FLYING AND HANDLING QUALITIES OF AIRPLANES

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By the flying qualities of an airplane are meant those stability and control characteristics which have an important bearing on the safety of flight and on the pilot's impressions of the ease of controlling an airplane in steady flight or in maneuvers. This paper will describe briefly the progress which has been made in setting up requirements for satisfactory flying qualities and will discuss some of the methods for predicting these qualities from calculations and wind-tunnel tests.

In the years prior to the war, relatively little was known about what characteristics of an airplane constituted satisfactory handling qualities. This does not mean that there had been no research on the subject of airplane stability. A great deal of theoretical work on this subject had been done. This theoretical work, however, was not able to take into account the characteristics of the human pilot and his relation to the airplane. On the other hand, human pilots had for many years expressed opinions with regard to the handling qualities of aircraft, and it was known that in some cases their opinions conflicted with the results of the theory. In developing a new airplane, therefore, there was no reliable procedure to provide for satisfactory flying qualities in the original design. Generally, it was necessary for a series of trial-and-error changes to be made in flight tests until the test pilot was satisfied with the qualities of the new airplane. The success of this procedure depended on the skill of the test pilot and unfortunately it did not provide a basis for avoiding poor characteristics in future designs.

It was thought that the main factors influencing the pilot's opinions of an airplane were the control motions and forces required in normal flight and in maneuvers. The first attempt to formulate a set of requirements based on these characteristics was made in 1937, but it was realized immediately that a great deal of information was required on the handling qualities of existing airplanes before a reliable set of requirements could be written. As a result the NACA undertook a program to measure the flying qualities of various airplanes. The initial results of this program are given in reference 1. Most of the available knowledge of flying qualities has been obtained from these flight tests which have been carried out on about 75 airplanes of all types, ranging from light planes to the largest bombers. In these tests, recording instruments were used to obtain quantitative measurements of control movements, control forces, and airplane motions while the pilots performed certain specified maneuvers. Procedures for making tests of this type are presented in reference 2. The results of many of these tests have been published as NACA wartime reports. From the fund of information accumulated in these reports it has been possible to prepare a set of requirements for satisfactory handling qualities in terms of quantities that may be measured in flight or predicted from wind-tunnel tests and theoretical analyses (reference 3). When an airplane meets these requirements, it is fairly certain that the airplane will be safe to fly and desirable from the pilot's standpoint. Additional sets of requirements have been prepared by the military services (reference 4) in order to provide for the requirements of military aircraft. Similar research has been carried out in England and an attempt along these lines was also made in Germany, but the number of airplanes which were tested in flight was considerably more limited.

A report (reference 5) has been recently published which discusses the reasons for the flying qualities requirements, the design factors involved in obtaining satisfactory flying qualities, and the methods used in predicting the stability and control characteristics of an airplane. Some of the methods for predicting the handling qualities of a proposed airplane will now be described.

The flying-qualities requirements tie in with the concepts of dynamic stability in that certain requirements are specified for the characteristics of the uncontrolled motion of the airplane. The great majority of the requirements, however, pertain to the control positions and forces required in certain specified flight conditions and maneuvers. In order to predict the ability of an airplane to satisfy these requirements, solution of the equations of motion is not generally required. The required control positions and forces may be predicted by considering the airplane to be in an equilibrium condition. The forces and moments acting may then be estimated either by means of wind-tunnel tests or simply by calculations based on the dimensions of the airplane.

Investigations of varying complexity are required for these predictions depending on the flight conditions, speeds, and types of airplane involved. For conventional airplanes, the control positions required in straight flight or in steady maneuvers in conditions where the thrust coefficient is low may be estimated with sufficient accuracy for practical design purposes simply from a knowledge of the dimensions of the airplane. The effects of power on longitudinal and directional stability, in the case of propeller-driven airplanes, cannot be predicted with such a high degree of accuracy. Wind-tunnel tests of a powered model are desirable in estimating these effects. If accurate predictions of the control forces are desired, particularly on a large airplane, tests may be made of the actual control surfaces in a large wind tunnel, or at least tests of large-scale models of the control surfaces. Finally, the effects of compressibility should be determined from tests of a complete model in a high-speed tunnel. Such a complete investigation is not usually required, however, particularly for conventional airplanes, because of the large amount of data accumulated during the war on the characteristics of many airplane configurations.

Some of the data applicable to the prediction of flying qualities will now be given. Methods for predicting the longitudinal stability in the power-off condition from a knowledge of the dimensions of the airplane are given in references 6 and 7.

In these methods, the effects of the fuselage, idling propeller, wing, and tail are calculated. The effect of the upwash ahead of the wing on the fuselage and propeller pitching moments and of the downwash from the wing and propeller on the tail must be taken into account in order to obtain accurate results.

Calculation of the directional stability likewise involves estimating the contributions of the various airplane components and their mutual interference effects. The data of references 8 and 9 may be used to estimate many of these quantities. The effects of the propeller may be obtained from reference 10.

Comparison of calculated values of directional stability on a large number of airplanes with measured values has shown that this quantity may be predicted fairly accurately for airplanes with smoothly streamlined canopies. On airplanes with poorly designed canopies, the wake of the canopy passing over the vertical tail greatly reduces its effectiveness and it is rather difficult to estimate what percent of the vertical tail area should be considered effective. Some wind-tunnel data on the effects of canopies on directional stability may be found in reference 11.

Another item of importance which may be estimated quite accurately is the rolling velocity obtained in a steady roll with a given aileron deflection. Methods for making this calculation are described in detail in a report which summarizes the results of NACA lateral-control research (reference 12).

Several reports have been published comparing stability and control characteristics predicted from the dimensions of the airplane with those measured in flight (references 7, 9, and 13). In general, these results are in good agreement for flight conditions where the thrust coefficient is low. Calculations of the effects of power on the stability characteristics are more difficult, and usually it is desirable to resort to wind-tunnel tests of a powered model in order to obtain accurate results. Various attempts have been made, however, to devise semiempirical methods to determine the effects of power, based on the large number of wind-tunnel tests of powered models which were conducted during the war years (reference 14). It is also possible to estimate the effects of power by comparison with the results of tests for a similar design. The effects of power on longitudinal stability as measured in flight on a number of airplanes are given in reference 15.

The procedure for conducting wind-tunnel tests of a powered model is described in detail in reference 16. Methods for analyzing the results of wind-tunnel tests for determination of flying qualities are given in references 17 and 18.

Several reports have been published comparing the flying qualities of aircraft as measured in flight with those predicted from wind-tunnel tests (references 19 and 20). Usually the agreement with regard to control positions is satisfactory. The prediction of control forces is subject to more uncertainty. One point which may be mentioned in connection with the prediction of control forces is that generally the hinge-moment parameters C_{h_α} and C_{h_δ} may be predicted only with a certain degree of accuracy. In cases where this much variation will cause large changes in the stick forces it is apparent that the control-force characteristics will be difficult to predict accurately. The accuracy may be improved, however, by designing the airplane in such a way that the control forces are less sensitive to small changes in the hinge-moment characteristics.

Inasmuch as in the past much emphasis has been placed on the classical theory of stability, an attempt will be made to show how the items considered important in connection with flying qualities tie in with the classical theory of stability. First, the subject of longitudinal stability and control will be considered. The theory predicts that a statically stable airplane will perform two types of oscillation: the long period or phugoid motion, which is generally poorly damped, and the short period oscillation, which is always well damped when the controls are fixed. It has been frequently demonstrated that the period of the phugoid motion is so long that the damping of this oscillation has no correlation with the pilot's opinion of the handling qualities (reference 21). This fact is so well established that any explanation of it may seem superfluous. The emphasis placed in the past on the calculations of the characteristics of this mode of motion, however, has lead many engineers to be reluctant to discount its importance. In order to demonstrate the ease with which the pilot can damp out this oscillation, therefore, figure 1 is presented. This figure illustrates that not only can the pilot damp out the phugoid motion very rapidly but that only a very small motion of control is required.

Though the short-period oscillation is always stable with controls fixed, it may become violently unstable with controls free if certain unfavorable combinations of elevator hinge-moment characteristics are employed. When this motion is unstable, it results in an oscillation which produces accelerations approaching the structural strength of the airplane within a period of 1 or 2 seconds. Flight records of the type of oscillation are shown in figure 2 for both well-damped and unstable oscillations. A condition such as this unstable oscillation obviously cannot be tolerated and it is, therefore, required that this mode of motion be well damped. A theoretical analysis of this type of oscillation presented in reference 22 indicates that the motion may become unstable if the variation of hinge-moment coefficient with deflection C_{h_δ}

(the restoring tendency of the elevator) is reduced to zero, and stability is obtained by use of a bobweight or an elevator which tends to float against the relative wind. In the example shown in figure 2, the value of C_{h_δ} was reduced to approximately zero by use of a balancing tab.

The requirement for dynamic longitudinal stability is only one of a large number of requirements which must be satisfied in order that the longitudinal stability and control characteristics should be satisfactory. The other requirements deal with the characteristics of the elevator control in steady flight, in accelerated flight, in landing, and in take-off, and also with the trim changes due to power and flaps, and the characteristics of the longitudinal trimming device. An example of one of the requirements will be given to show how a quantitative requirement of this type aids in establishing certain features of the airplane design. The requirements for longitudinal control in accelerated flight specify the variations of elevator angle and elevator force with acceleration in maneuvers in which the angle of attack is increased rapidly to produce a condition of accelerated flight without much change in airspeed. Inasmuch as the elevator force per g change in normal acceleration is fairly independent of speed on conventional airplanes, this quantity is used as one means of specifying the elevator-force characteristics. The control-force gradient should not exceed about 6 pounds per g on highly maneuverable airplanes such as fighters and should be less than 50 pounds per g on transports, heavy bombers, and so forth. In order to prevent the pilot from inadvertently overstressing the structure, a pull force of at least 30 pounds should be required to reach the allowable load factor. An excessive value of force per g will result in an airplane which is difficult to fly or maneuver, whereas a negative value will make the airplane extremely dangerous to fly because a rapid divergence would result if the pilot released the control stick. Some factors which influence the force characteristics in accelerated flight are illustrated in figure 3. From this figure it is seen that the force per g increases as the center of gravity is moved forward. The variation of force per g with center-of-gravity position may be reduced by reducing the variation of elevator hinge-moment coefficient with deflection C_{h_δ}. The curve may be shifted by a constant amount at any center-of-gravity position by changing the variation of elevator hinge-moment coefficient with angle of attack C_{h_α}. On a given airplane the range of center-of-gravity positions over which satisfactory flying qualities are obtained may be limited by this force-per-g variation. An increase in the center-of-gravity range over which satisfactory force characteristics in steady maneuvers are obtained might be provided by reducing the value of C_{h_δ} and obtaining forces in the desired range by use of a positive value of C_{h_α}. Flight tests have shown, however, that this procedure, if carried too far, may result in undesirably light control forces in rapid maneuvers, because the pilot is able to deflect the control rapidly with very little force; then the force builds up as the acceleration increases. This condition is discussed more fully in reference 23.

The desire for light control forces over a large center-of-gravity range, therefore, conflicts with the requirement for desirable control feel. The requirements may be more easily satisfied, however, if the center-of-gravity range is located well forward of the position for neutral stability with the elevator fixed.

A few of the requirements for lateral stability and control will now be discussed. Here, again, the first requirement ties in with the classical concepts of dynamic stability. There is no requirement for spiral stability inasmuch as the spiral divergence is very slow and easily controlled and also because in most conventional airplanes the friction in the control system may hold the controls in a position to cause a much more rapid divergence than the spiral divergence with the controls in the trim position. The Dutch roll oscillation has a relatively short period, however, and it should be well damped so as not to require constant attention on the part of the pilot. On practically all conventional airplanes the Dutch roll oscillation with controls fixed is sufficiently well damped. Continuous lateral oscillations, known as snaking oscillations, have, however, been encountered on many airplanes as a result of slight motion of the controls induced by the oscillation. A report which presents a theoretical analysis of this type of motion and indicates means of avoiding it is available (reference 24). While the classical Dutch roll oscillation has given little trouble in the past, it has assumed a status of increased importance in connection with recent airplane designs employing swept wings.

Other lateral stability and control requirements deal with the aileron-control characteristics, the yaw due to ailerons, the limits of rolling moment due to sideslip, the directional stability, the side-force characteristics, and the pitching moment due to sideslip. In addition, the characteristics of the rudder and aileron trimming devices are specified.

Some unusual features of airplane stability and control which have been shown to be important for many types of airplanes and which have not been given a great deal of attention in the past will now be presented.

One factor which has been found to be very important in affecting the flying qualities of many high-speed airplanes is the distortion of the control surfaces and of the airplane structure under aerodynamic loads. Data presented in figure 4 illustrate one effect which is quite frequently encountered. This figure shows the effect of stabilizer incidence on the variation of stick force with speed in straight flight. An analysis based on the assumption of a rigid airplane would indicate that there should be no change in the curve of stick force against speed due to changing the stabilizer incidence provided the airplane were retrimmed at the same speed by use of the trim tab. In practice it is found that a negative stabilizer incidence, which requires down elevator deflection for trim in high-speed flight, usually results in rapidly increasing push forces at high speeds. This effect is caused by progressively increasing distortion of the elevator covering and twisting of the stabilizer as the aerodynamic forces are increased. This condition is very undesirable because if the pilot should release the stick at high speeds, excessive acceleration would be encountered in the pull-out. The effect of positive stabilizer incidence is to produce rapidly increasing pull forces at high speeds which violates the requirement for static longitudinal stability. These effects cannot, of course, be predicted from wind-tunnel tests of a rigid model. These distortion effects may be avoided, however, by use of the correct stabilizer setting so that the elevator is lined up with the stabilizer in high-speed flight. A similar effect of distortion on the rudder-force variation with speed is obtained by varying the setting of the vertical fin. These and other effects of distortion due to aerodynamic loads may be isolated from compressiblity effects in flight tests by making runs at different altitudes. Distortion effects set in at a given value of indicated airspeed, whereas compressibility effects occur at a given Mach number. A theoretical analysis of the effects of fabric distortion on stability is given in reference 25.

Many of the design factors which may be used to aid in meeting certain of the flight-qualities requirements are of a conflicting nature so that compromises in the design will generally have to be made in order to meet all the requirements as closely as possible. The most frequently encountered problem is that of providing sufficiently light control forces without reducing the effectiveness of the control surfaces below the specified values. All the control-force values which enter into the requirements, such as the force per g, the aileron force required in a roll, the rudder force required to offset aileron yaw, and so forth, tend to increase as the product of the span and the square of the chord of the control surface, and as the dynamic pressure. As airplanes are made larger and faster, therefore, an increasing degree of aerodynamic balance is required on all the control surfaces to meet the handling-qualities requirements. For example, figure 5 illustrates the approximate reduction in C_{h_δ} of the elevator required to meet the elevator control-force requirements as a function of airplane weight. A great deal of research has been done during the war years on means of balancing control surfaces, some of which is summarized in reference 11. Nevertheless, it is impractical to balance control surfaces more than a certain amount because variations in contours of the control surfaces of different airplanes of the same type, within production tolerances, result in variations of C_{h_δ} of the same order as the value required. On large airplanes, therefore, some aerodynamic or mechanical device is required to multiply effectively the pilot's effort by a large factor, in order that light forces may be obtained without utilizing an impractically large degree of balance. Such devices include spring tabs (reference 26) and hydraulic booster mechanisms.

Inasmuch as the handling-qualities requirements are based largely on experience with conventional airplanes, further research will probably be required to find whether additional requirements are necessary for the unconventional types of airplanes that are now being contemplated for very high speed flight. Because of the great range of speed and altitude encountered by such airplanes it may be impossible to meet the handling-qualities requirements without relying on mechanical devices to provide stability and desirable control forces. With such devices the method of the control of the airplane may differ considerably from that normally used. Research will therefore be required to find the reaction of the pilot to these unusual control forces. Preliminary research on this subject may be carried out without making actual flight tests by the use of simulators designed to behave in the same manner as the airplane.

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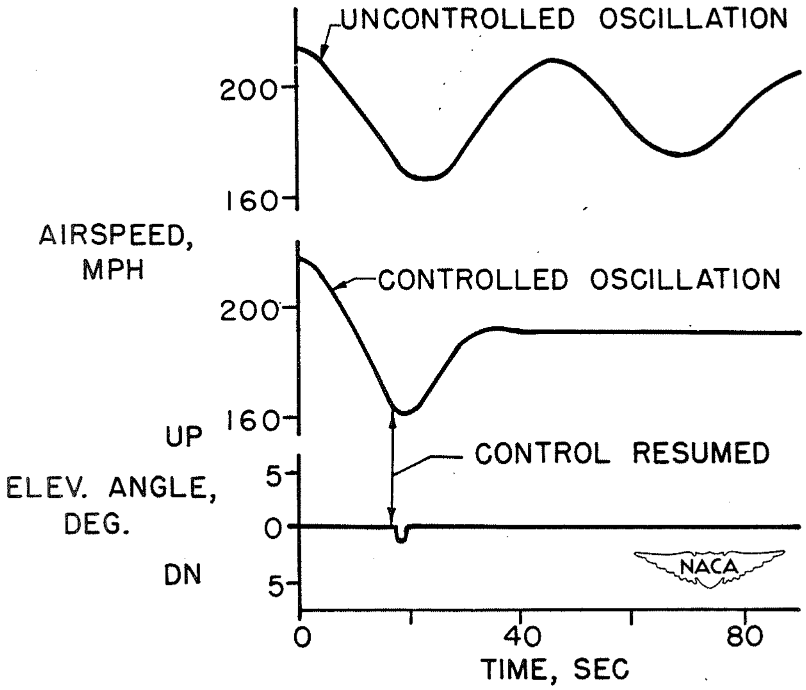

Figure 1.- Phugoid oscillations.

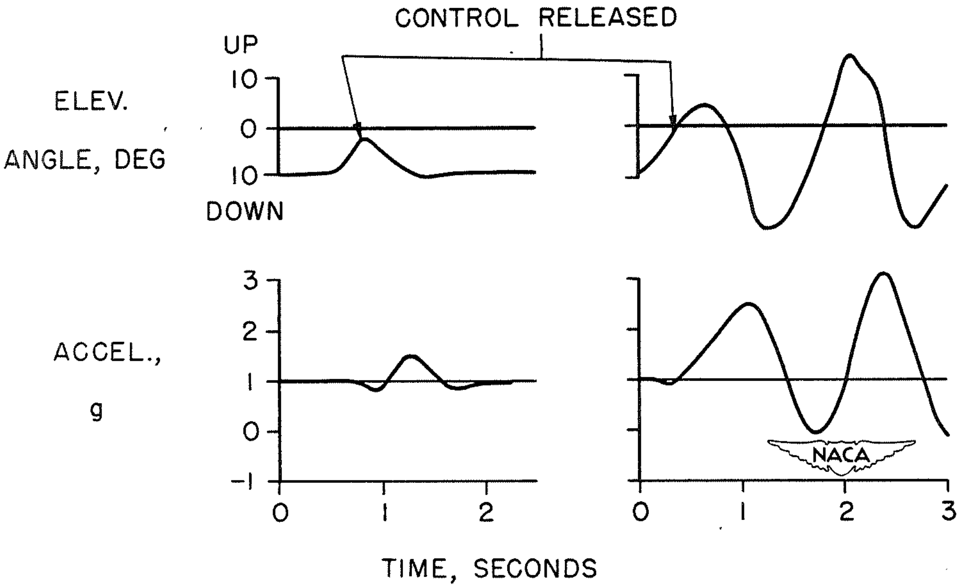

Figure 2.- Short-period oscillations.

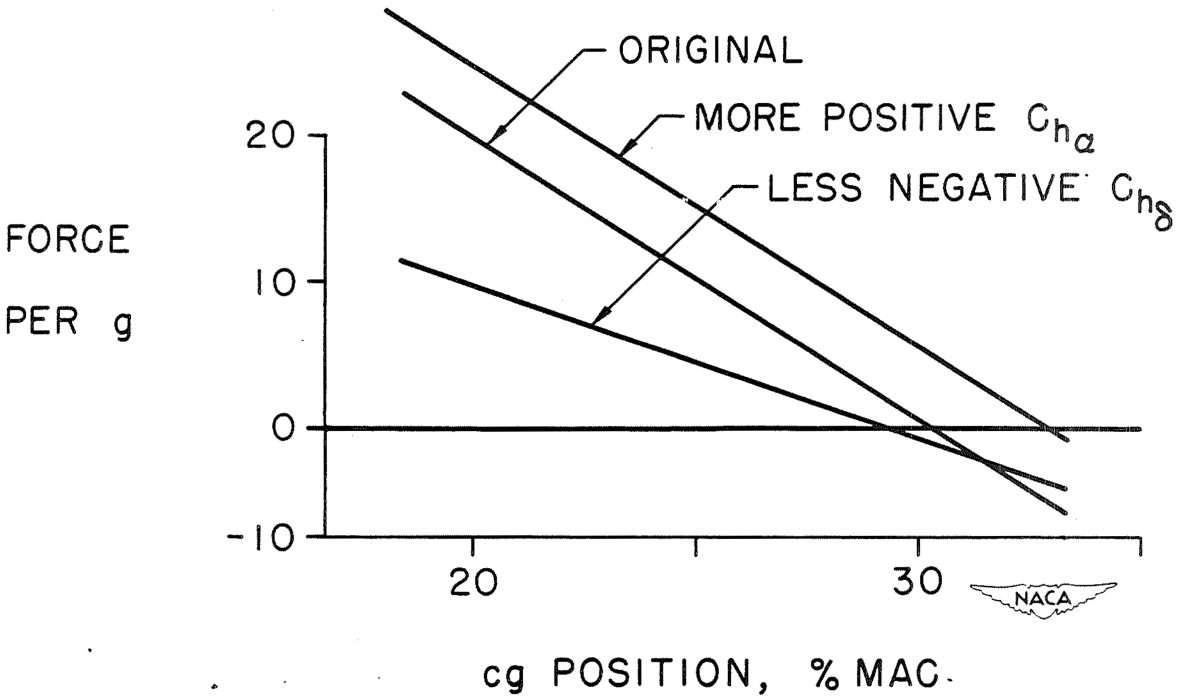

Figure 3.- Elevator forces in maneuvers.

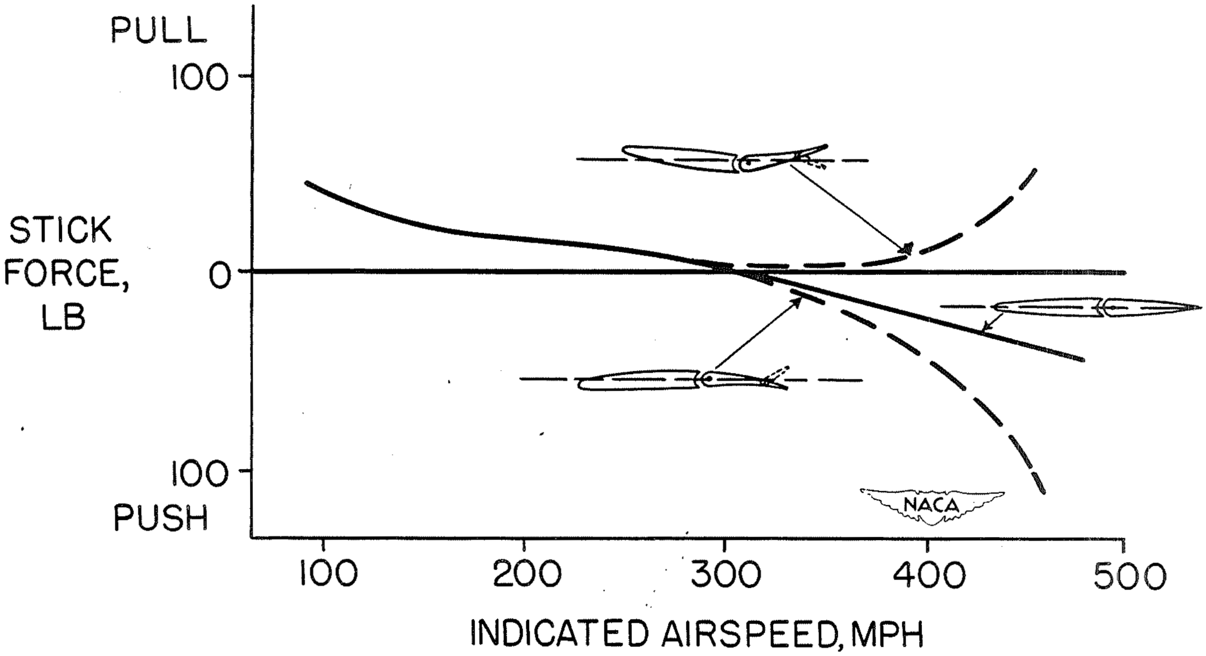

Figure 4.- Distortion effects.

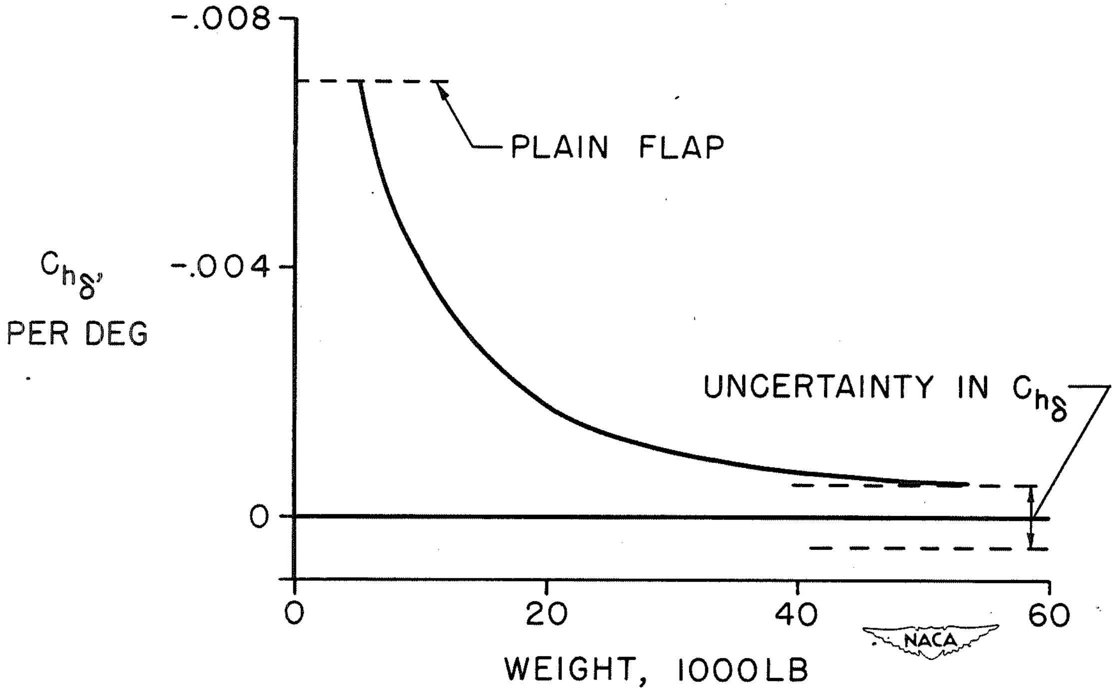

Figure 5.- Elevator balance.