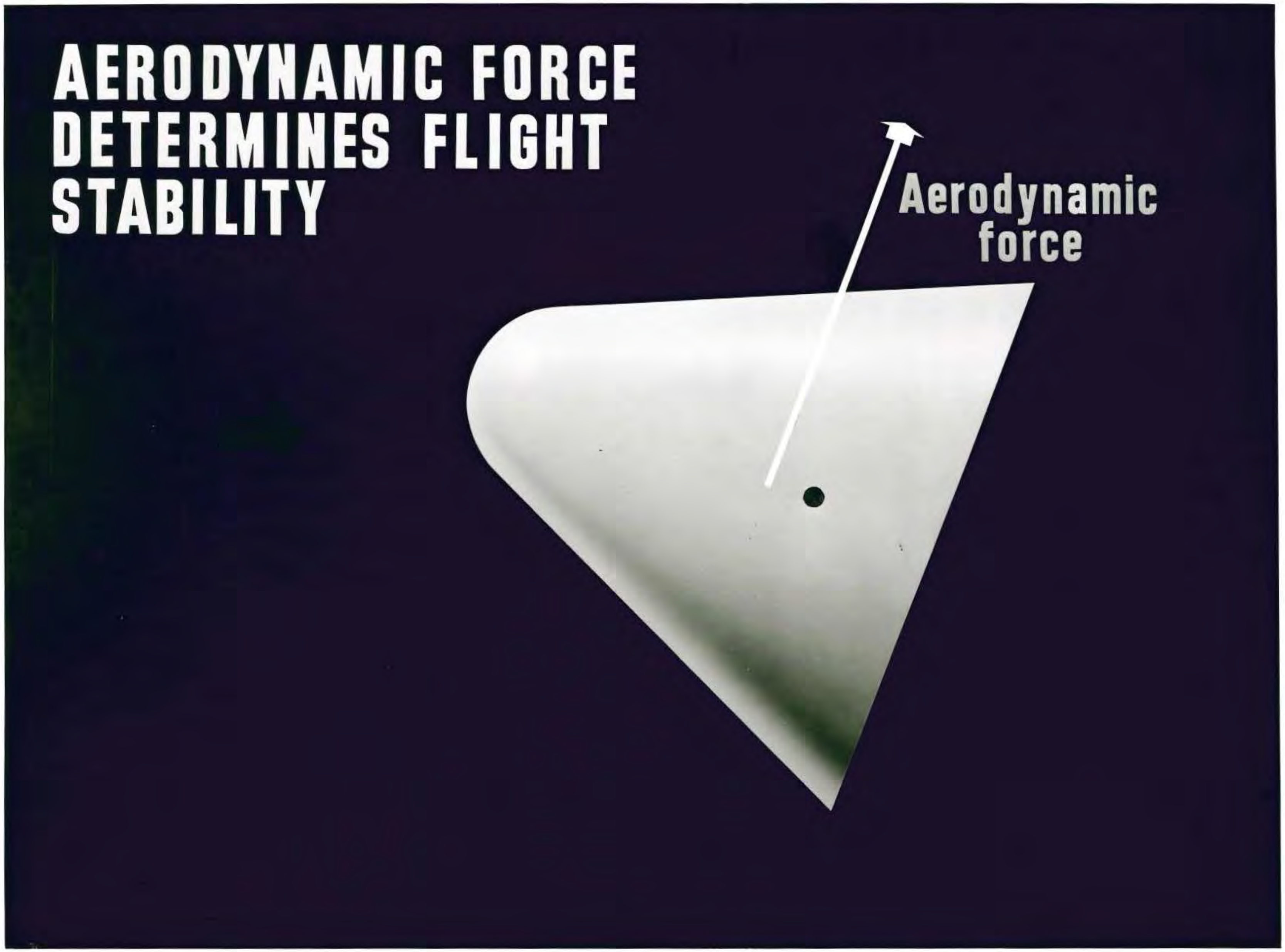

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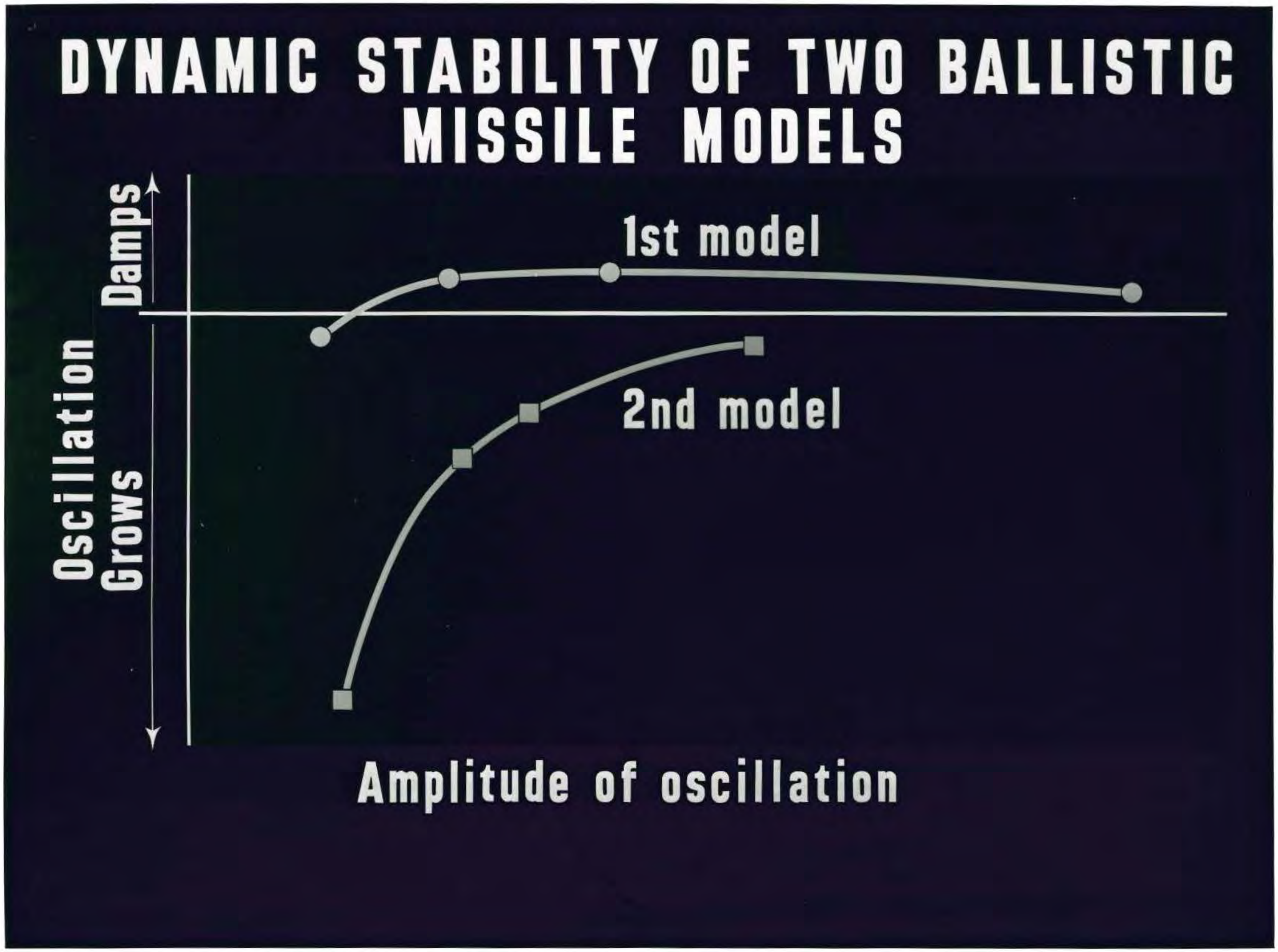
DYNAMIC STABILITY OF TWO BALLISTIC MISSILE MODELS
Damps
Oscillation Grows
1st model
2nd model
Amplitude of oscillation