STATIC STABILITY AND CONTROL

presented by

1- by 3-1/2-Foot Wind-Tunnel Section

Theoretical Aerodynamics Section

Early in determining the general arrangement of a new airplane or missile, the designer is concerned with the problem of making the new aircraft stable and controllable under all anticipated operating conditions. Various design criteria established after many years of experience have enabled the designer in the past to guarantee good flying qualities in terms of safety and ease of piloting in both steady and maneuvering flight. For today's flight speeds, however, the designer is confronted with many new problems to which the old design criteria are no longer applicable. It is our purpose here to acquaint you with a few outstanding problems and to show you what we of the NACA are doing to aid the designer in their solution.

Let us consider the longitudinal balance of an airplane. The airplane may be likened to the beam and pivot shown on this demonstration panel, where the force L is balanced by the much smaller force B at a greater distance from the pivot. The pivot corresponds to the center of gravity of the airplane, the force L corresponds to the lift acting at the center of lift of the wing, and B corresponds to the balancing force which must be developed by the longitudinal control surface of the airplane, whether it be a trailing-edge flap on the wing or a conventional tail. In our simple analogy essentially the same considerations apply for aircraft with or without tails, but here we will consider only the tailless type with control provided by a plain trailing-edge flap. We will thus replace the beam and pivot by this representative tailless, triangular-wing aircraft balanced for level flight at subsonic speeds.[1]

An airplane is said to be statically stable if the forces which develop when it is momentarily displaced tend to return the airplane to its position of equilibrium. The airplane shown here with the center of lift behind the center of gravity is stable because a nose-up displacement is accompanied by an increase in lift which acts to restore the airplane to its position of balance. Equilibrium is established when the moment of the lift about the center of gravity is balanced by the moment due to the control surface.

One of the greatest problems confronting the designer of supersonic aircraft stems from the fact that the center of lift of the wing moves rearward rapidly during the increase from subsonic to supersonic speeds.

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[1]A half-span model of the airplane is superposed on the beam and pivot illustrated on the demonstration panel.

The movement of the center of lift and its effect on the balance of the airplane can be illustrated with this simple working model.[2] As I increase the Mach number, the center of lift shifts rearward, the motion being most pronounced in the vicinity of Mach number 1. In order to maintain the airplane in balance, the force developed by the control surface must increase at a corresponding rate. The actual motions have been oversimplified and greatly magnified here in order that they may be seen more clearly.

The problem of maintaining balanced flight through the transonic speed range is still further complicated by a continuous decay in the effectiveness of the control surface itself. Thus, control deflections for balance become very large, resulting in reduced maneuverability and in higher drag and therefore in reduced aerodynamic efficiency. This subject is discussed to some extent in another exhibit concerned with high speed and range. The large control deflections required with a plain flap such as this introduce forces of such large proportions into the control system that the control surfaces cannot be moved without power boost. This very undesirable increase in control force for the triangular-wing airplane is illustrated in the first chart (Chart A). This chart shows the abrupt manner in which the control force for level flight increases as the airplane is accelerated from subsonic to supersonic speeds. The control forces for maneuvering flight, although greater in magnitude, vary in much the same manner. At subsonic speeds the control forces are within the physical capabilities of an average man (point to illustration) but at supersonic speeds a pilot of superhuman strength (illustrated here) would be required for direct manual control. Thus for a simple control of this type, the designer would have to provide a power boost system which, together with structural complications, would increase the weight of the airplane.

Since these large changes in control force and other stability and control problems are largely due to the movement of the center of lift which accompanies changes of Mach number, the NACA has directed its attention toward devising means of minimizing this movement. We have found that wing plan form is an important parameter in controlling the movement. On the next chart (Chart B) are shown three wings of widely different plan form with the over-all travel of the center of lift in the transonic speed range represented by the widths of these shaded regions. These wings were selected from a large number which have been investigated in the various NACA facilities, and the area of each wing has been adjusted to provide the required lift for landing. The over-all travel of the center of lift for these swept wings is seen to be less than for this unswept wing. If the variation with angle of attack in landing and maneuvering were also taken into account on the chart, the differences in the travel for the swept and unswept wings would be

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[2]The model has been constructed such that visual changes in center-of-lift position, balancing force, and control deflection occur as a Mach number indicator is moved slowly from 0 to 2.

somewhat less than shown here for the transonic speed range alone. For swept wings of higher aspect ratio the center-of-lift travel in maneuvering flight often gives rise to an abrupt pitch-up motion, a characteristic which is discussed in further detail at the research airplane exhibit. The center-of-lift travel, although minimized by the choice of certain plan forms, still remains a troublesome problem from the stability-and-control standpoint and is only one of several important factors which must be taken into account in selecting a wing for a particular type of aircraft.

The characteristics of the control surface also contribute to the large variations of control force with Mach number; accordingly, research effort is currently devoted to the development of more effective controls and to the reduction by aerodynamic means of the forces required to move the controls. Preliminary results of this research are illustrated on the next chart (Chart C). Here are shown the variations with Mach number of the control forces required in level flight for the triangular-wing airplane with a plain flap and with a flap balanced aerodynamically by altering the shape of the control surface in this region. (Point to chart). Forces for the plain flap are represented by the solid line. Forces for several of the more promising aerodynamically balanced flaps investigated to date are represented by this shaded region, inasmuch as our research program on controls is incomplete, and the optimum design has not been found. It is apparent that at transonic and supersonic Mach numbers these balances have substantially reduced the control forces and, therefore, also the power boost and structural weight that would be required to actuate the controls. The amount of the reduction in control force at a Mach number of 1.3 is shown by the relative sizes of these men (point out on chart). We are endeavoring to improve further the degree of control balance with the ultimate objective of providing means for designing control surfaces which can be operated manually at all speeds.

In the case of an aircraft with a tail the problem of providing adequate stability and control over the speed range is further complicated by the effect of the wing on the flow over the tail. The next speaker will discuss some aspects of the stability problem for aircraft having both a wing and a tail. (Introduce next speaker.)

As a result of recent theoretical work, it is now possible in many cases to calculate directly the lift and the effectiveness of a tail surface if the flow field in which it operates is known. So the problem of calculating tail loads and longitudinal stability is often one of determining the flow field at the tail location. In other words, we have to investigate the flow in the vicinity of the tail due to the presence of the wing and fuselage.

When a wing is producing lift, the air approaching the lower surface tends to flow outward around the wing tips and produces a circulatory motion behind the wing. As a result, the sheet of air leaving the trailing edge tends to curl up at the edges like this and eventually it rolls up into two trailing vortices. Perhaps you have seen these in the form of vapor trails behind airplanes flying in a humid atmosphere. Associated with this sheet of air, called the vortex sheet, is a circulatory motion throughout the entire flow field as illustrated here on this transparent plane. The flow field shown by the arrows can actually be calculated if the position and shape of the vortex sheet are known.

Theoretical analysis has shown that the vortex sheet rolls up more rapidly as the wing span is reduced. So on a missile like this one the vortex sheets would be essentially rolled up into trailing vortices at the tail location and the tail would behave quite differently than it would behind a wing of large span where the vortex sheet is relatively flat at the tail location. A wing combination like this one is called a cruciform wing and is often used on missiles that have to maneuver rapidly. However, the presence of the additional wing surface complicates the problem of determining the flow field. Not only are there now two vortex sheets rolling up into four trailing vortices behind the wing, but the behavior of each sheet is affected by the presence of the other. This mutual influence causes intricate vortex patterns that depend on the wing geometry and the angle of bank. We are going to illustrate one example shortly.

So far we have not discussed the presence of the body or fuselage which will certainly affect the flow field in the vicinity of the tail. Recent theories and experiments have shown that at moderate angles of attack the body itself gives rise to a pair of vortices starting from the body nose and trailing back above the body surface. So now we have, for a missile like this one, the four vortices from the wing panels and the two from the body. The body, of course, besides producing its own vortices, influences the paths of the ones shed by the wing.

Considerable theoretical and experimental work is being done at this laboratory on the flow fields produced by various wing and body combinations and several interesting techniques have recently been developed for visual studies. One method involves a tank of water instead of a wind tunnel and the model is driven into the water on a vertical track. By the use of aluminum powder, the vortex sheet is made visible on the water surface and can be photographed from above. This gives the same view of the flow field as would be seen here on the transparent plane if we moved the plane progressively downstream. Since the vortex sheet behind a wing moving slowly through water behaves essentially the same as one behind a wing moving in air at either subsonic or supersonic speeds, these pictures give a useful guide for more elaborate theoretical and wind-tunnel studies. We will now show a brief movie of some simple models tested in the water tank. These are wing models with no fuselage.

Here is an over-all view of the water-tank apparatus with a plane-triangular-wing model mounted on the strut. . . . The camera is mounted directly above the model. . . . . Now the dry aluminum powder is being applied to the trailing edge. . . . . Here we are setting the angle of attack, and now we will have a sample run to demonstrate the equipment. . . . . You will notice the small pilot model on the side that indicates the depth of the real model in the tank. . . . .

Here is an actual run as seen from the camera above the model. This is a triangular wing of aspect ratio 2 at 20^{o} angle of attack. . . . Notice that the center of the sheet moves down while the rolled-up portions trail straight back as indicated by the side markers. . . . Here is the same run repeated. . . . As you can see from the pilot model, this run takes us about three chord-lengths behind the wing. . . . This is again the same wing but with aluminum powder on the water surface to show the entire flow field. . . .

Now we have a cruciform triangular wing banked 45^{o} at an angle of attack of 17^{o}. The phenomenon you will see here of the upper two vortices passing between the lower two actually occurs within a few chord lengths behind the wing.

For the simpler cases where the vortex sheets roll up into trailing vortices in a very short distance and follow regular patterns, like the ones you have just seen, we have succeeded in predicting the paths of the vortices with reasonable accuracy. With this information we can calculate the flow field at the tail and from that determine the contribution of the tail to the stability of the aircraft. The value of such a calculation can be seen from this chart. We have plotted here on the dashed curve the experimental pitching moment or nose-up or nose-down tendency experienced by a missile of this type at various angles of attack. The downward trend in the green regions indicates that if the missile deviates from its path in a nose-up direction it develops an increased nose-down tendency. This is typical of a stable airplane or missile. In the red region, the opposite trend occurs so the missile is unstable in this range. In fact, one can think of a stable aircraft as sitting in the bottom of a trough like this, so, if it moves away from this equilibrium position, it rolls back again. On the other hand, an unstable aircraft is, in a sense, balanced on a hilltop and once disturbed does not return to equilibrium. The cause of the instability in this angle range was not generally understood until quite recently when calculations were made of the positions of the rolled-up vortices behind the wing. From these positions, the flow field at the tail and the stability of the missile were calculated and the results are shown on the solid curve. The agreement between the theoretical and experimental curves is remarkably good here considering their extreme variations. This indicates that the calculations have taken account of the essential features of the flow causing the instability so that we are now in a position to determine appropriate design changes.

While these results show that for some cases our knowledge of the flow field is quite adequate, there are many conditions where additional effects become important. In these cases we cannot as yet predict the flow fields accurately, but our research is aimed in that direction at the present time.

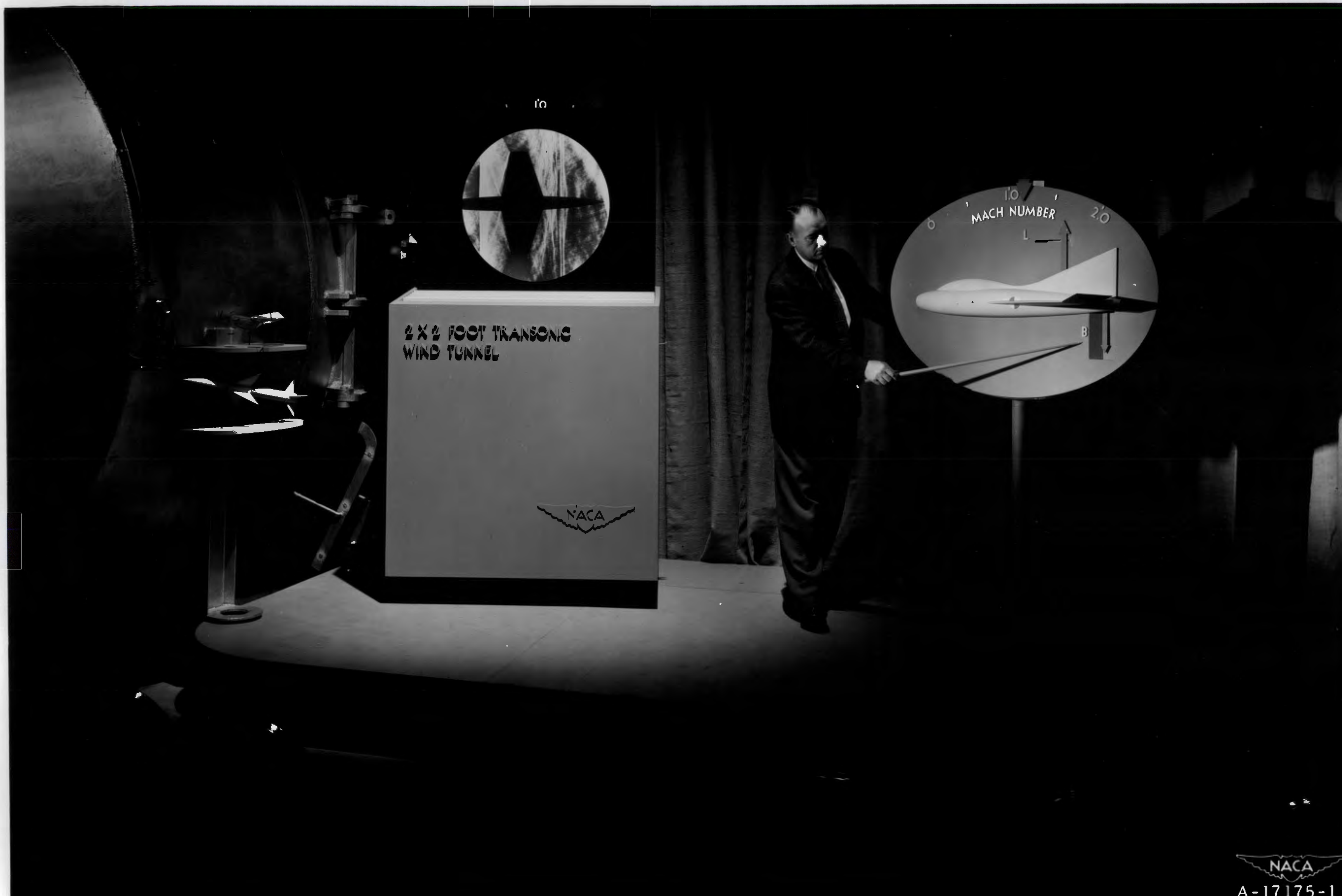
So far we have discussed some general aspects of the problems of stability and control. As you recall, the first speaker pointed out that these problems are particularly difficult when the airplane is traveling near the speed of sound. The next speaker will describe and demonstrate for you one of the test facilities recently put in operation for research on these and other problems in the transonic speed range.

Until recently experimental facilities for research studies at transonic speeds were few and had generally been developed as temporary expedients for obtaining research information in this speed range. However, as some of you learned at the Langley Laboratory Inspection a year ago, the NACA has succeeded in developing a number of transonic wind tunnels employing so-called "ventilated" test sections by means of which airspeeds can be varied continuously and smoothly through a Mach number of unity from subsonic to supersonic values. The transonic tunnel promises to be a valuable research tool from two standpoints. Not only is it free from the choking phenomena which prevent the attainment of transonic Mach numbers in conventional wind tunnels but, by reducing the interference of the walls on the flow over the models, permits the testing of larger models under flow conditions more nearly representative of full-scale free flight.

The 2- by 2-foot wind tunnel to your left is a transonic tunnel which has recently been put into operation. It is a variable-density wind tunnel with a test section 2 feet square and is presently being used in the investigation of some of the stability and control problems discussed here today.

We will demonstrate this equipment for you by establishing successively subsonic, sonic, and supersonic flow over a typical research model. Because my voice cannot be heard above the noise of the equipment, I will describe the course of events before operating the tunnel. By means of a schlieren optical projection system you will see the silhouette of the model in the test section in plan view as illustrated on this photograph. The tunnel speed will be increased steadily to a Mach number of 1, at which point you will observe standing shock waves about the model in an approximately vertical plane. For the majority of you this will be your first opportunity to witness continuous sonic flow. Supersonic flow will then be established and you will then see the shock waves become increasingly inclined. The Mach number will be indicated by the dial at the top of the projection screen.

Display for presentation of "Static Stability and Control"



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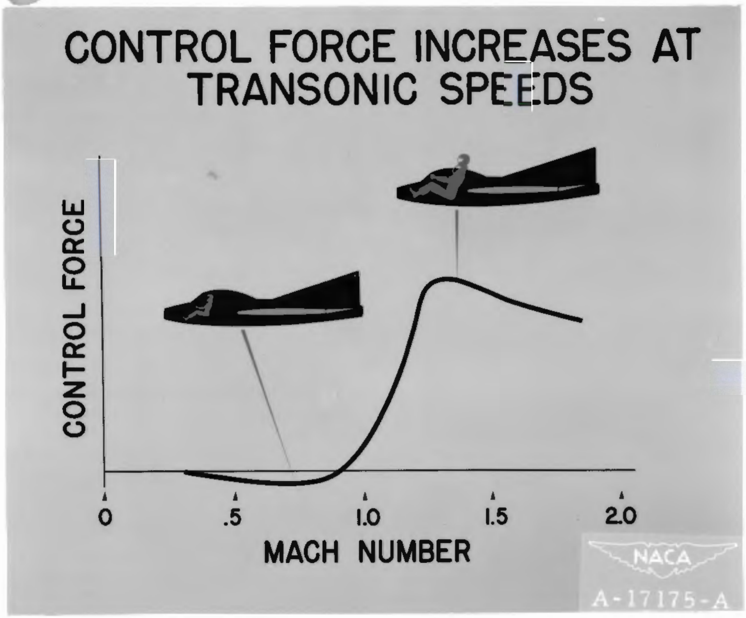

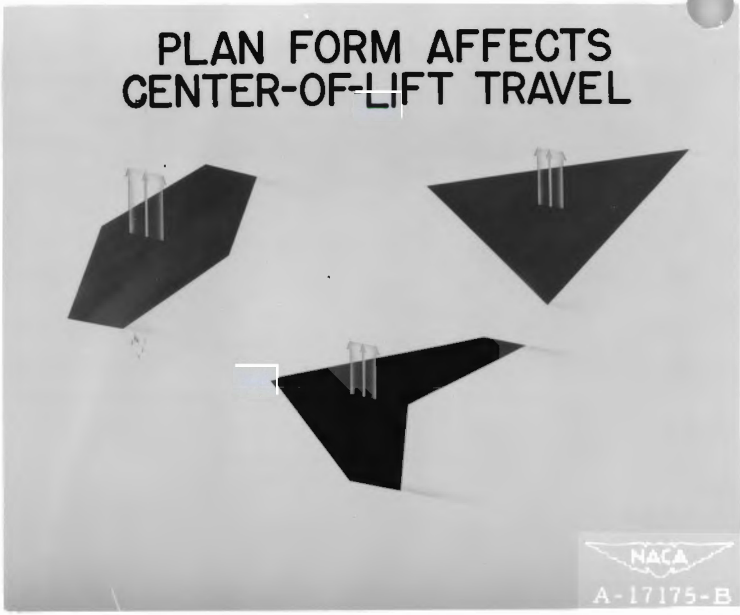

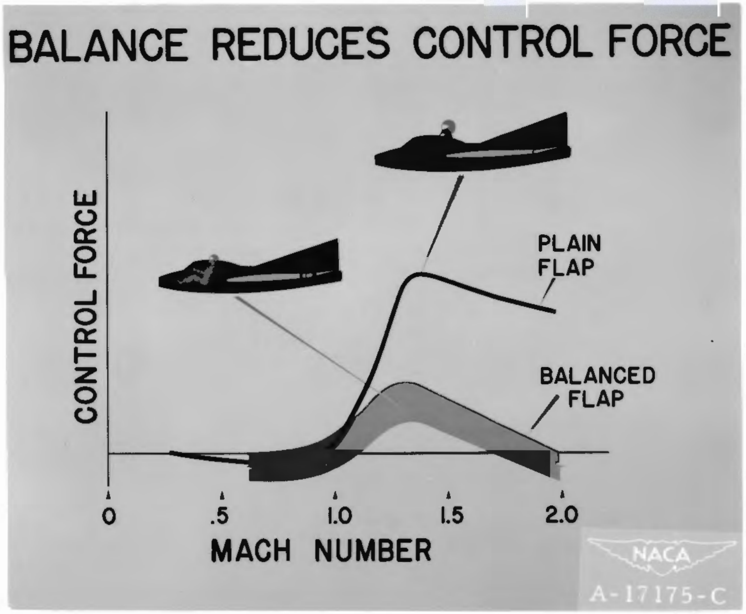

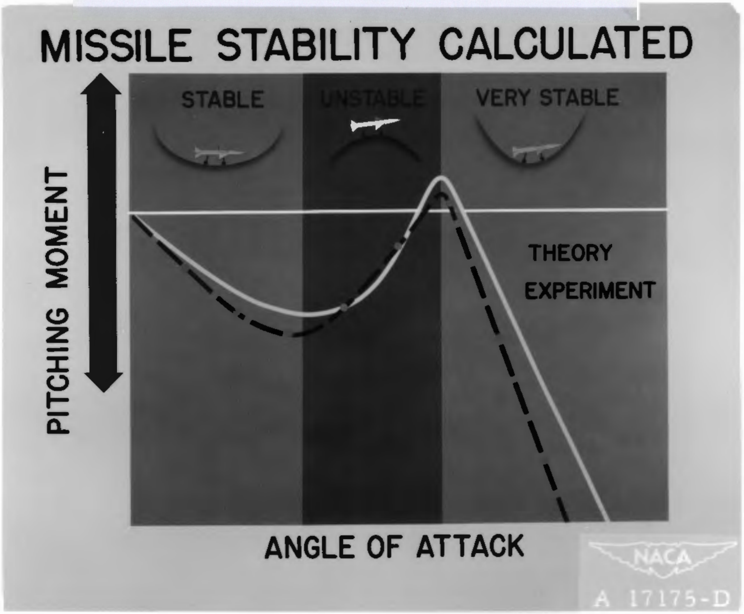

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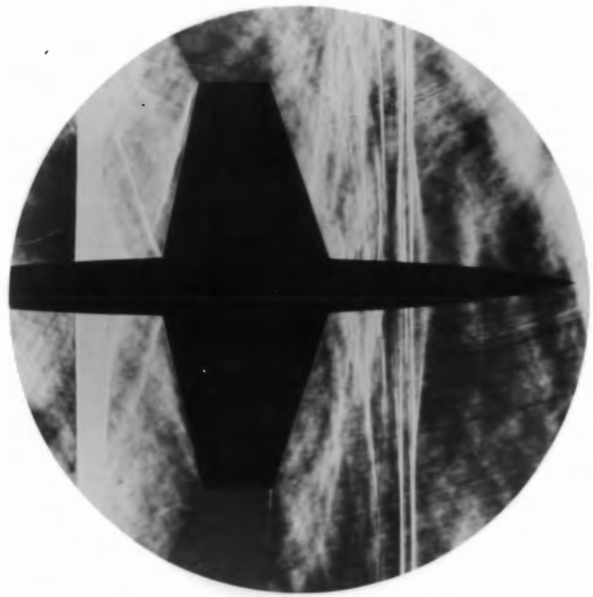

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