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A MASS-DISTRIBUTION CRITERION FOR PREDICTING THE EFFECT OF CONTROL MANIPULATION ON THE RECOVERY FROM A SPIN

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SUMMARY

Results of spin-tunnel tests of 65 models indicated that when the airplane design simulated that of the earlier single-engine type, with mass distributed chiefly along the fuselage, aileron-with and elevator-up settings aided recovery, and the rudder was the predominant control for recovery. When the design approached the design of multiengine airplanes (or the more recent single-engine airplanes with wing tanks and wing armament) with the mass distributed chiefly along the wings, however, aileron-against and elevator-down settings were conducive to the most rapid recovery and the elevator was the predominant control.

The primary importance of the mass distribution of an airplane in determining its spinning characteristics is demonstrated and a useful criterion for predicting the optimum control manipulation for recovery, based on a nondimensional mass-distribution parameter, is presented. Charts that should be useful for such predictions to both the pilot and the designer are included.

INTRODUCTION

During the past 5 years, 65 models, representing airplanes covering a wide range of dimensional and mass design characteristics, have been tested in the NACA free-spinning wind tunnel. As is to be expected, these models have shown varied spin and recovery characteristics, reflecting the differences in the proportions and mass distribution of the models. A consistent difference, however, in spin and recovery characteristics was early apparent

between models heavily loaded along the fuselage and those lightly loaded along the fuselage, or heavily loaded along the wings. In an effort to establish mass distribution, and not aerodynamic characteristics, as the primary factor causing this difference, a series of special tests was undertaken for many of the models, and results of such tests have been accumulated for 19 representative designs. For these tests, the mass distribution of each model was varied and models whose mass distribution was originally chiefly along the fuselage were reloaded until the mass was distributed chiefly along the wings. Models loaded chiefly along the wings likewise had their mass distribution reversed.

A qualitative analysis of the results was obtained for 65 models tested in the spin tunnel, as well as of the results of special tests for 19 of these models. Definite rules have been formulated concerning the effects of control manipulation on the recovery from the spin, as influenced by the airplane mass distribution. A criterion based on a nondimensional mass-distribution parameter has been established for predicting these effects.

APPARATUS AND TESTS

The spin-testing technique in the NACA free-spinning wind tunnel and the construction of spin models are described in detail in reference 1. The models, constructed of balsa, are ballasted for dynamic similarity to the corresponding airplane by installation of proper weights at suitable locations. An automatic clockwork delayed-action mechanism or a magnetic remote-control mechanism is installed in the model to actuate the controls for recovery.

The model with the rudder set with the spin is launched in the spin by hand into the vertical upward air stream of the tunnel. The airspeed is adjusted to equal the vertical rate of descent of the model and the model is thus kept at a fixed height until recovery is attempted. Recovery is generally attempted by reversal of the rudder alone from full with to full against the spin, although the mechanism may be arranged to move any or all of the controls. The recovery is judged by the number of turns from the movement of the rudder to the cessation of the spinning rotation. The effect of aileron setting on the spinning characteristics is usually evaluated by a comparison of

the number of turns necessary for recovery by rudder reversal alone from spins for which, for example, the ailerons are set (not moved) with the spin (right aileron up in a right spin) and the number of turns necessary for recovery from spins for which the ailerons are set against the spin. Results of spins in which the elevator is full up are compared with results obtained for spins with elevator neutral or full down. In a few instances, for the special tests, the effects of aileron and elevator settings have been based on a comparison of the vertical speed and the attitude of the steady spin.

The models tested in the spin tunnel have covered a wide range of dimensional and mass characteristics and include seaplane and landplane, biplane and high- and low-wing monoplane types, and multiengine and single-engine designs. The 19 models used in the special tests represent different types. For the special tests, the mass characteristics were varied by moving ballast weights from either the wing tips or the fuselage extremities to the center of gravity or by moving ballast weights to either the wing tips or the fuselage extremities from the center of gravity, the position of the center of gravity being kept constant.

RESULTS

The data analyzed are presented in figures 1, 2, and 3. These figures are an attempt to represent graphically, by a single point, the important mass-distribution characteristics of each model. In table I the models are given numerical designations to permit their identification in the figures.

In the Euler equations of motion, the influence of the mass distribution depends on three factors: $I_X - I_Y$, $I_Y - I_Z$, and $I_Z - I_X$, where I_X, I_Y, and I_Z are the moments of inertia about the X, Y, and Z body axes, respectively. For presentation in the figures, these factors have been made nondimensional by dividing by mb^2, where m is the mass and b is the span of the airplane. The parameter $\frac{I_Z - I_X}{mb^2}$ was taken as the ordinate for the figures. This parameter is a factor affecting the inertia

pitching moment and increases when mass is added along the fuselage. The abscissa $\frac{I_Y - I_Z}{mb^2}$ is the factor affecting the inertia rolling moment and the negative values numerically increase as weight is added along the wings. Inasmuch as the sum of the three mass parameters is equal to zero, the value of the third parameter, $\frac{I_X - I_Y}{mb^2}$, may be indicated by a third scale at 45° to the ordinate and abscissa scales. This third parameter is a factor affecting the inertia yawing moment, the large positive values indicating that the mass distribution is chiefly along the wings and the large negative values indicating that the mass distribution is chiefly along the fuselage. The three parameters may also be written as $\frac{k_Z^2 - k_X^2}{b^2}$, $\frac{k_Y^2 - k_Z^2}{b^2}$, and $\frac{k_X^2 - k_Y^2}{b^2}$, respectively, where k_X, k_Y, and k_Z are the radii of gyration about the X, Y, and Z axes, respectively.

Figure 1 shows the effect of aileron setting on the recovery characteristics as indicated by routine tests. Aileron data were available for only 53 of the models. The type of points used to designate the different models indicates whether setting the ailerons with the spin or against the spin reduced the turns for recovery. Figure 2 gives similar information for the elevator, data being available for 60 of the models. The points indicate whether elevator-up settings or elevator-down settings are more favorable for recovery. Figure 3 presents the results of special tests of 19 models with altered mass distribution. In this figure, different mass arrangements of the same model are represented by the same number and the letter "a" is employed to denote the altered or abnormal loading condition. The symbols indicate the effects of both ailerons and elevator settings.

DISCUSSION

Criterion for prediction of control effects.- An inspection of the figures shows a distinct grouping of the points representing the different effects of control

settings. Partial separation of the effects is obtained by independent consideration of each of the three mass parameters. The most complete separation, however, appears to be given by consideration of the inertia yawing-moment parameter $\frac{I_X - I_Y}{mb^2}$.

Examination of figure 1 indicates that at a value of the inertia yawing-moment parameter $\frac{I_X - I_Y}{mb^2}$ of -50×10^{-4}, almost complete separation of the aileron effects takes place. For larger negative values, ailerons with the spin usually had a favorable effect on the recovery characteristics and ailerons against the spin had an unfavorable effect. As the parameter value of -50×10^{-4} was approached, instances were observed where aileron setting had no noticeable effect on the recovery characteristics. For negative values of the parameter numerically smaller than -50×10^{-4} and for positive values, the aileron effect reversed so that aileron settings against the spin had a favorable effect on recovery; whereas aileron settings with the spin were detrimental. In the vicinity of this reversal value, a critical region existed for which it appears that only slight variations in mass distribution may completely reverse the aileron effect. An exception to the general rule was obtained in this region in only one instance.

The effect of elevator settings, according to the data of figure 2, tends to reverse in the neighborhood of a value of the yawing-moment parameter of zero. There appears to be a critical region between the values of $\pm 20 \times 10^{-4}$ in which the effect of elevator settings may be in either direction. For negative values of the parameter numerically greater than -20×10^{-4}, elevator-up settings were usually conducive to most rapid recovery. In several instances, however, for models that gave either very flat or very steep spins, the elevator setting had little or no effect. For positive values of the parameter greater than 20×10^{-4}, on the other hand, elevator-down settings were very definitely instrumental in effecting satisfactory recovery. In an extreme case, no recovery could be obtained from the elevator-up, aileron-neutral spin by full rudder reversal alone; whereas movement of the elevator alone from the full-up to the full-down position gave satisfactory recovery.

The data from the special tests for 19 models, given in figure 3, appear to prove that the separation indicated for elevator and aileron effects in figures 1 and 2 depend predominantly on the mass distribution of the models rather than on aerodynamic factors. The 19 models tested are believed sufficiently representative of different airplane types to permit a generalization of the conclusion. Model 16, for example, represents a lightly loaded, single-engine reconnaissance monoplane whereas model 6 represents a high-speed, heavily loaded, twin-engine attack airplane. It must be appreciated that aerodynamic factors may modify the results for some combinations of mass arrangement and extreme aerodynamic design to the extent that the control effects may be dictated by the aerodynamic characteristics.

Sequence of control manipulation for recovery.- The conclusions drawn from the figures are particularly significant in that they indicate that the relative importance of the different airplane controls for recovery from the spin may change radically between airplanes of different types. Prior to the recent extended application of wing armament for combat types, airplane structural design procedure was such that the airplane was characterized structurally by relatively light wings. Practically all the disposable load was carried in the fuselage, although some gasoline might be carried near the center of the wings. These characteristics still apply to the private-owner class of airplanes. This structural arrangement of the airplane results in a mass loading chiefly along the fuselage and the value of $\frac{I_Z - I_X}{mb^2}$ will tend to be large and positive, while the value of the inertia yawing-moment parameter $\frac{I_X - I_Y}{mb^2}$ is negative. The installation of wing engines tends to increase the weight along the wings and it can therefore generally be assumed that multiengine airplanes have high negative values of the parameter $\frac{I_Y - I_Z}{mb^2}$, and positive values of the parameter $\frac{I_X - I_Y}{mb^2}$. Present-day military design of single-engine airplanes is also toward heavy wings. The desire for increased range has increased the amount of gasoline carried in the wings. Guns and ammunition are carried outboard of the propeller, and the metal wings with the mechanism for retracting the

landing gear are inherently heavier than in older designs.

The results of the model tests show that, for the earlier single-engine military design and the present-day privately owned airplanes, the rudder is generally the predominant control for recovery from the spin and that full rudder reversal is the most effective control manipulation. Movement of the elevator to the down position before the reversal of the rudder tends to shield the rudder and retard recovery; whereas, movement of the elevator after the rudder has been completely reversed and rotation has begun to slow up may offer a favorable pitching moment, tending to aid recovery without adversely affecting the rudder action. Movement of the elevator alone rarely gives recovery. Because high rates of descent will probably be associated with recovery with full-down elevator, the amount the elevator is moved down will depend on how much assistance is needed from the elevator to produce a satisfactory recovery. The effect of ailerons will be contrary to the effects expected in normal flight and holding the ailerons against the spin will retard recovery; whereas holding the ailerons with the spin will assist recovery.

For multiengine airplanes and for the more recent single-engine military designs, the elevator tends to become the predominant control for recovery. The movement of the elevator down is essential to a rapid recovery. Rudder reversal, although of less importance than elevator reversal, will generally improve recovery. Aileron position is critical and aileron settings with the spin may greatly retard recovery; whereas aileron-against settings will be favorable. All controls for airplanes of these types have the effects that would be expected of them in normal flight.

It may be said in summarizing that, for airplanes of relatively light loading along the wings, full rudder reversal before moving the elevator down is imperative; moving the elevator down after the rudder reversal is desirable. For airplanes heavily loaded along the wings, moving the elevator down is imperative; full rudder reversal is desirable.

Application to flight.- The values of the criterion at which the aileron and elevator effects in the spin reverse, as shown by the figures, apply strictly to models only. The general conclusions, however, should be applicable to flight, although, because of possible scale

effects, the reversals may occur in flight at somewhat different values of the criterion than are indicated by the tunnel data.

The meager comparative flight data available indicate that the values for the reversal of aileron and elevator effects will probably be changed somewhat but there are not enough full-scale data available to fix the flight values. It is desirable that more flight data be obtained in an effort to establish definitely the values in flight at which the aileron and elevator effects reverse.

Explanation of mass effects.- A possible explanation of the dependence of the effectiveness of the elevator and ailerons on the mass distribution is presented briefly.

The application of Euler's dynamical equations to the case of an airplane in a steady spin gives, for the inertia yawing moment about the body axis, the expression

$$(I_X - I_Y) \sin\Phi \cos\alpha\Omega^2$$

where

Φ is the angle of wing tilt to the horizontal, positive when right wing is down

α angle of attack

Ω angular velocity about spin axis

For a spin in any given direction, the algebraic sign of the inertia yawing moment depends only on the algebraic signs of $I_X - I_Y$ and the angle Φ. In a right spin, the tunnel results indicate that setting the ailerons with the spin leads to a positive value for Φ; whereas setting the ailerons against the spin leads to a negative value of Φ. For models loaded so that $I_X - I_Y$ is negative, setting the ailerons with the spin will produce a favorable effect in that the inertia yawing moment will be negative and will act to turn the airplane away from the direction of rotation (against the spin). Conversely, for designs where $I_X - I_Y$ is positive, ailerons set with the spin will produce an inertia yawing moment in the direction of the spin. The fact that, for the results presented in chart 1, the reversal of aileron effect does not take place when $I_X - I_Y$ is zero can be attributed to secondary

aerodynamic factors. A similar explanation may be applied to the elevator effect, as the model results indicate that setting the elevator up usually leads to a positive value of Φ and elevator down to a negative value of ϕ for a right spin.

For the present, only the qualitative effects of the controls are considered. No attempt is made to predict the magnitudes of these effects which are probably influenced by many secondary factors, such as the autorotation characteristics of the wings or the yawing moment due to sideslip. The values of the inertia pitching and rolling moments also undoubtedly influence the spin and recovery characteristics, although on the basis of existing data they do not appear to be of primary importance in the prediction of the direction of the control effects.

CONCLUDING REMARKS

Data presented indicate that mass distribution is a primary factor in determining the direction of aileron and elevator effects in recovery from the spin and that the directions of the effects and the optimum control procedure for recovery, therefore, may be predicted qualitatively on the basis of the mass-distribution parameter.

When the airplane design simulates that of the earlier single-engine airplane, with mass distributed chiefly along the fuselage, aileron-with and elevator-up settings can be expected to aid recovery. When the design approaches that of a multiengine airplane (or the newer single-engine airplane with wing tanks and wing armament), with mass distributed chiefly along the wings, aileron-against and elevator-down settings will be conducive to the most rapid recovery.

From the normal control configuration for spinning (rudder full with, elevators full up, and ailerons neutral), the most rapid recovery for any airplane will generally be obtained by full, rapid rudder reversal followed immediately by rapid movement of the elevators to the full-down position and of the ailerons in the direction determined by the mass criterion. For airplanes loaded chiefly along

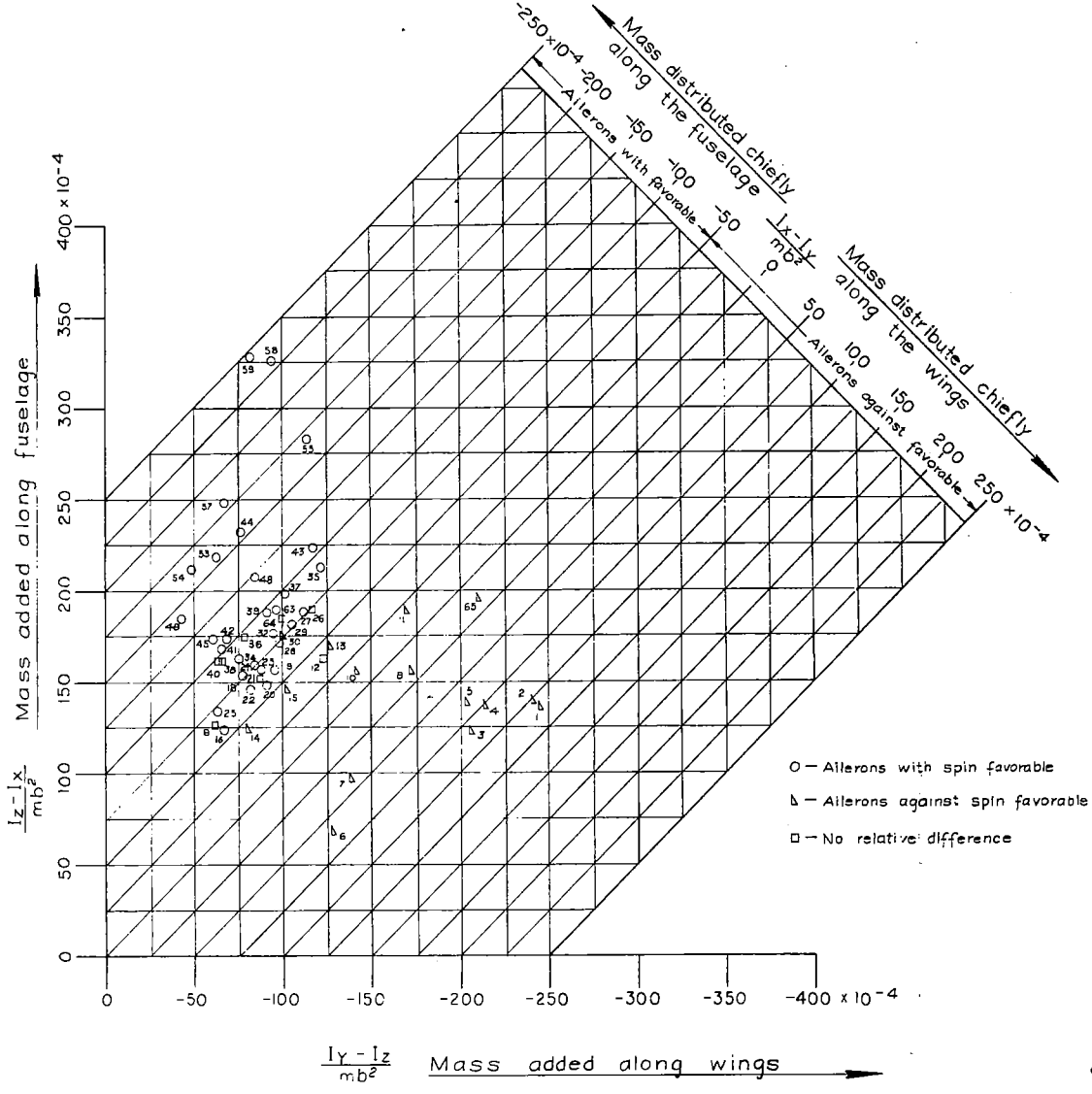

Figure 1.- Prediction of aileron effect, during recovery, by use of mass parameter.

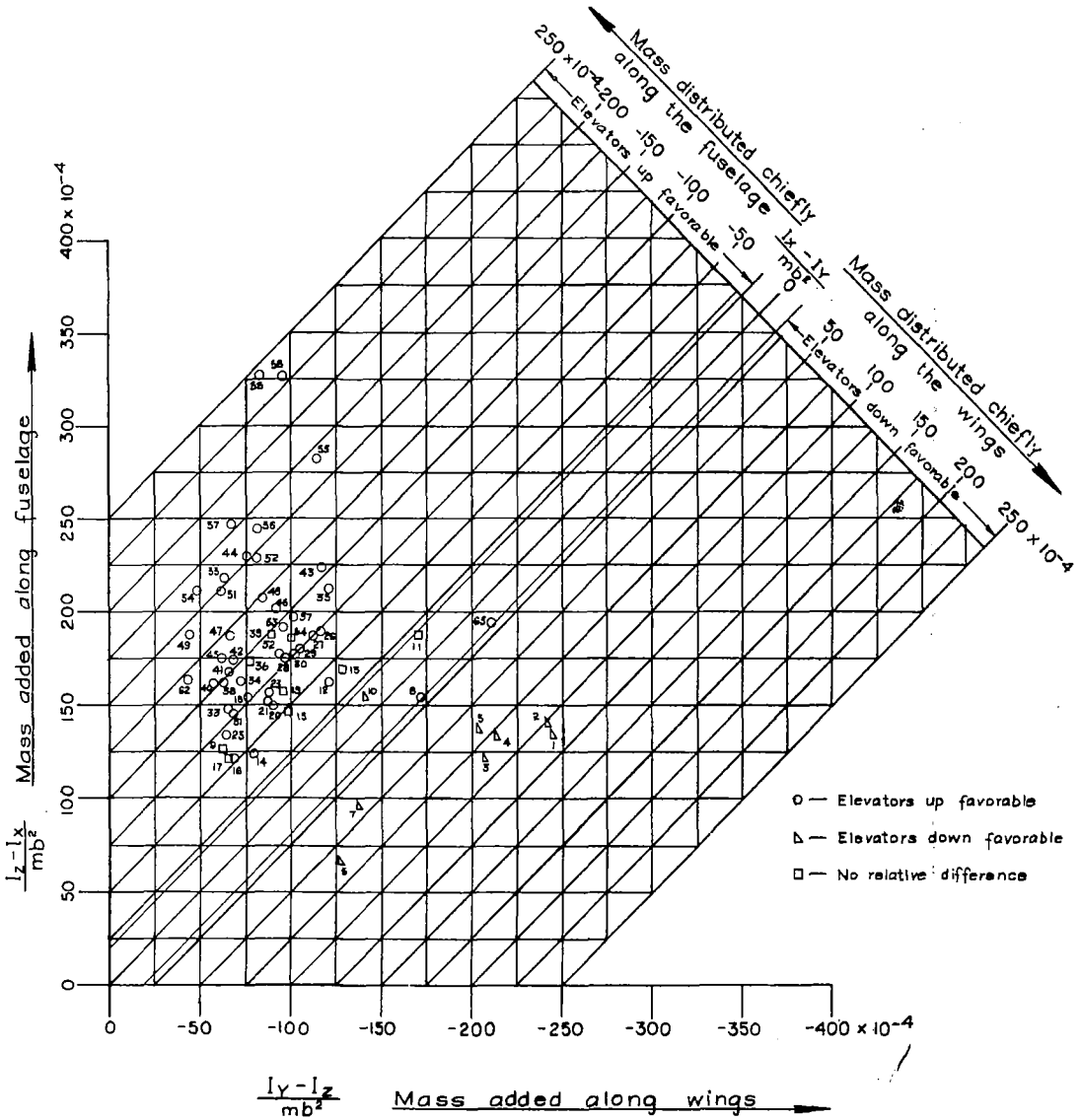

Figure 2.- Prediction of elevator effect, during recovery, by use of mass parameter.

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The primary importance of mass distribution of an airplane in determining its spinning characteristics is demonstrated. Useful criterion for predicting the optimum control movements for recovery, which is based on a nondimensional mass distribution parameter, is presented. Charts useful for such predictions are included. Results of tests indicate that when the design distributes the mass chiefly along the fuselage, aileron-with and elevator-up settings aid recovery. If the design distributes the mass chiefly along the wings, the opposite settings give the most rapid recovery.

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