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Airc. Loads Calibration Lab

AEROELASTIC PHENOMENA OF SWEPT WINGS

A TALK GIVEN AT THE 1949 BIENNIAL INSPECTION OF THE LANGLEY AERONAUTICAL LABORATORY

By Franklin W. Diederich and Martin Zlotnick

Aeroelastic phenomena involve the interaction of aerodynamic forces and structural deformations. They tend to be important when the aerodynamic forces are large, which occurs at high speeds, and when the structure is relatively flexible, as for instance the structure of a thin wing, a swept wing, or a wing designed for low wing loading. Of the many conceivable aeroelastic phenomena we will concern ourselves only with a few of the quasi-steady ones; aerodynamic center shift, divergence, loss of control and control reversal.

When a wing carries a load it is subjected to bending and twisting forces which tend to deform the wing. With the aid of this model, which represents a sweptforward wing, it is seen that the load tends to increase the angle of attack at the tip. Hence the tip tends to load up; as a result the center of the wing lift, usually refereed to as the aerodymamic center, moves out toward the tip and tharefore forward. The outward shift of the load leads to higher stresses in the structure, the associated forward shift of the aerodynamic center affects the stability of the airplane. If the speed is sufficiently high the wing may twist off altogether; this speed is known as the "divergence" or "elastic divergence" speed.

If this wing were sweptback, the load would tend to decrease the angle of attack at the tip; this would cause an inboard and forward shift of the aerodynamic center, as well as a decrease in the over-all load. Consequently, a sweptback wing cannot diverge.

The purpose of an aileron is to cause a change in lift on the wing. In so doing it gives rise to twisting forces as well, which tend to decrease the angle of attack at the tip and hence to decrease the lift created by the aileron. This aeroelastic action consequently results in a certain amount of loss in the aileron control. If the control is lost altogether the aileron reversal speed is said to have been reached.

A great deal of work at the Langley Laboratory has been directed in the past few years toward devising a reliable and convenient systemic procedure for analyzing aeroelastic effects on swept wings from known physical and geometric characteristics of the airplane. A few calculations have been made by means of this procedure and allow us to discuss in a general way the effect of sweep on some aeroelastic phenomena.

On the chart a speed factor, which consists of the ratio of the design speed to a parameter based on the stiffness, size, type of construction and similar properties of a wing, is plotted against the sweep,-- sweepback on the right sweepforward on the left. The factor is plotted for the phenomenon of aerodynamic center shift -- which was described by means of the model --, for divergence, control loss, -- as previously described --, and aileron reversal. Also shown is the relative position of flutter. Since flutter depends on more parameters than the other phenomena its relation to the others is somewhat uncertain, so that a range of flutter speeds is shown.

It is seen that for sweptforward wings a 2 percent shift in aerodynamic center as previously described on the model is encountered even at relatively low speeds. The figure of 2 percent is chosen arbitrarily; whether or not it is significant depends on the other stability parameters of the airplane. If the airplane can be made to travel at sufficiently high speed it will next encounter aeroelastic divergence.

An unswept wing is not as likely to encounter aeroelastic difficulties. If it does they may be flutter, reversal, or divergence, but they will occur only at very high speeds. For a moderately sweptback wing control difficulties will tend to constitute the most important aeroelastic problem. For highly sweptback wings, on the other hand, significant shifts in the aerodynamic center may be encountered even at relatively low speeds; again the figure of 2 percent is chosen arbitrarily. At higher speeds the wings will tend to run into control difficulties and ultimately into control reversal, if the speed is sufficiently high.

This chart may be used to throw some light on the old controversy of strength against stiffness as design criteria. The two terms are not synonymous; strength means ability to carry a load, stiffness means the ability of carrying the load with little structural deflection. It is obvious that a wing must be strong enough to carry its load. The importance of stiffness is not nearly so obvious; it arises largely from aeroelastic considerations.

This chart has been plotted in such a way that the lines on it indicate the speed at which a wing will run into aeroelastic difficulties if it is designed on the basis of strength considerations alone. The swept-wing airplane shown on the chart, for instance, which is typical of current design practice, would experience an aerodynamic center shift of about 3 percent and a loss of control in the order of 70 percent if it were designed for strength alone. Since these figures are usually deemed excessive the structure would have to be stiffened beyond the amount associated with the required strength.

In contrast to the swept-wing plane, the unswept airplane shown on the chart, which is also typical of current design, appears to be quite free from aeroelastic difficulties, provided its design for strength is based on the best available aerodynamic parameters.

While only relatively few specific calculations have been made by means of the methods of analysis developed at this Laboratory and while only quasi-steady phenomena have been treated so far for swept wings, a certain insight into the phenomena has been gained which has allowed us to draw some general conclusions and which has shed some light on the questions of strength and stiffness as design criteria.

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MAXIMUM LIFT

A TALK GIVEN AT THE 1949 BIENNIAL INSPECTION OF THE LANGLEY AERONAUTICAL LABORATORY

By Paul W. Harper and Roy E. Flanigan

In connection with projected airplane and missile designs the subject of maximum lift and the associated buffet boundaries have become increasingly important from both the structural and maneuvering standpoint. From work which has been accomplished at the NACA it is possible to illustrate the general problem as well as to present some recent results obtained in special investigations of maximum lift and buffet boundaries.

The first chart gives an overall picture of the maximum lift and buffet boundaries to a Mach number of 2. The ordinate scale is lift coefficient, and the abscissa is Mach number. Maximum lift is given here by the blue curves which are the upper boundaries of the red shaded areas. These shaded areas represent known or probable buffeting regions. An airplane, flying at lift coefficients and Mach numbers given by the shaded areas experiences a general vibration or shaking which results indirectly from wing flow separation.

The results were obtained from many sources, both experimental and analytical, and do not apply in their entirety to any one airfoil.

For purposes of discussion the chart can be divided into 3 broad Mach number regions. The subsonic region - for speeds below a Mach number of approximately 0.8; the transonic region -

for speeds between approximately 0.8 and 1.2; and the supersonic region for all higher Mach numbers.

In the better known subsonic region the lower blue curve is typical of the variation of maximum lift which might be obtained from steady wind tunnel tests of a low drag airfoil. It is known that, among other variables, the maximum lift in this region depends to a large extent on the abruptness of the pull-up preceding stall. The approximate increase in lift to be expected due to this factor is given by the upper blue curve. So far as is known this factor is ineffective at higher Mach numbers. Buffeting in the subsonic speeds occurs only at maximum lift.

At supersonic Mach numbers the maximum lift boundary given by the blue curve above M = 1.2 is based primarily on wind tunnel tests. Such tests have indicated the existence of buffeting at these speeds. Its possible extent and severity are illustrated by the intensity of the shading.

In the transonic region the maximum lift boundary given by the dashed curve has been established partly by limited experimental data and partly by fairing between the better known maximum lift boundaries to either side. It is seen that buffeting now occurs over a considerable range of lift coefficient. The so called buffet boundary given by this line has been well established by flight tests. The intensity of shading indicates that at a given Mach number buffeting becomes more severe as maximum lift is approached.

The next chart shows the pressure distributions and wakes which are associated with maximum lift and which are believed typical of the various Mach number regions. Those typical of the subsonic region are given at the bottom for a Mach number of 0.4. The angle of attack at maximum lift is about 12° in this case. Because of the steep adverse pressure gradient near the nose, separation occurs at the nose and effects the whole upper surface of the airfoil. The solid curve behind the airfoil illustrates the energy loss in the wake-- the dotted curve representing the amplitude of fluctuations behind the wing shows that these fluctuations extend beyond the confines of the wake.

The middle figure given for a Mach number of 0.9 is considered typical of conditions in the transonic region. Here the angle of attack at maximum lift is approximately half that for subsonic speeds. Also, the steep adverse pressure gradient occurs around the middle of the airfoil so that the separated portion covers only half the upper surface, and the wake, as a consequence, may be narrower. Measurements made with the F-51D airplane have indicated less severe buffeting in the transonic region than in the subsonic region but penetrations have not been made very far above the buffet boundary.

Schlieren photographs have indicated that at supersonic speeds a wake may exist somewhat as shown in the upper figure. Maximum lift now occurs at angles of attack around 45° and separation may possibly occur well forward on the airfoil.

The next chart illustrates to some extend the importance of maximum lift in terms of load factor and altitude. Here, the load factor on the ordinate scale is plotted against Mach number. The limiting loads and buffeting zones are given for two altitudes, sea level and 50,000 feet. These lines which represent the maximum accelerations in the V-g diagram correspond to the maximum lift boundaries given in the first chart. The small inset figures represent the pilot "g" tolerances for the normal and the prone positions. The main point to be noted is that at relatively high altitudes maximum lift limits the obtainable load factor to values below the "g" tolerances over a wide range of Mach number. At 50,000 feet the "g" tolerance for the normal position is only exceeded above a Mach number of 1.4, and the "g" tolerance for the prone position is only exceeded above a Mach number of 2.

It has been known for some time that maximum lift is affected by the pitching velocity during the pullup so that higher loads may be obtained in flight than tunnel tests indicate. In order to evaluate this pitching velocity on the lift effect, wind tunnel tests were made on the small model which you see om your left. The model is designed to rotate throughout an angle of attack range from -3° to +30° at various constant rates of pitching velocity equivalent to full scale conditons. A short period of rest occurs prior to each pullup to permit steady flow conditions to resume.

In the next chart are seen some systematic results obtained with this model up to a Mach number of 0.8. The pitching velocites indicated correspond to full scale. The lower curve gives the maximum lift for zero pitching velocity. The upper curve gives the limit value of the coefficient obtained. No further increases in lift were noted for higher pitching velocities. It is seen that the curves merge at a Mach number of about 0.6 The line is shown dotted above this Mach number because a definite maximum in the lift curve was not obtained. The lower dotted curve labeled "buffeting boundary" represents the lift coefficients at which the records indicated force oscillation.

We have supplemented our experimental work on maximum lift with analytical studies. The next chart illustrates the degree of success attained. This chart showing force coefficient against angle of attack applies to a Mach number of 2.3 and shows by the circles and squares the measured lifts and drags. The dotted curves to the left of the vertical line are computed results obtained from the usual linear theory. To the right of the vertical line the shock wave becomes detached and linear theory can no longer be applied. In this region a semi-theoretical method has been developed which as you can see predicts the lift and drag very well throughout the maximum lift range.

In summary, it appears that in the subsonic and supersonic regions maximum lift can be obtained either by computation or by recourse to existing experimental data. In the transonic region the boundaries are as yet only approximate. In the subsonic range tests have shown a very narrow region of high intensity buffeting which occurs simultaneously with $C_{L_{max}}$. The region of buffeting and the intensity of buffeting in the transonic and supersonic regions are still largely unknown.

A FLIGHT INVESTIGATION OF THE EFFECT OF COMPRESSIBILITY ON APPLIED GUST LOADS

by Jack Funk and Philip L. Smith

One effect of compressibility at subcritical speeds in steady flow is to increase the slope of the lift curve with Mach number. If this increase is applied to gust load calculations the gust load is increased in proportion. As an illustration of this effect, the gust load factor computed for a high speed airplane is shown as a function of flight speed on this chart. The lower line was calculated assuming that the lift curve slope was independent of Mach number so that the load factor increases directly with speed at any altitude. The two upper curves were calculated for sea level and 20,000 feet assuming that the usual steady flow compressibility correction applies. It can be seen that the load factor increases more rapidly when the compressibility correction is applied than when it is neglected. The chart indicates that at a Mach number of 0.7 at sea level, the load factor increases from about 4.3g to 5.7g, or about 25%. If this 25% increase is applied to airplane design, it would result in a significant increase in structural weight.

Since the application of steady flow results to transient conditions is somewhat in doubt, a flight investigation of the effect of compressibility on gust loads was undertaken by the NACA and the All Weather Flying Division of the U. S. Air Force. The flight tests consisted of flying jet propelled airplanes through clear, rough air over a given course at one altitude but at different speeds. From the measured reactions of the airplane, the turbulence pattern for each flight was determined. If the correct equation relating the airplane reactions to the turbulence pattern is used to obtain the gust frequency distributions, then all distributions should be the same regardless of speed. If we have made the wrong assumption in regard to any factor, then the flights at different speeds would show different distributions.

The next chart shows the test results for speeds of 200, 350 and 450 mph. The corresponding Mach numbers were from .28 to .62. The plot represents the gust frequency distributions expressed in miles or exceed a given gust velocity when compressibility effects on the slope of the lift curve are neglected. It can be seen that the gust experience at the three speeds is in excellent agreement. On the basis of our flight test procedure, therefore, it is concluded that compressibility does not enter into the computation of gust loads for the test airplane. The results shown here were verified by other tests at 200 and 500 mph, or up to a Mach number of .68.

It is not known whether these results apply to all airplanes and further studies are necessary. It is apparent, however, that if the results could be generally applied, a 25% reduction in gust load factor at a Mach number of 0.7 is obtained. This reduction might result in decreased airplane structural weight, or an increase in performance, payload or range.

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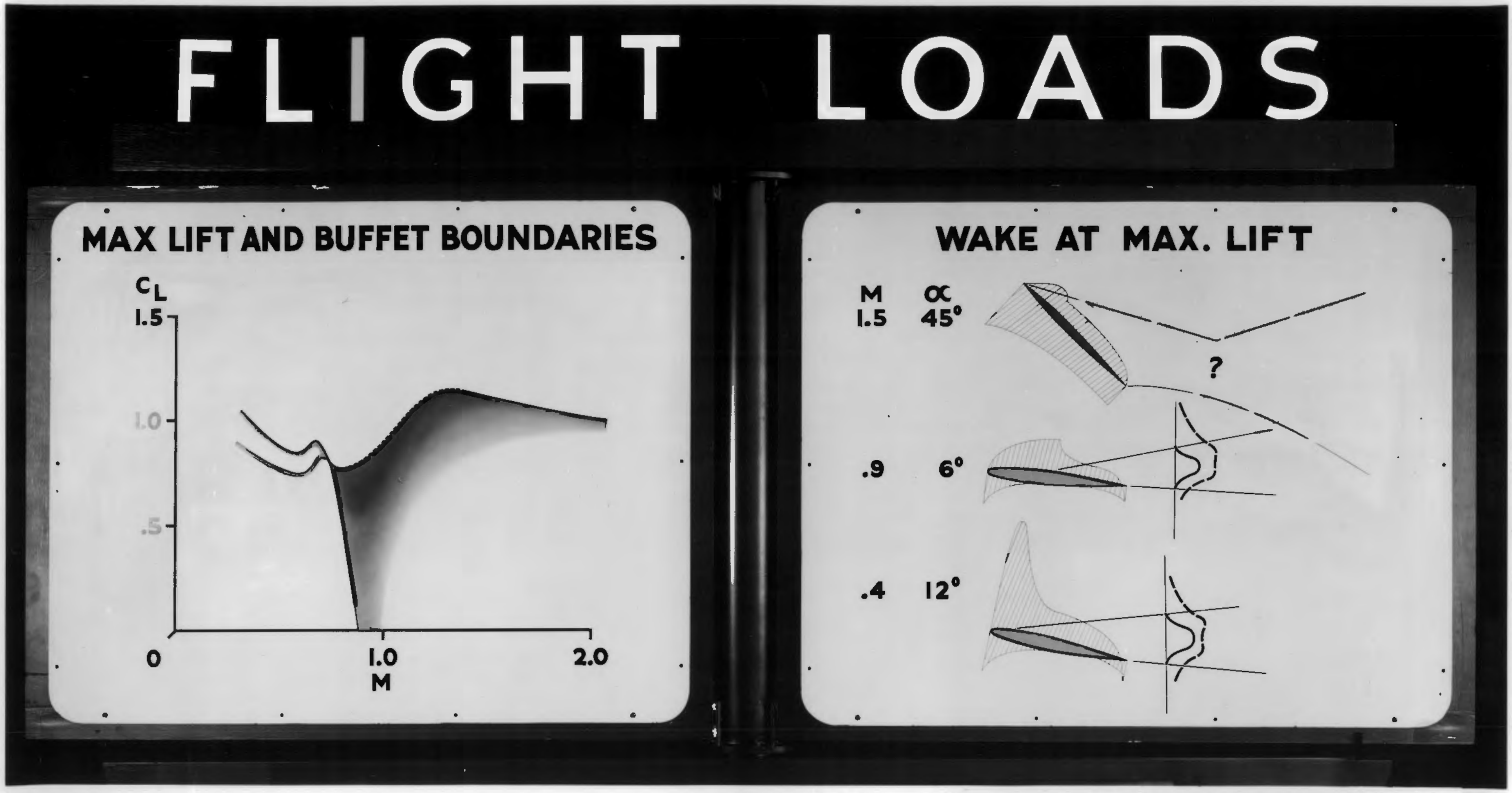

FLIGHT LOADS

MAX LIFT AND BUFFET BOUNDARIES

WAKE AT MAX. LIFT

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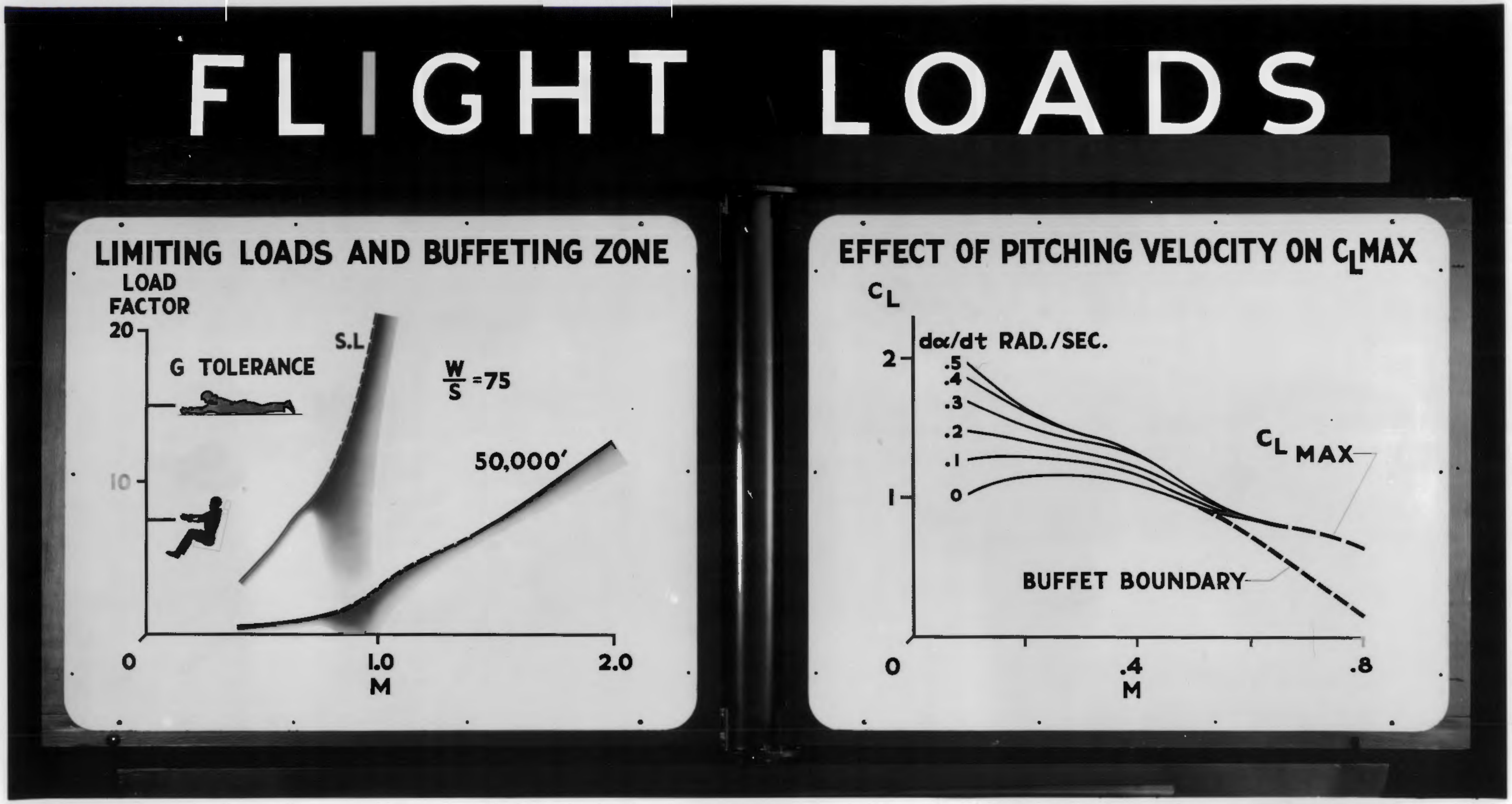

FLIGHT LOADS

LIMITING LOADS AND BUFFETING ZONE

EFFECT OF PITCHING VELOCITY ON C_LMAX

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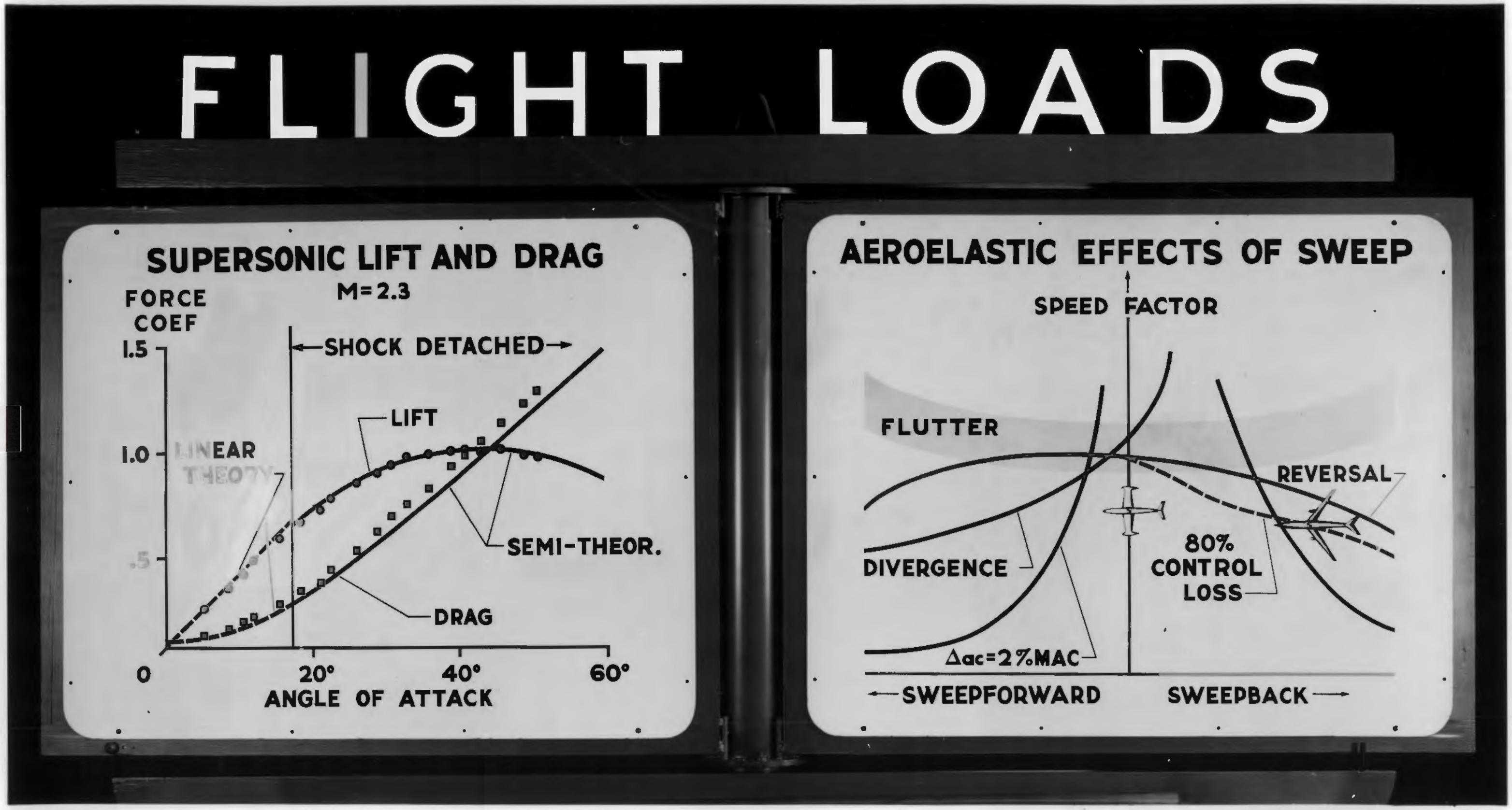

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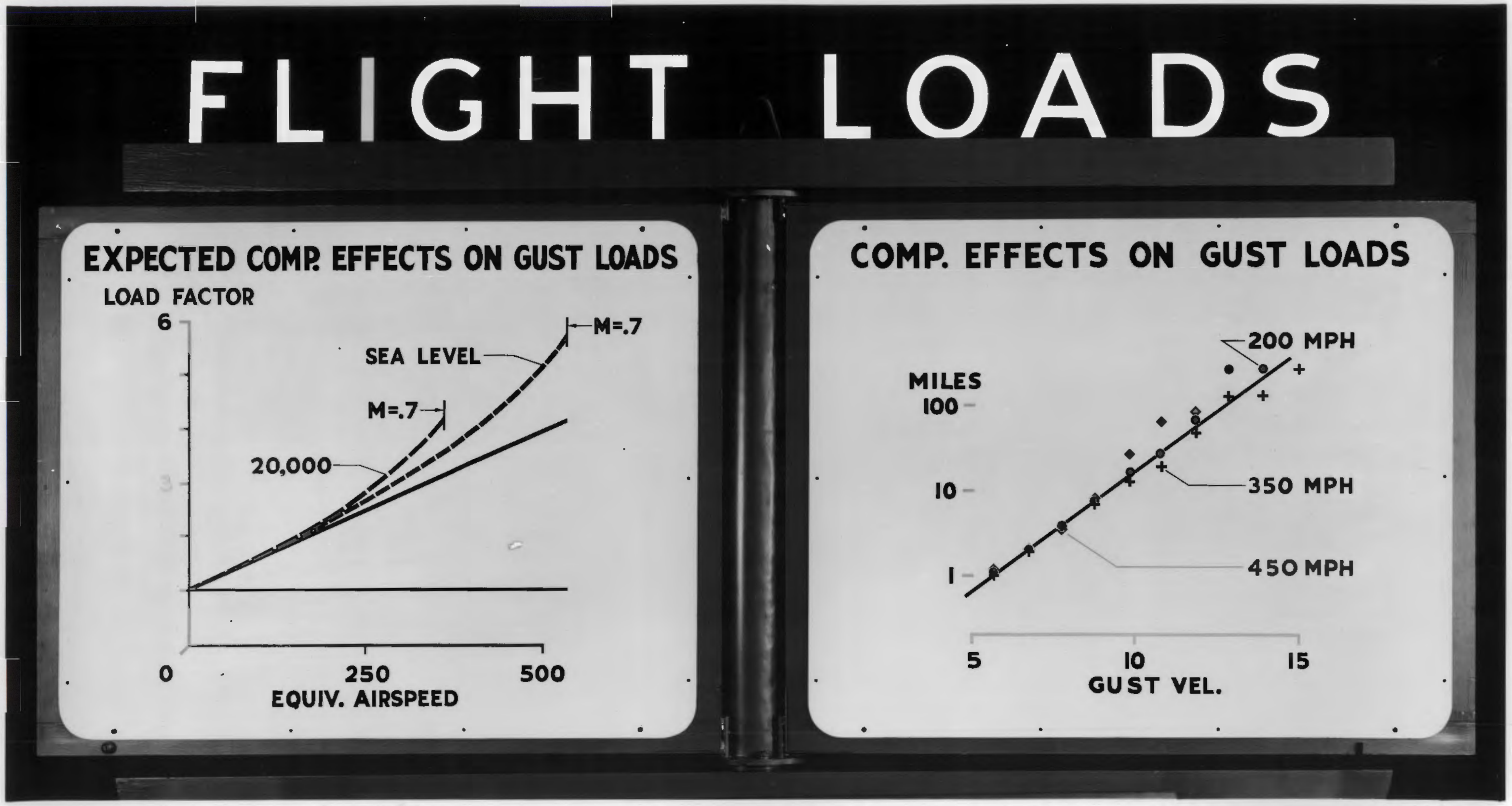

FLIGHT LOADS

EXPECTED COMP. EFFECTS ON GUST LOADS

COMP. EFFECTS ON GUST LOADS

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