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SUMMARY OF SPIN TECHNOLOGY AS RELATED TO LIGHT GENERAL-AVIATION AIRPLANES

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SUMMARY

A summary has been made of all NASA (and NACA) research and experience related to the spin and recovery characteristics of light personal-owner-type general-aviation airplanes. Very little of the research deals with light general-aviation airplanes as such, but many of the airplanes and models tested before and during World War II were similar to present-day light general-aviation airplanes with regard to the factors that are important in spinning. The present paper is based mainly on the results of spin-tunnel tests of free-spinning dynamically scaled models of about 100 different airplane designs and, whenever possible, includes correlation with full-scale spin tests. The research results are discussed in terms of airplane design considerations and the proper use of controls for recovery.

Three factors are found to be of almost overriding importance in spinning for this type of airplane. These factors are the relative distribution of the mass between the wing and fuselage, the density of the airplane relative to that of the air, and the tail design. The mass distribution and relative density determine the tail-design requirements and the control movements required for recovery. An empirically determined design factor is available as a guide for the design of the tail to insure good spin recovery. The rudder is generally regarded as the primary recovery control. The elevator can be very effective in some cases, such as positive (wing-heavy) loadings or recovery during the incipient spin, but it might prove to be ineffective for fully developed spins, flat spins, or cases in which the mass distribution or center-of-gravity position has been changed.

INTRODUCTION

The technology of spinning seems to receive little attention from most people associated with airplanes – from design to operation – because it is not a normal part of the operation of most airplanes. Most general-aviation airplanes are no longer required to be able to recover from a fully developed spin (ref. 1), and spin training is no longer required for a private pilot's license. These factors, and many more, have led to a general lack of understanding of the basic principles of spinning. Consequently, a crisis usually develops when a new design is involved in a spin crash or when an old design has a series of spin accidents. In either case, the design is usually so fixed that the optimum design change to improve the spin-recovery characteristics involves so much time and money that it is ruled out in favor of a minimum, less expensive modification which is less desirable.

The purpose of the present paper is to summarize findings of the NASA (and NACA) research that relates to the spinning of general-aviation aircraft. This summary is intended to be sufficiently detailed to help the designer build safer airplanes by giving adequate treatment to spin recovery early in the design stage, and yet sufficiently general to help pilots and operators have a better understanding of spinning so that they may better cope with spin problems that occur with their airplanes. Most of the applicable research was performed before and during World War II and was not performed on general-aviation airplanes as such, but many of the airplanes and models tested during this period were similar to present-day general-aviation airplanes with regard to factors that are important in spinning. From these tests the effects of many pertinent design features were determined. This work is analyzed herein with regard to present-day light general-aviation airplanes and is updated with more recent spin experience applicable to this class of airplane, practically all of which is fragmentary and unpublished. The class of airplane toward which this summary report is directed is the personal-owner aircraft of less than about 1800 kg (4000 pounds) gross weight. The analysis is made, however, in terms of nondimensional parameters so that it may be more broadly applicable.

SYMBOLS

b	wing span, m (ft)
F	force, N (lb)
I_X, I_Y	moments of inertia about X- and Y-axis, respectively, kg-m^2 (slug-ft^2)
$\frac{I_X - I_Y}{mb^2}$	inertia yawing-moment parameter
L	distance from center of gravity of airplane to centroid of fuselage area S_F, m (ft)
L_1	distance from center of gravity of airplane to centroid of rudder area S_{R1}, m (ft)

L_2	distance from center of gravity of airplane to centroid of rudder area S_{R2}, m (ft)
m	airplane mass, kg (slugs)
R	spin radius, m (ft)
S	wing area, m^2 (ft^2)
S_F	fuselage side area under horizontal tail, m^2 (ft^2)
S_{R1}	unshielded rudder area above horizontal tail, m^2 (ft^2)
S_{R2}	unshielded rudder area below horizontal tail, m^2 (ft^2)
TDPF	tail-damping power factor
TDR	tail-damping ratio
URVC	unshielded-rudder volume coefficient
W	weight, kg (lb)
X,Y,Z	longitudinal, lateral, and vertical body axis of airplane, respectively
α	angle of attack, deg
μ	relative-density factor, $m/\rho Sb$
ρ	air density, kg/m^3 ($slugs/ft^3$)
ϕ	angle between Y body axis and horizontal measured in vertical plane, positive when right wing is down for erect spins, deg
Ω	airplane spin rate, turns/sec

THE SPIN

The spin has been defined as a motion in which an airplane in flight at some angle of attack between the stall and 90° descends rapidly towards the earth while rotating about a vertical axis. (See ref. 2.) The spinning motion is very complicated and involves simultaneous rolling, yawing, and pitching while the airplane is at high angles of attack and sideslip. Since it involves separated flows in the region beyond the stall, the aerodynamic characteristics of the airplane are very nonlinear and time dependent; and hence, at the present time, the spin is not very amenable to theoretical analyses.

The overall spin maneuver can be considered to consist of three phases: the incipient spin, the developed spin, and the recovery. An illustration of the various phases of the spinning motion is given in figure 1.

The incipient spin occurs from the time the airplane stalls and rotation starts until the spin axis becomes vertical or nearly vertical. During this time the airplane flight path is changing from horizontal to vertical, and the spin rotation is increasing from zero to the fully developed spin rate. The incipient spin usually occurs rapidly for light airplanes (4 to 6 seconds, approximately) and consists of approximately the first two turns. As indicated by full-scale tests and by the model tests of reference 3, the typical incipient-spin motion starts during the stall with a roll-off. Then, as the nose drops, the yawing motion begins to build up. About the half-turn point, the airplane is pointed almost straight down but the angle of attack is usually above that of the stall because of the inclined flight path. (See fig. 1.) As the one-turn point is approached, the nose comes back up and the angle of attack continues to increase. As the airplane continues to rotate into the second turn, the flight path becomes more nearly vertical, and the pitching, rolling, and yawing motions become more repeatable and approach those of the fully developed spin.

In the developed spin the attitude, angles, and motions of the airplane are somewhat repeatable from turn to turn, and the flight path is approximately vertical. The spin is maintained by a balance between the aerodynamic and inertia forces and moments. The spinning motion is made up of rotation about the airplane center of gravity plus translatory motion of the center of gravity; however, it is primarily a rotary motion and is affected mainly by the moments acting on it. A typical example of an airplane spinning motion and the forces in a spin is illustrated in figure 2.

The third phase, the recovery, is caused by a change in the moments so as to upset the balance between the aerodynamic and inertia moments. Such a change in the moments is obtained by deflecting the controls of the airplane. The specific control movements required in any particular airplane depend on certain mass and aerodynamic characteristics, which are discussed in the subsequent sections of this paper.

SIGNIFICANT FACTORS

Reference 2 is a summary paper in which many of the factors that affect spin and recovery are discussed. It affords much useful background information which is of interest with regard to the present problem, but it is oriented mainly toward modern high-performance military airplanes. The present paper, on the other hand, identifies and discusses the factors that are of particular significance with regard to the light airplane.

The picture that will evolve in the discussion is that three principal factors are of almost overriding importance in the spinning of light general-aviation airplanes: the relative distribution of the mass of the airplane between the wing and fuselage, the density of the airplane relative to the density of the air, and the tail configuration of the airplane. The relative density is generally fixed by performance considerations and cannot be accommodated to spin requirements. Of the other two factors, mass distribution is very important because it determines the control movements required for recovery and together with the relative density, it determines the tail-design requirements for recovery. The tail design is important because it must have certain features to provide the aerodynamic moments required for recovery and to damp the spinning rotation and also because it is the factor that can most easily be controlled by the designer, particularly in the latter stages of the design and development of the airplane.

Mass Distribution

The way in which the mass of an airplane is distributed between the wing and fuselage is the most important single factor in spinning because it determines the way in which the airplane, while spinning, responds to control movements, especially to elevators and ailerons. An airplane rotating in a spin can be considered to be a large gyroscope. Since there are mass and angular rotation about all three axes, inertia moments are produced about all three axes. In addition, aerodynamic forces and moments are acting on the airplane because of its motion through the air. The inertia forces and moments are opposite in sign to the aerodynamic forces and moments and are both equal and opposite for an equilibrium spin condition. An example of the aerodynamic and inertia moments balanced in pitch is illustrated in figure 3. Perhaps the clearest example of this balance is that for a wing-level spin, the nose-down aerodynamic pitching moment must be exactly balanced by the nose-up inertia pitching moment. In order for the airplane to recover from the spin, the equilibrium must be broken, and this is normally accomplished by changing the aerodynamic moment by moving a control or combination of controls that can cause the greatest antispin moment.

The mass distribution of all airplanes (general aviation, military fighters, bombers, etc.) can be grouped into three general loading categories, as shown in figure 4. The mass distribution of the airplane is evaluated in terms of the parameter $\frac{I_X - I_Y}{mb^2}$, which has been found to be a normalizing factor and which is nondimensional so that it is independent of the size and weight of the airplane. This parameter is important in determining the inertia yawing moment, which is a controlling factor in a spin, and is commonly called the inertia yawing-moment parameter. When the weight of the airplane is distributed mainly along the wing, the moment of inertia in roll is greater than that in pitch, and the value of this mass-distribution parameter is positive. This situation is referred to as a positive or wing-heavy loading, and features such as wing-mounted engines and tip tanks contribute to such a loading. Conversely, when the weight of the airplane is distributed mainly along the fuselage, the moment of inertia in pitch is greater than that in roll, and the value of the mass-distribution parameter is negative. This situation is referred to as a negative or fuselage-heavy loading, and features such as fuselage-located engines, fuel, luggage, and cargo contribute to such a loading. Almost all light general-aviation airplanes actually fall into the zero loading category of figure 4, where the moments of inertia in roll and pitch are about equal. However, there are some exceptions, especially when heavy tip tanks are installed on the wings. The zero loading range is generally considered to be the range between values of -50×10^{-4} and 50×10^{-4} for the inertia yawing-moment parameter. When the difference between the rolling and pitching moments of inertia is this small, the inertias contribute little, or nothing, to the recovery.

The loading of the airplane dictates the control movements required for recovery. (See refs. 2 and 4 to 7.) Deflection of the rudder to oppose the spinning rotation directly is always recommended, but in many cases, it is not adequate to provide recovery. For the wing-heavy loadings, down elevator is the primary recovery control. For fuselage-heavy loadings, the aileron is the primary recovery control; the aileron should be deflected with the spin, for example, stick right for a right spin. For the zero loading, the rudder is always an important control for spin recovery. Therefore, any airplane in this loading condition should have a rudder designed for effective spin recovery. Determining the elevator effectiveness in the zero loading range is difficult, especially where the "zero loading" tends toward fuselage-heavy loadings. However, in a subsequent section on tail design, the effectiveness of the rudder and, to some extent, the elevator is discussed, and the conditions under which the rudder and elevator would be more effective for a given loading are also discussed.

Relative Density

The relative-density factor is an indication of the density of the airplane relative to the density of the air in which it is flying. The formula for computing the relative-density factor is $m/\rho Sb$. The relative density is fixed by design requirements and varies according to changes in the gross weight and altitude, which are generally very small for light general-aviation airplanes. Therefore, it cannot be adjusted to accommodate spin requirements. However, the particular value of relative-density factor of an airplane is significant and does have an appreciable influence on the spin recovery. The variation of relative density with wing loading and wing span is given in figure 5 for sea-level air density. The values would be about 50 percent higher for an altitude of 4000 meters

(13 000 feet). Airplanes with high relative-density factors normally require more rudder and elevator effectiveness for spin recovery than airplanes with low relative-density factors (other factors being equal). The normal change in the gross weight due to passengers and fuel does not usually change the relative-density factor significantly. On the other hand, a steady increase in the gross weight over a period of years, due to an increase in performance and load-carrying ability of a particular airplane model, could appreciably increase the relative-density factor. Such an increase could cause greater rudder effectiveness to be required for spin recovery. On the basis of the results of model tests to determine the effects of relative density (refs. 8 and 9), the number of turns for recovery would be expected to increase as the relative density increases for a given airplane. Therefore, if there is an appreciable increase in the gross weight of an airplane due to periodic model changes, the tail design should be reexamined to determine if it is still adequate for satisfactory spin recovery.

Tail Configuration

Criterion for spin recovery.- The tail configuration is a very important factor in the spin and recovery characteristics of airplanes, especially for light airplanes that are in the zero or near-zero loading range, where the rudder is a primary recovery control. (See refs. 9 to 15.) A relatively large moment is needed to recover an airplane from a spin, especially a flat spin; therefore, it is important that the airplane control surfaces, particularly the rudder, be effective at spin attitudes. The special problem is that during a spin, much of the rudder usually is in the stalled wake of the horizontal tail and sometimes the wing, over which the dynamic pressure is low or abnormal airflow conditions exist.

A sketch illustrating the factors which are important in the tail configuration for spin recovery is given in figure 6. This figure illustrates the dead-air region over much of the vertical tail, which is caused by the stalled wake of the horizontal tail and which seriously decreases the effectiveness of the rudder. In order to have good rudder effectiveness, a substantial part of the rudder must be outside the horizontal-tail wake. Another important, but less obvious, consideration is that the fixed area beneath the horizontal tail be sufficient to damp the spinning motion, since it has been found (ref. 10) that this area contributes much of the damping of the spinning rotation.

The criteria for tail design for spin recovery were determined many years ago from spin-tunnel tests of about 100 different models. In setting up the tail-design requirements, the factors considered were the inertia yawing-moment parameter, the airplane relative-density factor, and the tail-damping power factor. Both the inertia yawing-moment parameter and the airplane relative-density factor have previously been discussed. The tail-damping power factor is an empirically determined parameter based on various geometric properties of the vertical and horizontal tail which have been found to relate to the observed spin and recovery characteristics. Its value is an indication of the effectiveness of the overall tail configuration in terminating a spin.

The method of computing the tail-damping power factor is given in reference 9 and is discussed with particular reference to light airplanes in reference 10. For the reader's convenience, the tail-damping power factor is discussed again in the present report, and illustrations are given in figure 7 to show the method of computation. As indicated in figure 6, the rudder must have a substantial amount of area outside the horizontal-tail wake in order to be effective, and also, the fuselage must have a substantial amount of area under the tail in order to provide damping of the spinning rotation. When converted to coefficient form, the unshielded rudder area multiplied by its moment arm from the center of gravity is referred to as the unshielded-rudder volume coefficient, and the fuselage side area under the horizontal tail multiplied by the square of its moment arm is referred to as the tail-damping ratio. These two coefficients are used to calculate the tail-damping power factor. When the concept of tail-damping power factor was being formulated, some method had to be devised to define the position and extent of the wake of the horizontal tail (fig. 7). An analysis of the model results at that time showed that if the tail-damping ratio coefficient was less than 0.019, the spin angle of attack (relative wind) could be assumed to be 45° and a wake boundary could be assumed to be defined by the 30° and 60° lines of figure 7. If the tail-damping ratio coefficient was greater than 0.019, the spin angle of attack (relative wind) could be assumed to be 30° and the wake boundary could be assumed to be defined by the 15° and 45° lines of figure 7.

A particularly important point brought out by the form of the equation for tail-damping power factor is that both the fixed area beneath the horizontal tail and the unshielded rudder area are required to give significant values of this parameter. The reason for this situation is that the damping provided by the fixed area is required to steepen and slow the equilibrium spin, and rudder power is required to provide the change in moment necessary to effect a recovery.

A summary of the tail-design requirements for insuring satisfactory recovery is presented in figure 8. This figure gives the boundaries for satisfactory spin recovery for aircraft which have relative-density factors for values from 6 to 35 and for a range of inertia yawing-moment parameters from -280×10^{-4} to 120×10^{-4}. These criteria should not be used for airplanes that have values of relative-density factor or inertia yawing-moment parameter outside these limits. Regions of satisfactory and unsatisfactory recovery characteristics are given for recovery by rudder reversal alone and for recovery by simultaneous rudder and elevator reversal. The recovery characteristics for a given airplane are considered unsatisfactory if the tail-damping power factor falls below the boundary line for the relative-density factor for that airplane.

For very lightweight airplanes, the aerodynamic contribution to the recovery moment can be much larger than for corresponding heavier airplanes, and consequently, a smaller tail-damping power factor may be required for spin recovery. The tail-damping power factor required for satisfactory spin recovery for these aircraft is plotted to a larger scale in figure 9. This figure gives the boundaries for satisfactory spin recovery for airplanes which have values of the relative-density factor of 6 and 10 and for a range of values of the inertia yawing-moment parameter from -120×10^{-4} to 120×10^{-4} (ref. 10). As the inertia yawing-moment parameter increases in the positive direction (weight increased along the wings), the required tail-damping power factor increases for satisfactory recovery by rudder alone. However, at the same time, the effectiveness of the elevator increases for recovery. Therefore, if recovery is attempted by rudder reversal followed by elevators down (for zero and wing-heavy loadings), the required tail-damping power factor could be smaller.

Caution should be used in relying on the elevators alone for spin recovery. It is important to point out that most of the models used in the tests to determine the boundaries in figure 9 had large elevators with large trailing-edge down deflections (elevator leading edge at about 50 percent chord of the horizontal tail and down deflections of 15° to 20°). Therefore, when correlation of present-day airplanes is made with the boundaries given in figure 9, the elevator size and down deflection should be considered. Another factor to consider is the effect of center of gravity. Experience has shown that in most cases, an airplane will spin flatter as the center of gravity is moved rearward. When the elevator alone is relied on to provide recovery (for fuselage-heavy loadings), the elevator effectiveness usually decreases at the flatter spin attitudes and in many cases has been demonstrated to be completely ineffective for spin recovery. Because of the rather indeterminate nature of some of these factors relating to the effectiveness of the elevator for recovery, it is recommended that, as a factor of safety, a sufficiently large tail-damping power factor be provided in the original design so that recovery by rudder alone can be obtained without the use of the elevators.

In some cases, it has been found that simultaneous reversal of the rudder and elevator gives unsatisfactory recovery characteristics, whereas the reversal of the rudder alone with the elevator up gives satisfactory recoveries. This result is believed to be due to the rudder being shielded by the downward movement of the elevator. For this reason, it is recommended that, when both the rudder and the elevator are reversed for recovery, the rudder should be reversed first, and then about one-half to one turn later, the elevator should be deflected down. This technique was proved in full-scale spin tests conducted on several airplanes by the NACA in 1935 (ref. 14), and the results from these tests led to the so-called NACA recommended spin-recovery technique: Briskly move the rudder to full against the spin; after the lapse of appreciable time (approximately one-half turn), briskly move the elevator to approximately full down, and hold these controls until the recovery is complete. It is important to note that when these results were obtained in 1935, the airplanes of that day probably were in the zero loading condition previously discussed and today this recovery technique would apply only for airplanes that have similar loadings. As previously pointed out, the control technique required for spin recovery is primarily dictated by the mass distribution in the airplane. Therefore, for airplanes of different loading conditions, this control technique recommended in 1935 would probably not apply.

Rudder effectiveness.- In general, two types of rudders are used on general-aviation airplanes today: full-length rudders and partial-length rudders. Full-length rudders extend to the bottom of the fuselage, whereas partial-length rudders generally terminate at or above the top of the fuselage. (See figs. 6 and 7.) Regardless of the design, however, the rudder should provide an adequate tail-damping power factor for good spin recovery. In general, the optimum horizontal-tail position to provide the maximum unshielded rudder area is different for partial-length and full-length rudders.

For full-length rudders, the part of the rudder below the horizontal tail provides most of the unshielded area. Therefore, high and forward positions of the horizontal tail are usually the most effective configurations for spin recovery for designs employing full-length rudders.

For partial-length rudders, all the rudder is above the horizontal tail, and the top part of the rudder provides most of the unshielded area; therefore, low and rearward positions of the horizontal tail are most effective to provide the needed unshielded rudder area. For example, in reference 16, test results indicated that spin-recovery characteristics would become worse as the center of gravity moved rearward, but just how much worse depended on the tail-damping power factor and the position of the horizontal tail on the vertical tail. Low values of tail-damping power factor and high horizontal-tail positions (for partial-length rudders) were adverse to recoveries and had about the same effect as moving the center of gravity rearward. It is believed that the low horizontal-tail positions unshielded more of the rudder and were thereby favorable to recoveries.

One particular point that should be recognized with regard to tail design is that with a low horizontal tail and a sweptback vertical tail, it is possible that almost the entire vertical tail, including the rudder, might be in the stalled wake of the horizontal tail. Such a tail design is characteristic of some modern light general-aviation airplanes and would have approximately zero tail-damping power factor. This does not imply that recovery from the spin would be impossible, since the elevator would have some effect, particularly in the incipient spin. But the certainty of recovery would be jeopardized because of both the foregoing and the following qualifications with regard to the use of the elevator for recovery.

Elevator effectiveness.- For airplanes with partial-length rudders and often for full-length rudders with a low horizontal tail, the rudder is usually mostly shielded by the horizontal tail and is, consequently, ineffective for spin recovery. Therefore, the elevator is relied on for most of the spin recovery. Even so, an almost universal control technique suggested for recovery is rudder reversal followed by deflection of the elevators to neutral or down. Because most light general-aviation airplanes are required in the spin demonstrations of reference 1 to rotate only one turn before recovery attempt, this technique is usually successful, provided that recovery is attempted before one turn is completed. However, in many cases, it would be disastrous for the airplane to inadvertently wind up more than one turn because this technique may not recover the airplane if the spin has developed to two or more turns. The widespread random success of using the elevator as the main recovery control has led many persons to a false sense of security. Down elevator is almost always assumed to be able to recover. Consequently, the vertical-tail and rudder designs required for good spin-recovery characteristics are seldom considered. The reason that the effectiveness of the elevator for spin recovery decreases as the spin progresses beyond one turn involves many factors. Normally, a light airplane does not attain an equilibrium or balanced spin condition until after approximately two turns. During this time (before the two-turn spin point) the spin is somewhat slower and the average angle of attack is lower, both of which lead to the type of spin mode from which recovery is easier than from faster rotating or flatter spins. Therefore, the consequences of relying on the elevators alone may be fatal in a marginal situation. If the airplane loading is assumed to be near zero or wing heavy, where the elevators should be effective for spin recovery, the actual effectiveness of the elevators depends on such factors as the angle of attack, the tail length, the elevator size, the maximum down deflection angle, the spin rate, and the tail-damping power factor. As the angle of attack increases, the effectiveness of the elevator to produce a nose-down moment decreases (ref. 17); while at the same time, the amount of nose-down moment required for recovery increases because the spin is flatter.

Results from tests of full-scale airplanes have shown that the spin attitude can have a pronounced influence on the effectiveness of the elevator for spin recovery. In several documented spin test programs, good and rapid recoveries were obtained by rudder reversal and down elevator from spins that were steep and typical of median or forward center-of-gravity positions. However, poor recoveries, or no recoveries at all, were obtained from the flatter spins resulting from rearward center-of-gravity positions. It was shown in one case that the rudder was completely ineffective for spin recovery from any spin mode, steep or flat, because the rudder was shielded, and that the elevator was serving as the primary recovery control. This condition was satisfactory for steep spins but was ineffective for flatter spins. These results again illustrate the importance of a good rudder in a tail design for spin recovery.

Antispin fillets.- The purpose of antispin fillets is to increase the damping of the tail, which causes the spin rate to decrease and thereby cause the airplane to spin steeper. The characteristics of a typical antispin fillet are shown in figure 10. The effectiveness of antispin fillets for improving recovery characteristics of a given airplane generally depends on the tail-damping power factor, the relative density, and the mass distribution of the airplane. Generally, when an improvement is seen, the antispin fillets cause the airplane to spin at a steeper angle, where the recovery characteristics are better. On the basis of the results presented in reference 18, however, the addition of antispin fillets seems to offer only a slight improvement in the recovery characteristics, regardless of the relative density and the mass distribution. Therefore, if the recovery characteristics are on the borderline between satisfactory and unsatisfactory, the addition of antispin fillets might make a noticeable improvement in the spin and, consequently, the recovery characteristics. On the other hand, if the tail-damping power factor is well below that required for satisfactory recovery, any small improvement offered by the antispin fillets is not expected to be noticeable, and the recovery characteristics may still be unsatisfactory. Therefore, if a large improvement is needed in the recovery characteristics of a given airplane, the use of antispin fillets is not expected to offer any appreciable assistance.

The presence of antispin fillets in a tail configuration is important in computing the tail-damping power factor. In order to compute the tail-damping ratio, the length of the fillets is used in the determination of the fuselage side area beneath the horizontal tail. However, the fillets are assumed not to be wide enough to affect the wake above the horizontal tail and, therefore, are not considered in computing the unshielded-rudder volume coefficient.

Ventral and dorsal fins.- A typical ventral and dorsal fin configuration is shown in figure 10. The effectiveness of a ventral fin in improving the spin and recovery characteristics of airplanes generally depends on the tail-damping power factor and the relative density. In general, the ventral fin causes the airplane to spin slightly steeper because of the increased tail damping caused by the increased fixed area beneath the horizontal tail and, therefore, causes some improvement in the recovery characteristics. On the basis of the results obtained in references 16 and 19, the use of a ventral fin can be effective in improving the recovery characteristics if a small improvement is required to make the airplane recovery satisfactory. However, if a large improvement is needed, the addition of a ventral fin is expected to offer little or no help. Of course, if the basic problem is little or no unshielded rudder, the addition of a ventral fin is not expected to offer any improvement since the ventral fin affects only the tail-damping ratio. In such a case, if the ventral fin increases the value of the tail-damping ratio, even by a large factor, little or no effect is expected.

The addition of a dorsal fin to the vertical fin is expected, from the concept of tail-damping power factor, to have little or no effect on the spin and recovery characteristics, and such has been found to be the case. Tests conducted on the effects of dorsal fins on spin recovery are given in reference 18.

External Wing Tanks

External wing tanks can have two effects on the spin and recovery characteristics of an airplane. One is the aerodynamic effect that may occur because of the size and shape of the tanks, and the other is a mass effect which is due to the weight and location of the tanks and fuel.

Aerodynamic effects.- In general, the aerodynamic effects of a tank on the spin and recovery are small and are not noticeable unless the tanks are very large in comparison with the airplane. However, some effects have been seen on the spin-entry characteristics of military aircraft, especially those with underslung wing tanks. The effects have been observed in flight tests and are evidenced by a decrease in stability, which causes the airplane to be more prone to enter a spin. This same type of effect might be expected on light airplanes with tanks mounted under the wings. The aerodynamic effect of tip tanks is even less well established; but, in any event, the airplane may be more prone to enter a spin if the tanks, regardless of position, cause a decrease in stability.

Mass effects.- The mass effects of the tanks and fuel can be very pronounced, especially if the tanks are on the wing tips. Additional weight on the wings can change the loading and the technique needed for recovery. As previously pointed out and illustrated in figure 4, the primary recovery control is dependent on the loading distribution. As indicated in the figure, for the zero range loading, the rudder is the primary recovery control. However, as the weight increases along the wings (loading changes in the positive direction), the elevators become the primary recovery control. Note that the effectiveness of the rudder decreases (tail-damping power factor required for recovery increases) and the effectiveness of the elevator increases as weight increases along the wings. The recovery characteristics of an airplane with tip tanks can, therefore, change markedly with the fuel load, and particular caution should be taken to note possible large changes in the loading from the negative to the positive range (fig. 4), where the primary control for spin recovery would change from the rudder to the elevator. If wing tanks cause the airplane to be loaded in the positive direction, the elevators should be large enough with adequate down deflection to provide satisfactory spin recovery.

Wing Trailing-Edge Flaps and Landing Gear

On the basis of research conducted in references 17 and 20, the use of landing flaps would be expected to have an adverse effect on the spin and recovery. The extension of flaps usually causes the spin to be flatter and the spin rate to be slightly slower. In addition, the results of reference 17 show that the effectiveness of the rudder for spin recovery can decrease when the flaps are down. The wake behind the wing is believed to be larger when the flaps are down than when they are up, and thereby the tail is more likely to be in a region of reduced air velocity. These results are for low-wing airplanes and are not necessarily expected to apply to high-wing airplanes, where the tail surfaces are farther from the wake of the wing.

Extension of the landing gear usually has little effect on the spin and recovery characteristics (ref. 20), but slight adverse effects have been seen from lowering the landing gear on some airplanes. Therefore, it is generally recommended that the gear be kept in the retracted position when possible.

Wing Position

The position of the wing (high or low) is believed to have some influence on the spin and recovery characteristics of airplanes. There are no documented data to provide a technical analysis of what the effects may be, but the history of stall/spin problems associated with high- or low-wing airplanes indicates that a high-wing airplane is expected to have better spin and recovery characteristics than a low-wing airplane, all other factors being equal. The reason for the apparent improvement in spin characteristics of the high-wing airplane is believed to be related to the higher dihedral effect caused by the high-wing position and to improvement in the wake characteristics of the wing in the vicinity of the tail. The wake from a high wing is believed to pass above the tail so that the tail surfaces are not appreciably affected and the rudder and elevators are more effective in the spin recovery.

Tail Length

Tail length can have an appreciable effect on the spin and recovery characteristics of an airplane. Tail length is generally expressed nondimensionally as the ratio of the distance between the center of gravity and the rudder hinge line to the wing span. On the basis of the results of studies made in references 17 and 19, the recovery characteristics of an airplane are influenced to a much greater extent by the tail length than is indicated by the increase in the tail-damping power factor due to tail length. In one case, for example, the recovery characteristics for a long-tail model were satisfactory for a tail-damping power factor of 395×10^{-6}, whereas for the same model with a shorter tail, the tail-damping power factor had to be increased to about 520×10^{-6} before satisfactory recoveries could be obtained. The general effect of increasing the tail length is to cause the airplane to spin at a lower angle of attack and at a higher rate of rotation, whereas the shorter tail will cause the airplane to spin flatter and at a slower rate of rotation.

The results of tests conducted in reference 17 indicate that the effectiveness of the rudder in producing a yawing moment is much greater at lower angles of attack than at higher angles of attack. Also, the effectiveness of the horizontal tail in producing a nose-down moment increases when the horizontal tail is moved rearward (increased tail length). The implication of these results is that strong consideration should be given to designing an airplane with as long a tail as possible in order to begin with a basic design most conducive to good recovery characteristics.

Center-of-Gravity Position

The center-of-gravity position can significantly affect the spin and recovery characteristics of an airplane. (See refs. 15 and 21.) Usually, the effect is unpredictable and is dependent on the tail-damping power factor and other characteristics of the airplane. For this reason, tests are normally required to determine the effect of center-of-gravity position for a given airplane. In general, however, the airplane usually spins flatter as the center of gravity is moved rearward. (See ref. 16.) This result is, of course, adverse since the control effectiveness normally decreases as the airplane spin angle of attack increases. Whether or not the controls become ineffective for recovery of the airplane in the flatter attitudes cannot be determined by any empirical methods known by the author and must be determined experimentally for a given airplane.

Power

The effect of applying symmetrical power in a spin is believed to be insignificant. A number of varied observations have been made through the years by many people, and the conclusions regarding power effects on spins range from favorable to adverse. Since there has been no systematic study of the effects of applying power during a spin, random visual observations and sparse results constitute all the data available.

In some of the observed results, pilots reported a definite aid to recovery when applying symmetrical power (single-engine airplanes), and in other reports, pilots have observed a definite adverse effect when applying power. In almost all cases, the results were not obtained under controlled conditions. Therefore, the type of spin, the center of gravity, the angle of attack, the spin rate, and the line of thrust with respect to the center of gravity were not identified.

In a few cases where the effect of thrust has been measured under controlled conditions (ref. 22), the application of thrust had no effect unless the thrust axis was displaced from the center of gravity and thereby produced a moment. In these tests, both favorable and adverse effects were observed, depending on the type of moment produced and the loading condition of the model being tested. Since thrust effects can be adverse and unpredictable, it is generally recommended that for a single-engine airplane, the throttle be retarded to the idle position during a spin.

For asymmetric power for a twin-engine configuration with the engines mounted on the wings, power from only one engine can produce a large asymmetric yawing moment, which will be favorable or adverse to the spin and recovery, depending on the direction of the moment. Both model and full-scale spin-test results of multiengine airplane designs have shown that power on the outboard engine (e.g., the right engine in a left spin) can create a large prospin yawing moment, which can cause a flatter and faster spin. On the other hand, power on the inboard engine can create an antispin moment to aid spin recovery. Normally, the manipulation of thrust can be confusing and disastrous if the power is applied to the wrong engine. Therefore, unless asymmetric power is necessary to aid recovery, it is generally recommended that for a multiengine airplane, the throttle be retarded to the idle position on all engines during a spin.

CONCLUSIONS

A summary has been made of all NASA (and NACA) research and experience related to the spin and recovery characteristics of light personal-owner-type general-aviation airplanes. Very little of the research deals with light general-aviation airplanes as such, but many of the airplanes and models tested before and during World War II were similar to present-day light general-aviation airplanes with regard to the factors that are important in spinning. The following conclusions were drawn from a summary and analysis of all the information related to light general-aviation airplanes, and it should be noted that they do not apply to heavy, high-density airplanes, such as small transports and jet airplanes:

1. Three factors are of almost overriding importance with regard to spin and recovery characteristics:

   (a) The relative distribution of the mass of the airplane between the wing and fuselage, which is commonly expressed in terms of the inertia yawing-moment parameter, a nondimensional factor relating the rolling and pitching moments of inertia

   (b) The tail configuration, which must provide damping for the spinning rotation and the rudder power for recovery and which is commonly evaluated in terms of an empirically determined tail-damping power factor

   (c) The density of the airplane relative to the density of the air, which is commonly expressed in terms of the relative-density factor

2. The mass distribution and the relative density determine the tail configuration requirements and the control technique required for recovery. The relative density is generally fixed by performance requirements and cannot be adjusted to accommodate the spin.

3. An empirically determined factor, called the tail-damping power factor, based on tests of over 100 designs is available as a guide for the design of the tail to insure good spin recovery.

4. The rudder is generally the principal recovery control, but for positive (wing-heavy) loadings or for recovery during the incipient spin, the elevator can also be an important recovery control and can reduce the rudder power requirements. Experience has shown, however, that relying on the elevator is dangerous because it might become ineffective for fully developed spins, flat spins, or cases in which the mass distribution has been changed or the center of gravity has been moved behind the normal rearward limit because of changes in loading of the airplane due to growth or operational factors.

5. Significant secondary factors which might affect the spin are center-of-gravity position, wing position (high or low), tip tanks, and asymmetric power.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., November 5, 1971.

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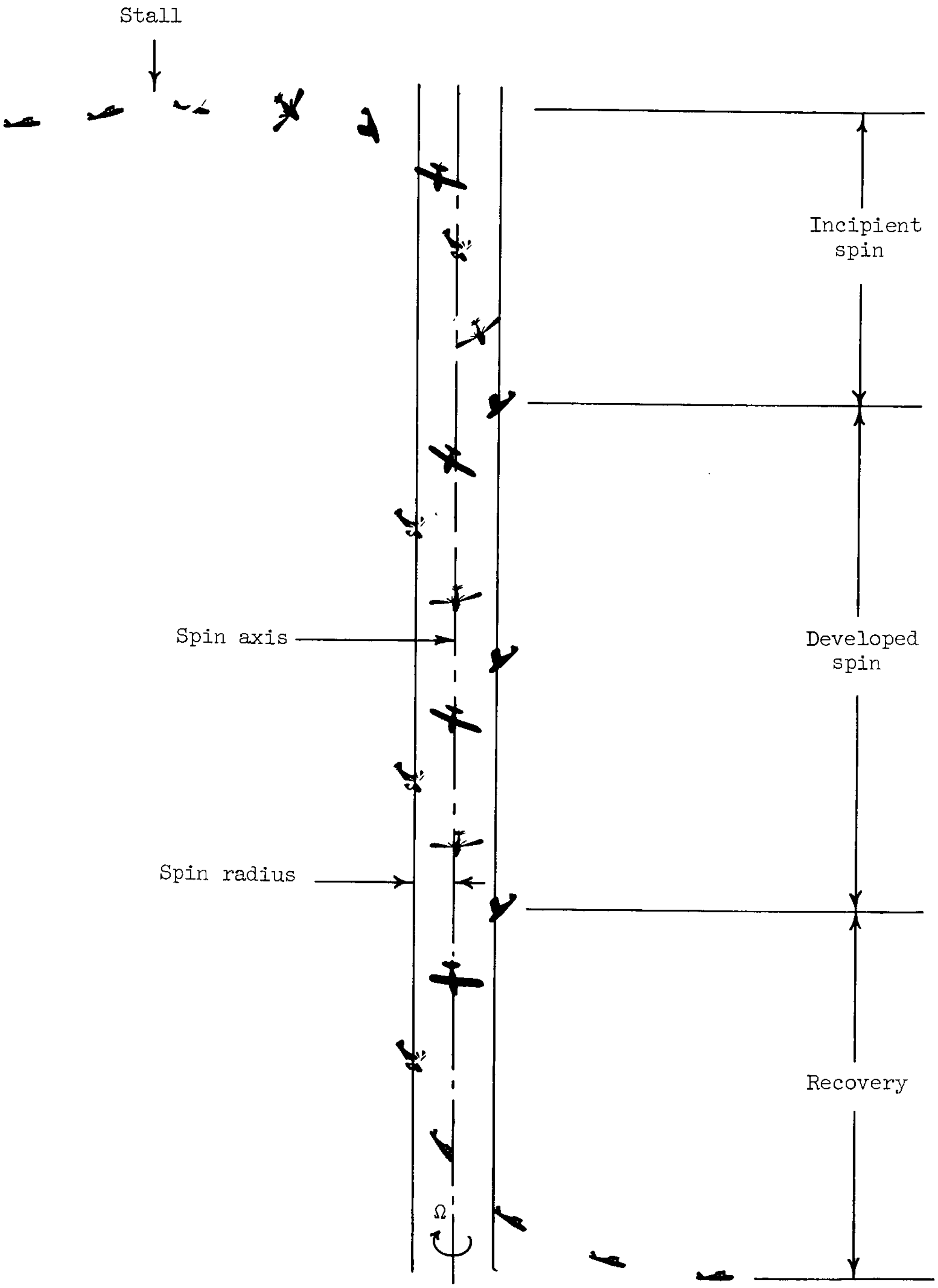
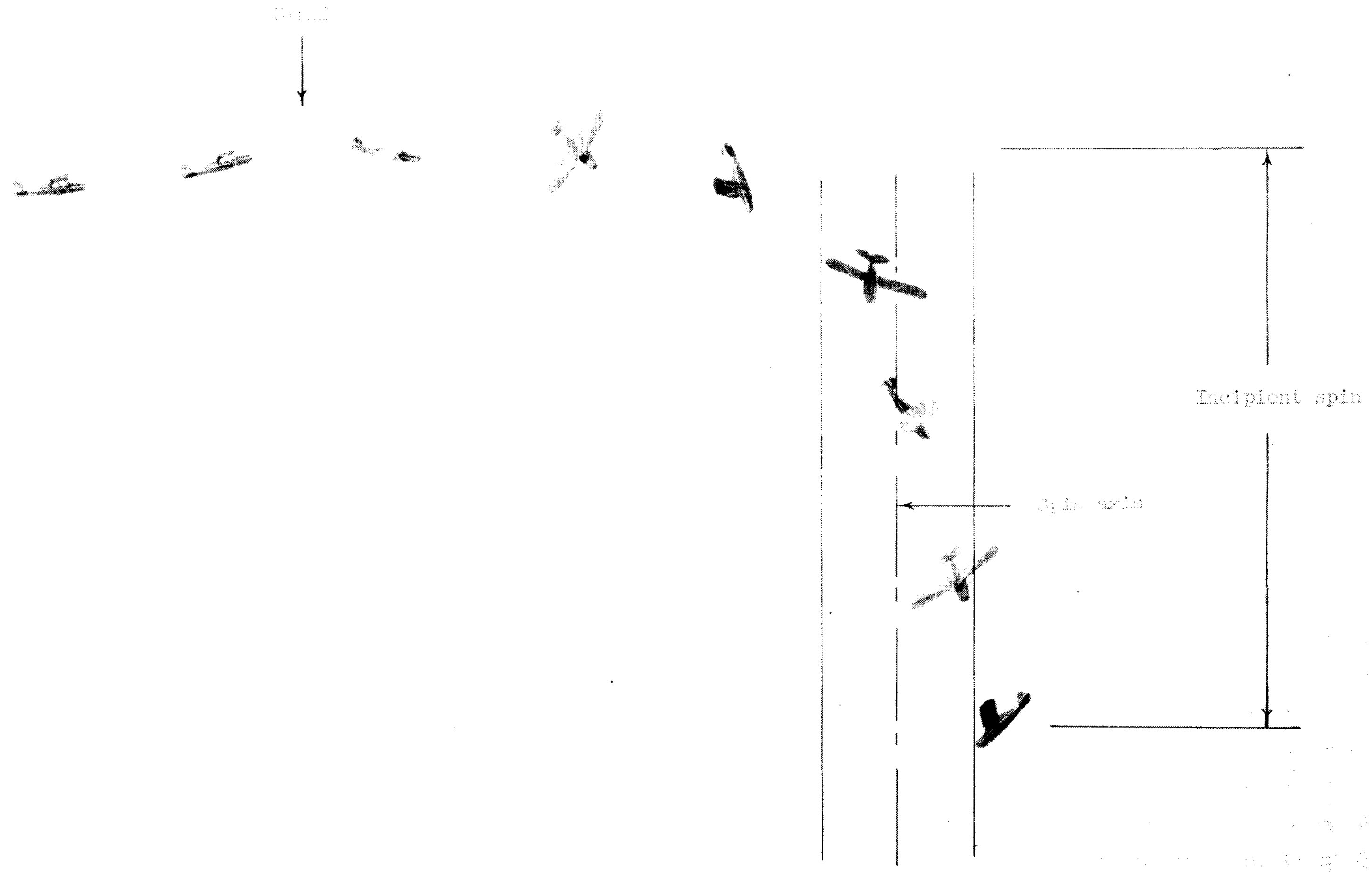


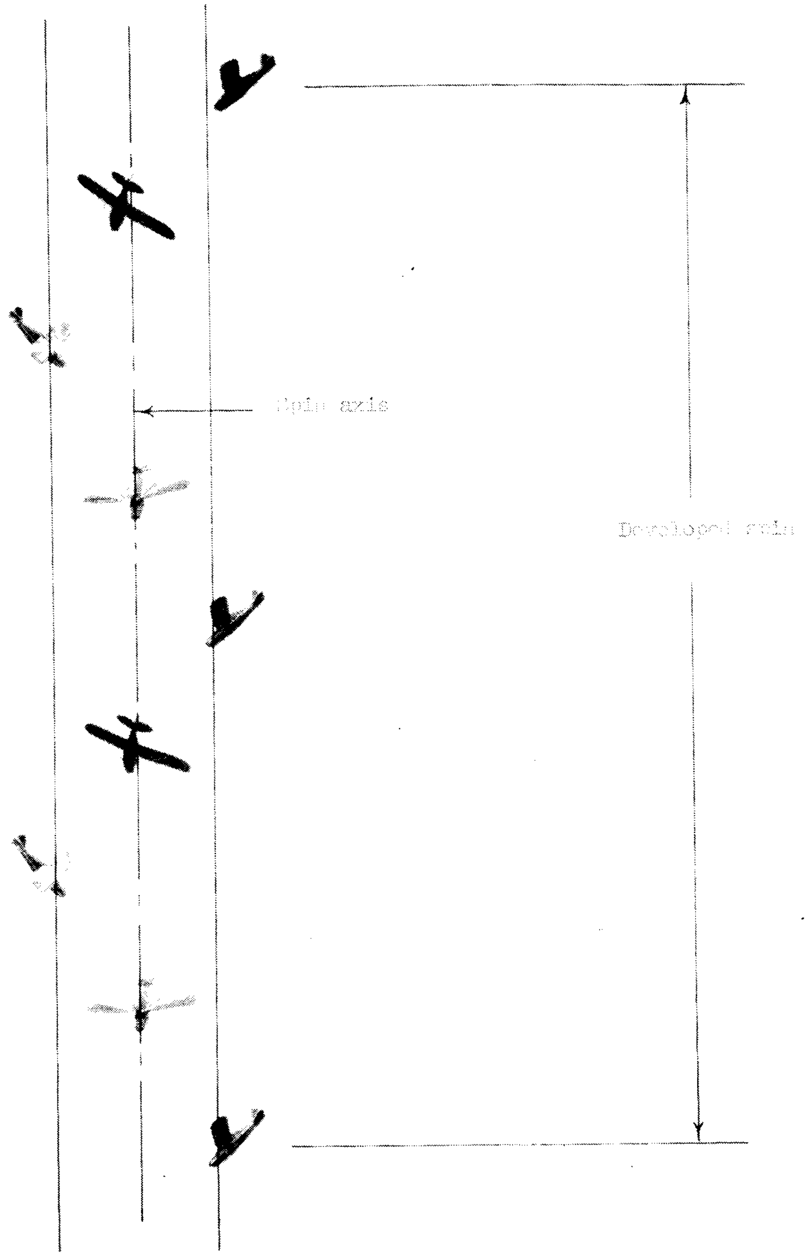
(a) Complete spin, stall through recovery.

Figure 1.- Illustration of spinning motion.



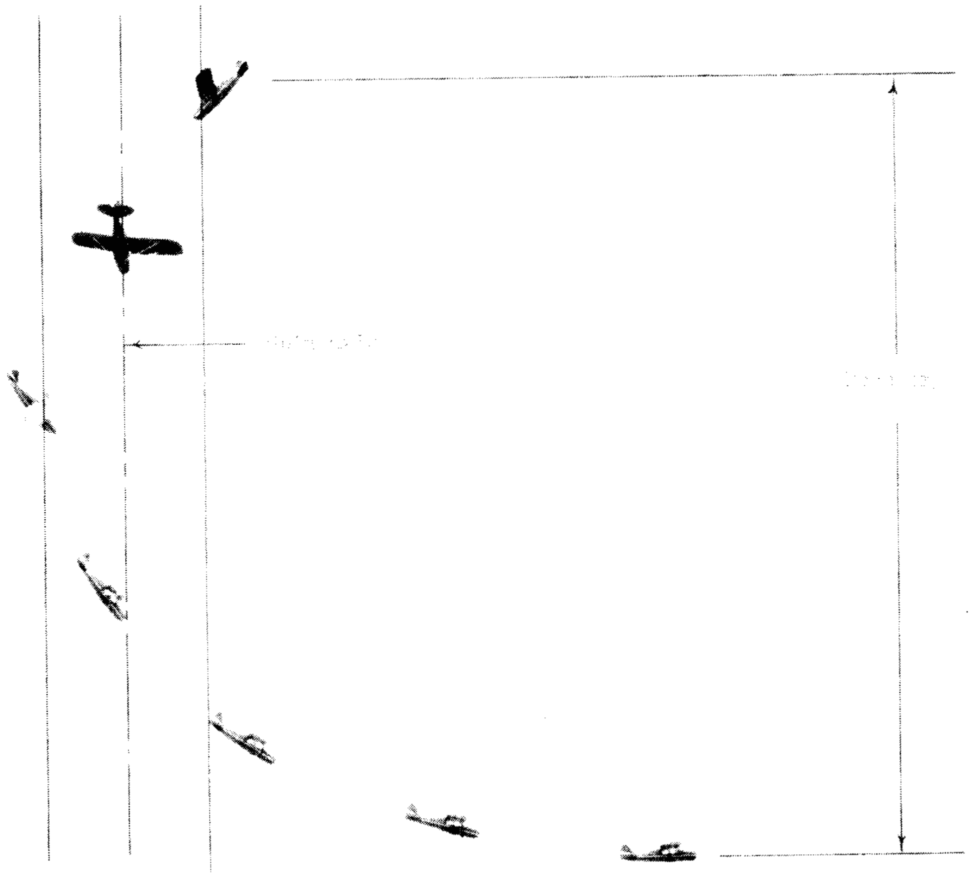
(b) Incipient spin phase.

Figure 1.- Continued.



(c) Developed spin phase.

Figure 1.- Continued.



(d) Recovery phase.

Figure 1.- Concluded.

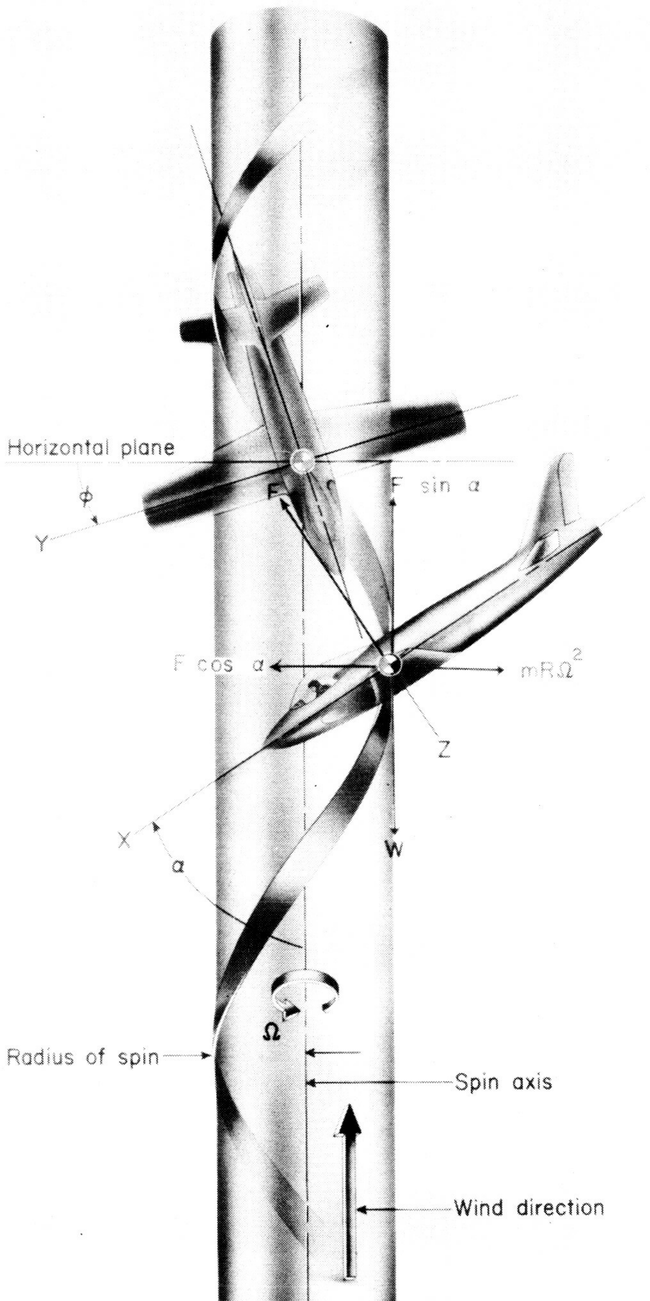


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Figure 2.- Balance of forces in a spin.

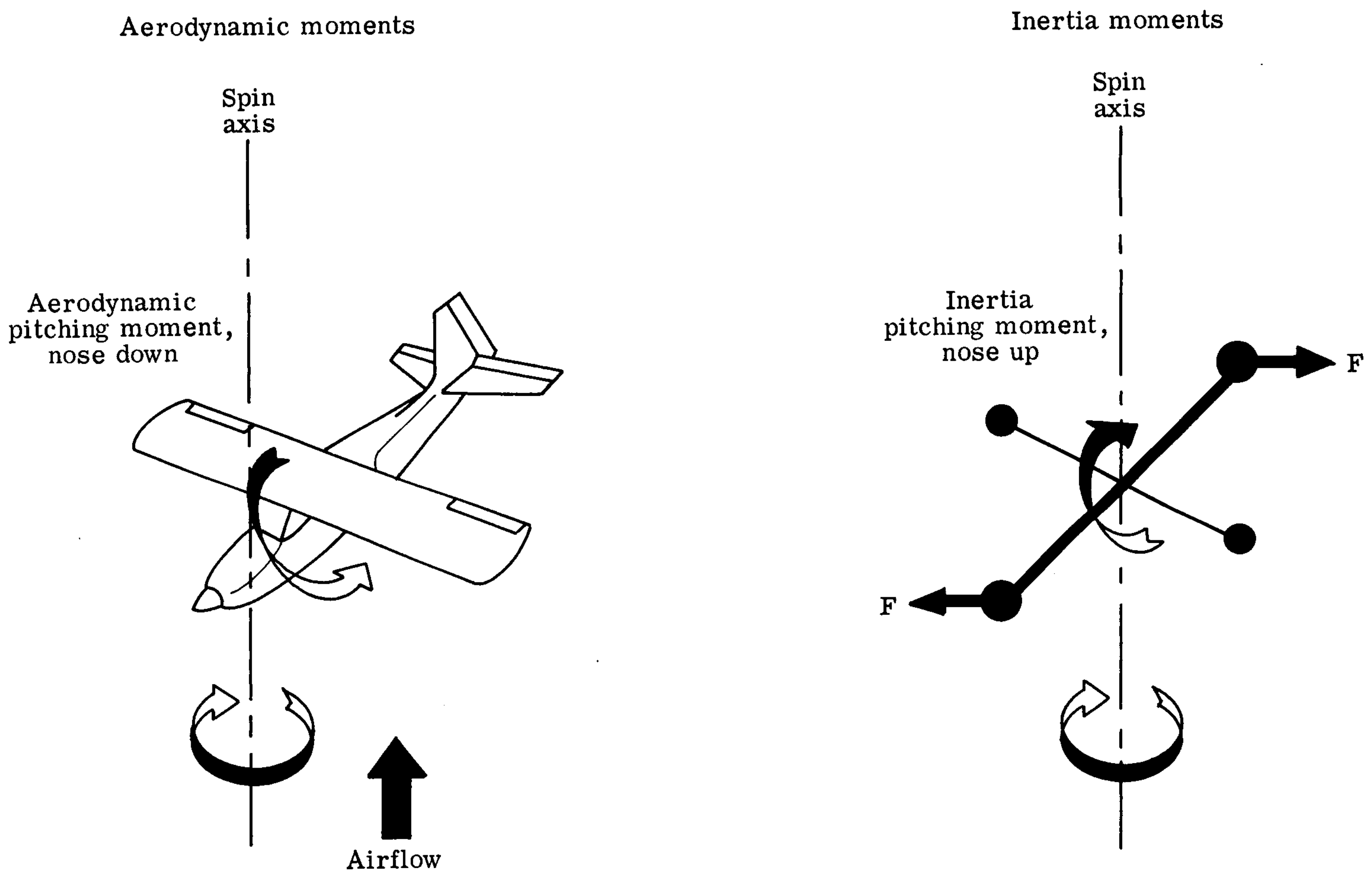


Figure 3.- Balance of aerodynamic and inertia pitching moments in a spin.

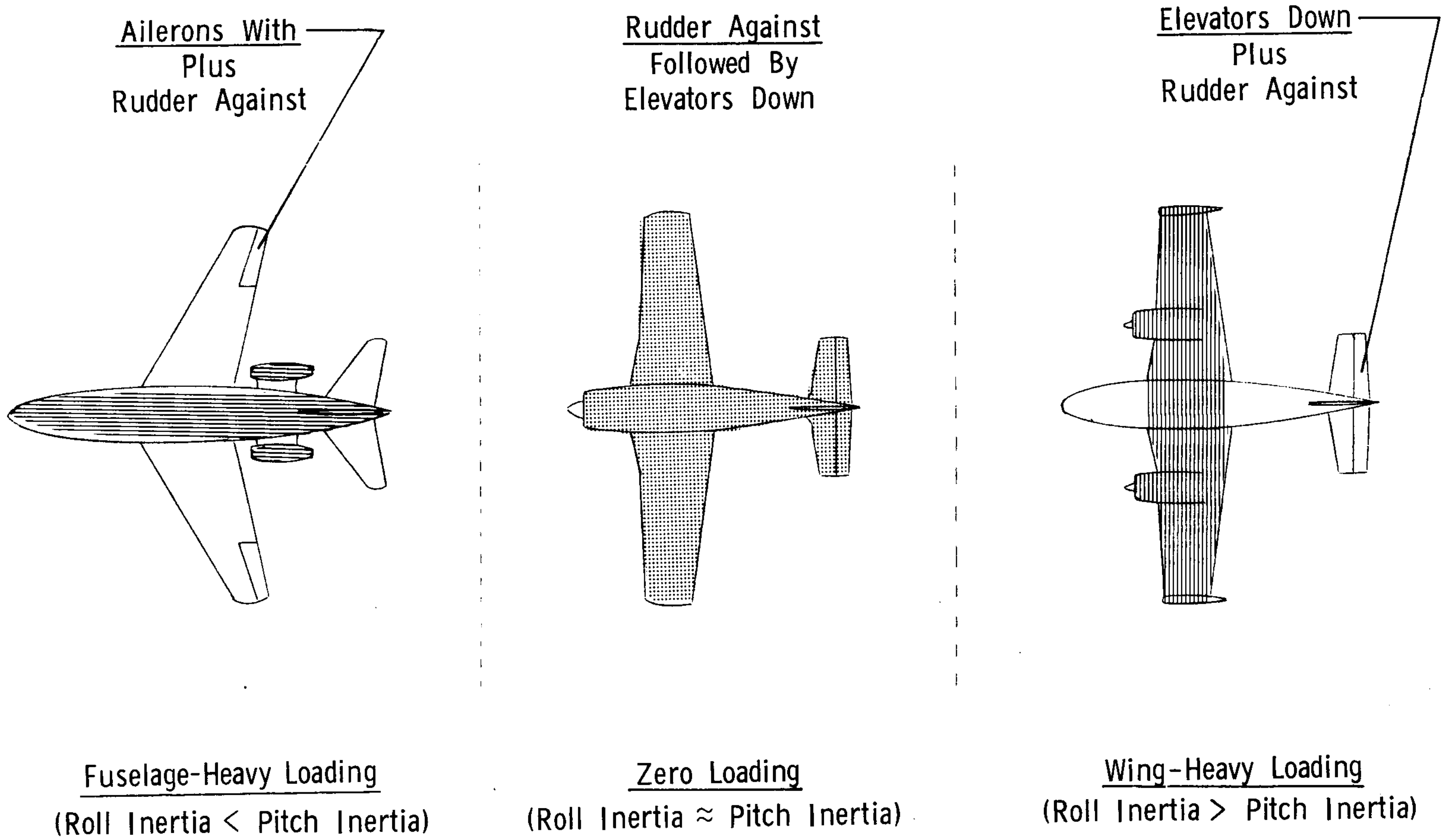


Figure 4.- Primary recovery controls as determined by mass distribution.

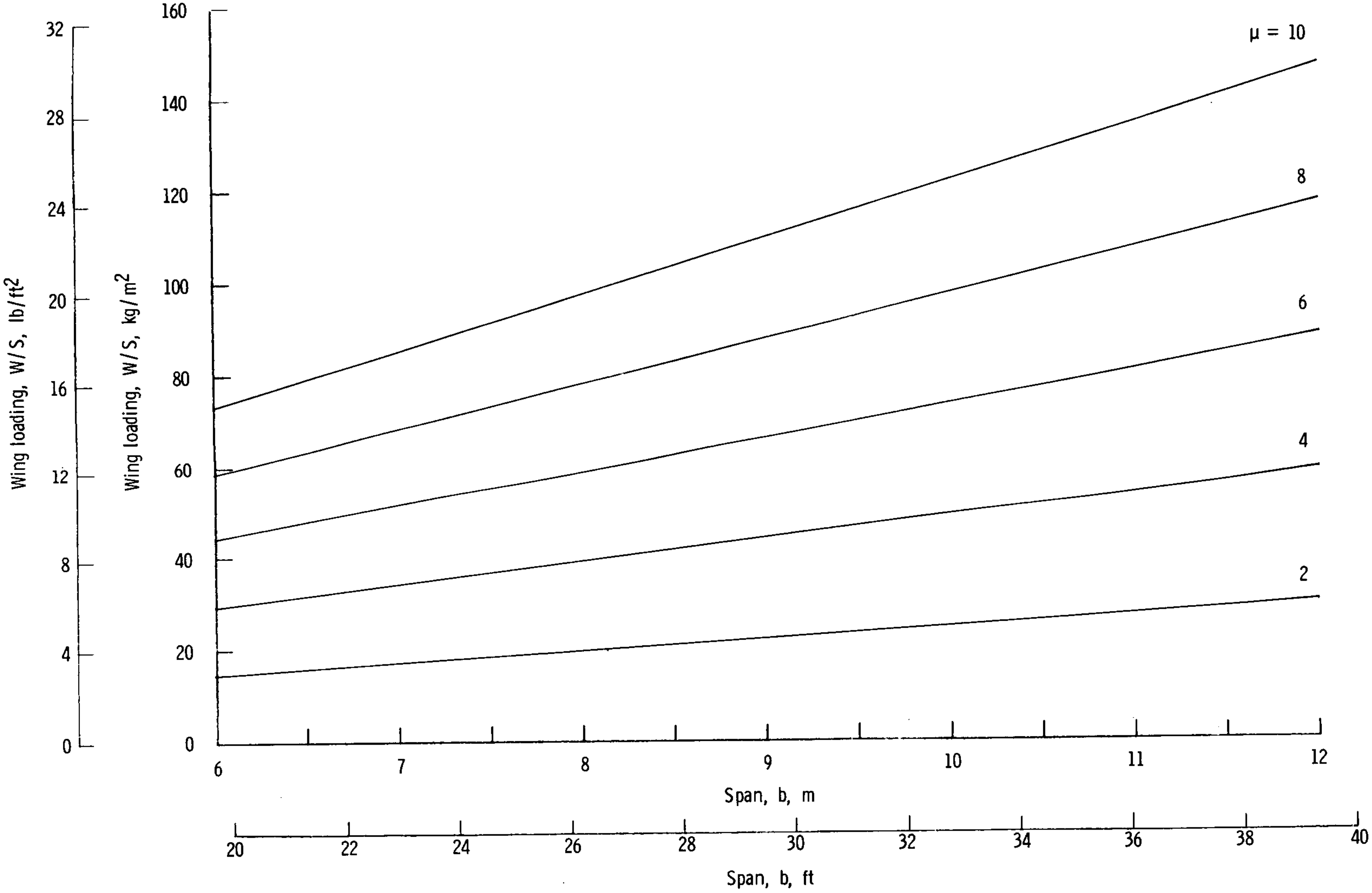


Figure 5.- Variation of relative-density factor with wing loading and span for light personal-owner-type general-aviation airplanes. Sea-level air density.

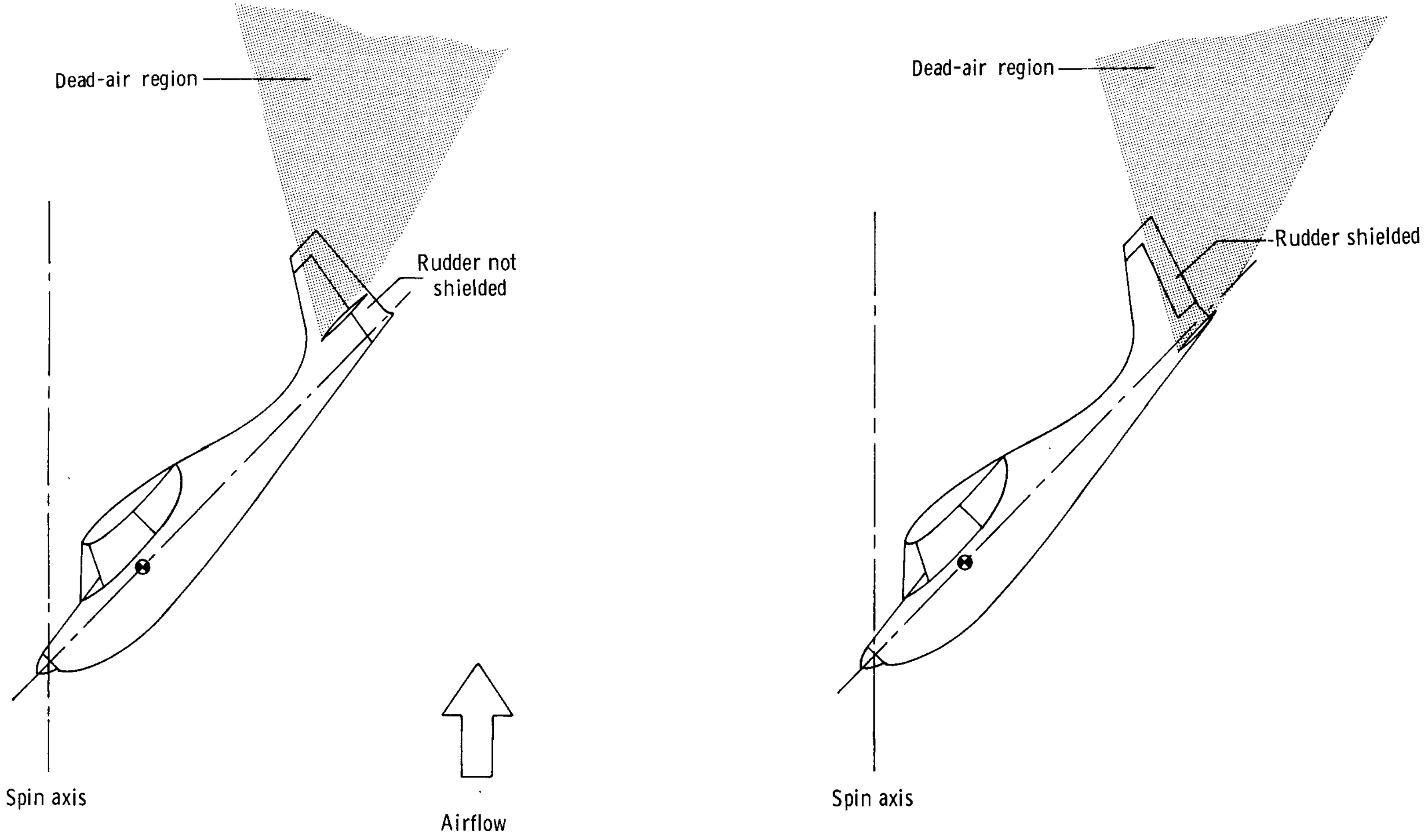
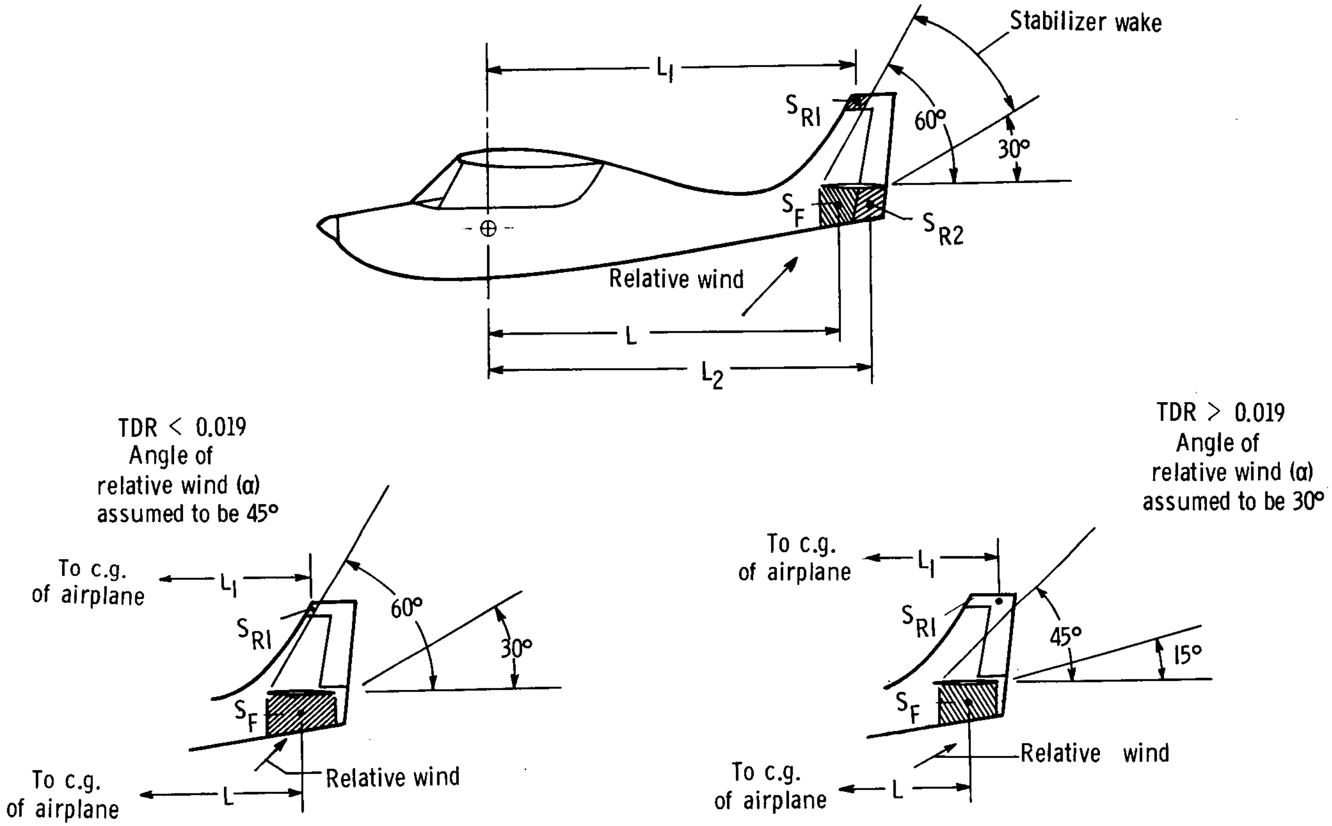


Figure 6.- Tail-design characteristics for spin recovery.



$$\mathrm{URVC} = \frac{S_{R1}\,L_1 + S_{R2}\,L_2}{S(b/2)}$$

$$\mathrm{TDPF} = \mathrm{URVC} \times \mathrm{TDR}$$

$$\mathrm{TDPF} = \frac{S_{R1}\,L_1 + S_{R2}\,L_2}{S(b/2)} \times \frac{S_F\,L^2}{S(b/2)^2}$$

$$\mathrm{TDR} = \frac{S_F\,L^2}{S(b/2)^2}$$

Figure 7.- Method of computing tail-damping power factor.

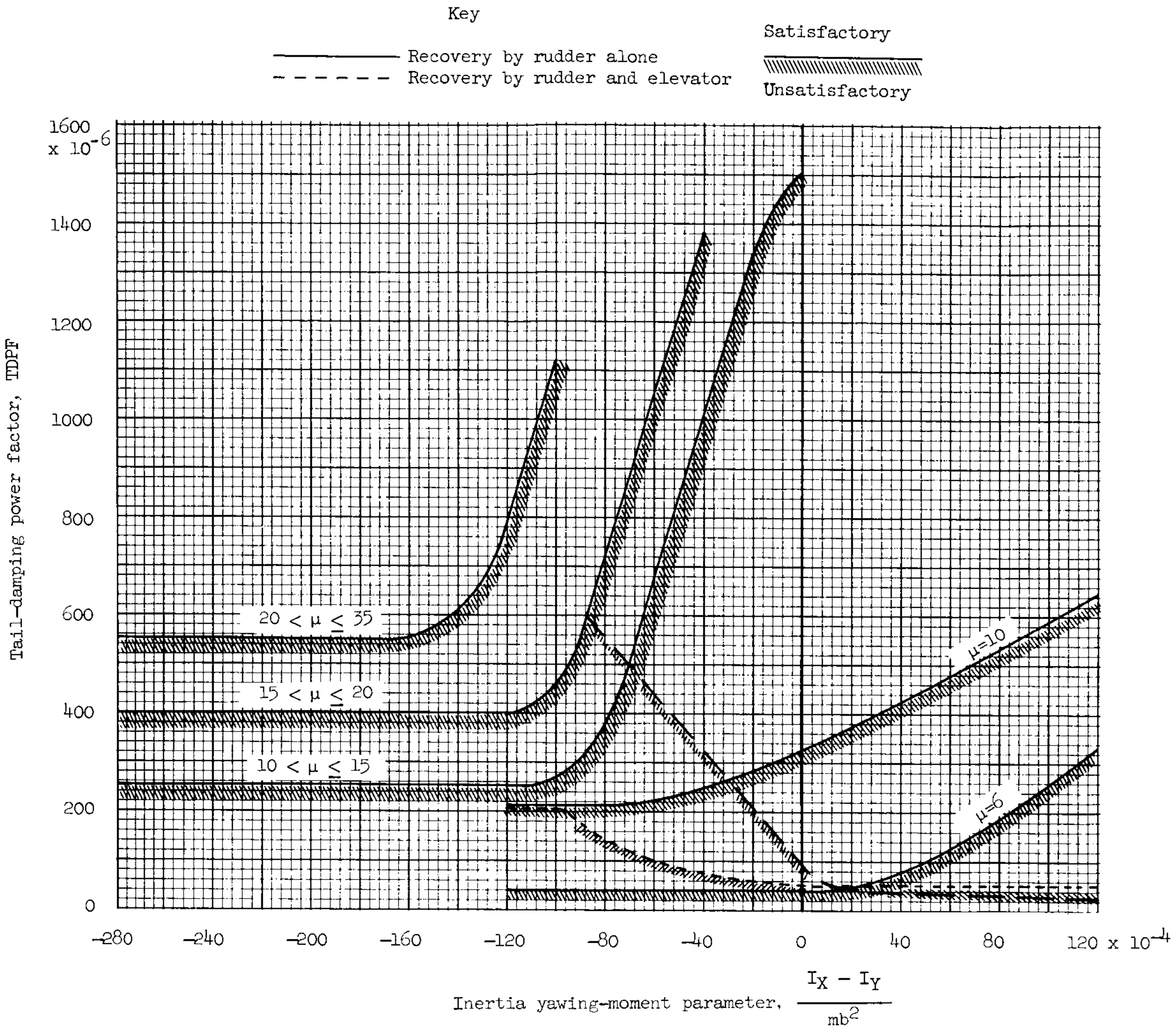


Figure 8.- Tail-design requirements for airplanes having relative-density factors from 6 to 35.

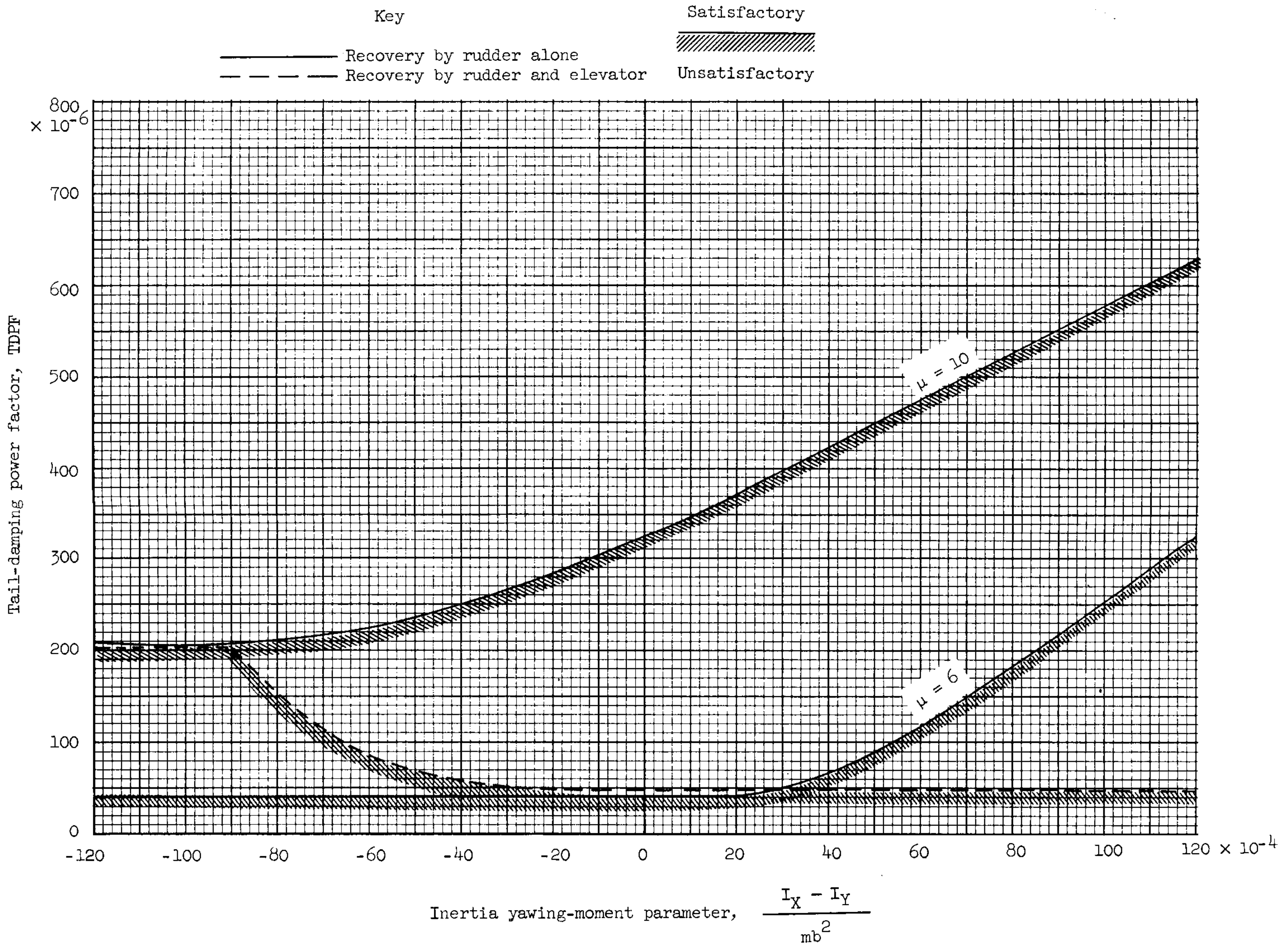


Figure 9.- Tail-design requirements for airplanes having relative-density factors of 6 and 10.

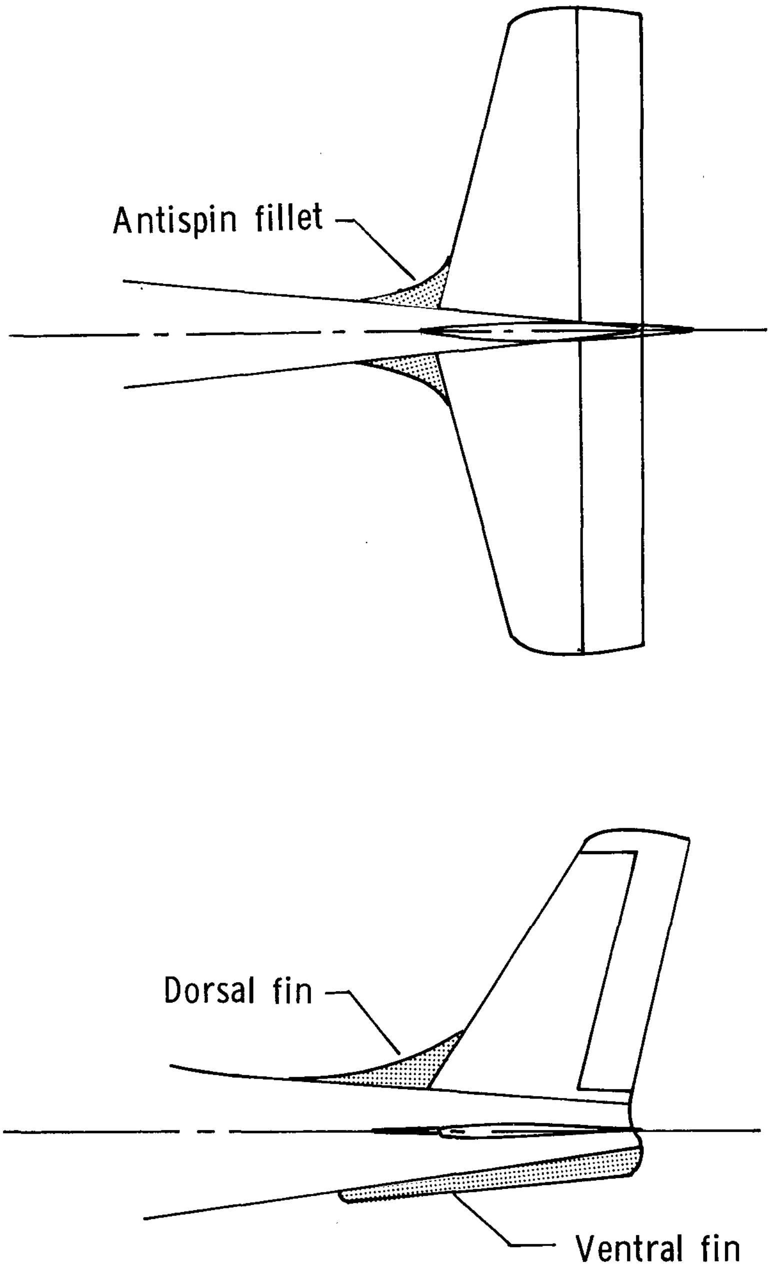


Figure 10.- Typical tail designs showing antispin fillets and dorsal and ventral fins.

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16. Abstract

A summary has been made of all NASA (and NACA) research and experience related to the spin and recovery characteristics of light personal-owner-type general-aviation airplanes. Very little of the research deals with light general-aviation airplanes as such, but many of the airplanes and models tested before and during World War II were similar to present-day light general-aviation airplanes with regard to the factors that are important in spinning. The present paper is based mainly on the results of spin-tunnel tests of free-spinning dynamically scaled models of about 100 different airplane designs and, whenever possible, includes correlation with full-scale spin tests. The research results are discussed in terms of airplane design considerations and the proper use of controls for recovery.

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