Influence of the Static and Dynamic Aerodynamic Characteristics on the Spinning Motion of Aircraft

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Since the aerodynamics strongly influence the spinning motion to be experienced by an aircraft, a prerequisite for analytically computing the spin is an awareness of the aerodynamic characteristics of an aircraft throughout the stalled angle-of-attack region. Obtaining this aerodynamic information is a formidable task and in some instances is beyond the present state-of-the-art. It is important, therefore, that the aerodynamic characteristics which have a significant influence on the spin be identified, so that future research efforts can be directed towards accurately determining the important aerodynamic characteristics. Consequently, the roles that the static, damping, cross and acceleration aerodynamic derivatives play in the spin were established during an analytical study and are discussed in this paper. For instance, it was found that the yawing moment characteristics associated with the lateral control and the effective dihedral are the two most important aerodynamic parameters involved in the spinning phenomenon; whereas the aerodynamic acceleration derivatives and the cross derivative C_{n_p} play an insignificant role. The information of this study can be also employed for identifying aerodynamic fixes that are most likely to act as antispin devices and for conceiving automatic control techniques for spin prevention or spin recovery.

Nomenclature

b = wing span, ft
$\bar{c}$ = wing mean aerodynamic chord, ft
I_x,I_y,I_z = moments of inertia about the x, y, and z, body axes, respectively, slug-ft^2
I_{xz} = product of inertia, slug-ft^2
$(I_x - I_y)/mb^2$ = inertia yawing moment parameter
$(I_y - I_z)/mb^2$ = inertia rolling moment parameter
$(I_z - I_x)/mb^2$ = inertia pitching moment parameter
m = aircraft mass (weight/32.2), slugs
p,q,r = components of the total angular velocity vector along the x, y, and z body axes, respectively, rad/sec
V = total linear velocity vector, fps
α = angle of attack, deg
$\alpha_{\text{TRIM MAX}}$ = maximum positive α at which the aircraft can be statically trimmed with the full aft stick, deg
$\alpha_{C_{n_\beta}=0}$ = α at which static directional stability is neutral
β = angle of sideslip, deg
$\dot{\alpha},\dot{\beta}$ = rate of change in α and β, respectively, rad/sec
δ_a = lateral control deflection, positive when left-wing control has trailing-edge down, deg
$\Delta\delta_e$ = longitudinal control deflection from initial trim position, positive when trailing edge is down, deg
δ_r = directional control deflection, positive direction when trailing-edge left
C_l = total rolling moment coefficient, positive value drives right wing tip down
C_n = total yawing moment coefficient, positive value drives nose to right
C_m = total pitching moment coefficient, positive value drives nose up
$C_{n_{\delta_a}}$ = $\partial C_n/\partial\delta_a$,/deg
$C_{l_{\delta_a}}$ = $\partial C_l/\partial\delta_a$,/deg
C_{l_β} = $\partial C_l/\partial\beta$,/deg
C_{l_p} = $\partial C_l/\partial(pb/2V)$, /rad
C_{n_p} = $\partial C_n/\partial(pb/2V)$, /rad
C_{l_r} = $\partial C_l/\partial(rb/2V)$, /rad
C_{n_r} = $\partial C_n/\partial(rb/2V)$, /rad
C_{m_q} = $\partial C_m/\partial(q\bar{c}/2V)$, /rad
$C_{m_{\dot{\alpha}}}$ = $\partial C_m/\partial(\dot{\alpha}\bar{c}/2V)$, /rad
$C_{n_{\dot{\beta}}}$ = $\partial C_n/\partial(\dot{\beta}\bar{c}/2V)$, /rad
$C_{l_{\dot{\beta}}}$ = $\partial C_l/\partial(\dot{\beta}\bar{c}/2V)$, /rad

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Introduction

THE spin is an uncontrolled large-angle six-degree-of-freedom motion experienced by an aircraft that is operating in the stalled aerodynamic region. During this maneuver, the center-of-gravity (point mass) prescribes a helical path about an axis in space. Eventually this spin axis becomes closely aligned with the Earth's vertical axis. The aircraft therefore descends rapidly towards the Earth. Angular motions are also encountered simultaneously about axes passing through the center-of-gravity.

Since spins serve no useful flight function and are prone to result in the permanent loss of the occupants and/or the aircraft, they are only entered inadvertently and usually for the first time by a given pilot. Consequently, it is vitally important that the pilot be informed of the spin characteristics that are associated with his particular aircraft. Analytical as well as model and full-scale experimental techniques are employed to determine these spin characteristics. Obviously, the analytical technique is the most economical and safest procedure for obtaining this information and is also the only technique available for the rigorous study of the spin mechanism.

The analytical technique currently used involves the simultaneous solution of the equations of motion and other associated mathematical expressions. However, the usefulness of the analytical technique is proportional to the level of confidence that has been established in the results. Confidence in a set of results is often accomplished by duplicating a known end product to some acceptable degree. In this instance, the objective has been to compute analytically the spinning motion that was recorded in flight with the full-scale article. For motions less complex than the spin, this after-the-fact motion-matching demonstration is usually achieved after some educated pot twirling (parameter variations), within reasonable limits, on the part of the engineer. This correlation road, however, has not been successfully navigated relative to aircraft spins. It was apparent, therefore, that greater knowledge was required relative to the spin mechanism and to the role that the various aerodynamic characteristics play in the spin before satisfactory computer-flight test correlation could be demonstrated.

Also, although the aerodynamics have a major influence on the spinning motion to be experienced by an aircraft, it is a formidable task to determine from wind-tunnel tests the static and dynamic aerodynamic characteristics for the full-scale airplane throughout the stalled angle-of-attack region. Because of this situation, it was important that the aerodynamic characteristics having a significant influence on the spin be identified in order that they may be obtained in the future to the accuracy required for computing full-scale spins. Accordingly, this paper addresses itself to the problem of ascertaining the influence that the static, rotary (damping and cross) and acceleration aerodynamic derivatives have on the spinning motion.

Technical Approach

Since the spinning phenomenon is a highly complex motion which is influenced by a host of nonlinear variables, conclusions, after limited analytical endeavors, have by necessity been couched in terms that severely limit their general applicability. The technical approach and scope of effort of this study were, therefore, predicated on achieving the necessary conditions for establishing definitive conclusions. To meet this objective, it was first necessary to conduct a spin mechanism study to become aware of the nonaerodynamic quantities that had to be included as variables during the subject aerodynamic investigations. This spin mechanism study investigated, for example, the influence of mass distribution, wing loading, entry altitude, and entry load factor on the spin (not discussed in this paper; see Ref. 1). Next, the influence of the static aerodynamic characteristics were determined on the logical assumption that some of them would have an appreciable influence on the spin. In the process of identifying the nonaerodynamic and static aerodynamic characteristics that have a major influence on the spin, a basic set of different types of spins (i.e., steep or flat, low or high rates of rotation, steady or oscillatory motion) were obtained. The influence of the dynamic aerodynamic derivatives on these different type of spins were then determined.

Procedure

It was felt that the most efficient technique for determining the influence of an aerodynamic quantity on the spin is to make a gross adjustment to the subject quantity and then observe the effect on the path of the center-of-gravity and the motion about the center-of-gravity relative to the incipient and developed phases of the spin. (The effect the subject quantity may have on the spin relative to the recovery phase was not investigated at this time.) This approach necessitated the formulation and development of an all-inclusive digital computer program tailored specifically to the study of the spin phenomenon; the solutions of which were presented automatically in the form of plotted time histories (see Ref. 1). The observed effects were then categorized as having appreciable, significant or insignificant influences. An appreciable rating indicates that the over-all nature of the spin was changed and could be easily recognized by a pilot, a significant rating indicates that a large change in some spin characteristic was evident and is of academic interest; whereas an insignificant rating indicates that no or only very slight effects were noted.

The procedures employed throughout this study were based on the desire to determine the pure (isolated) effect of a subject quantity on the spin. In the real world, any change in a particular quantity cannot be accomplished without incurring to some degree simultaneous changes in other quantities or characteristics. The use of the analytical technique, however, lifts these restrictions as illustrated by the following: 1) A single aerodynamic quantity may have its value doubled, reduced to zero, sign changed, etc. without affecting any other aerodynamic quantity. The adjustment in the value of an aerodynamic characteristic is accomplished conveniently by using a multiplicative factor that multiplies the base aerodynamic characteristic by a desired constant. 2) In order to represent aircraft having different mass distributions, multiplicative factors are also used. These factors multiply only the contribution of the inertial coupling terms in the equations of motion. In this manner, the inertial coupling effect can be magnified or diminished without having to change an inertia value (I_x, I_y, or I_z) which would incur a corresponding change simultaneously in the contribution of some aerodynamic acceleration and damping characteristic.

Basic Aerodynamic and Inertia Data

The aerodynamic characteristics employed as a base for the investigations discussed in this text are presented in Ref. 1. It was observed that the aerodynamic characteristics in coefficient form fall within a fairly narrow band for a wide range of different types of operational aircraft. The aerodynamic characteristics used as a base for this study are therefore generally representative of the aerodynamic characteristics associated with winged vehicles. In addition, the individual gross adjustments to the base aerodynamic characteristics investigated in this study encompass the variations realized among the widely different aircraft configurations.

Since the required equipment, mission, maneuvering capabilities, etc. are specified for a type of aircraft and there is an industry-wide awareness of the latest level of sophistication possible in structural design and material, it is not surprising that there are only small differences in the over-all aircraft density (lb/ft^3 of volume) among given types of aircraft (e.g., fighter). Therefore, as was the case for the aerodynamic coefficients, the ratios of the total aerodynamic forces to weight and the ratios of the total aerodynamic pitching, rolling and yawing moments to the I_y, I_x, and I_z inertias, respectively are of the same order of magnitude for a large number of vehicles. For the present study, therefore, the individual inertias and weight were held constant and the normal and angular accelerations that were computed during the incipient and developed spin phases are representative of the motions possible with modern highly-maneuverable aircraft.

Although the over-all aircraft densities are similar, the distribution of the mass along the body reference axes covers a considerable range. This fact is illustrated in terms of the inertia parameters for various aircraft in Fig. 1.

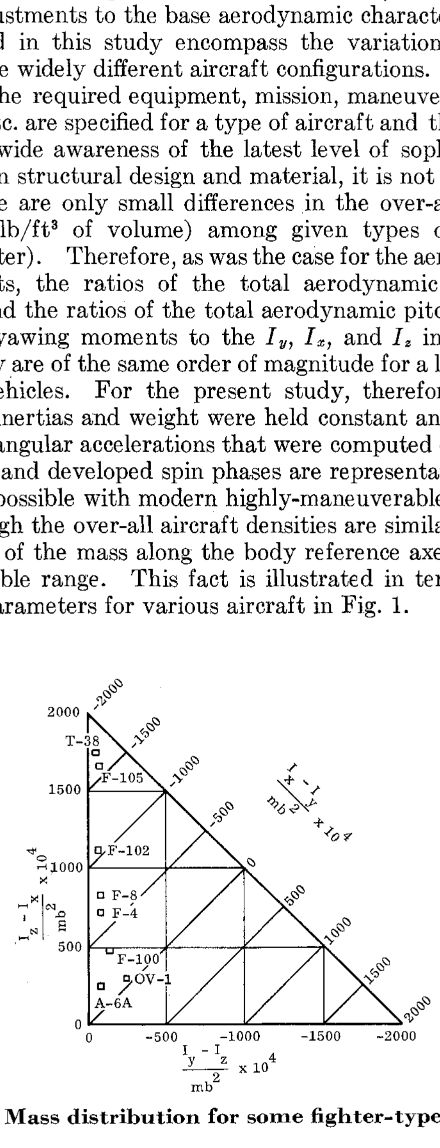

Fig. 1 Mass distribution for some fighter-type aircraft.

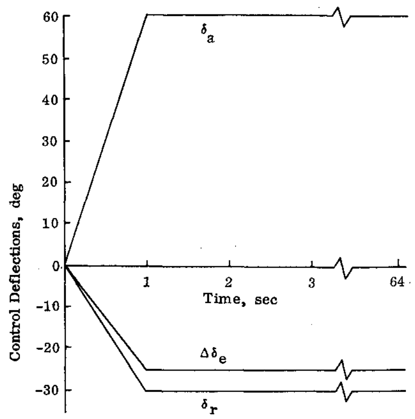

Fig. 2 Time history of control inputs applied during the study.

As can be seen, the mass is distributed along the fuselage axis to varying degrees, i.e., the A-6A has its mass distributed only slightly more in the fuselage than in the wings whereas the mass of the T-38 is concentrated heavily in the fuselage. It is also shown that the $I_y - I_z$ term is close to zero for modern aircraft. In order to represent all of these aircraft, it was necessary that the above inertia parameters be investigated as described in the previous section.

For this investigation, therefore, the term $I_y - I_z$ was set to zero and values of -200×10^{-4} and -1700×10^{-4} were selected for the inertia parameters $(I_x - I_y)/mb^2$ and $(I_z - I_x)/mb^2$. The cross product of inertia I_{xz} is a very small value for modern aircraft and was assumed therefore to be zero during this study.

Initial Spin Entry Conditions

The basic spin entry altitude for the various investigations presented herein was 40,000 ft. This altitude was selected on the bases that aircraft spend most of their operating time at this altitude and entering a spin at a low altitude (20,000 ft) would be considered academic for most modern fighter type aircraft because of their high rate of sink.

The most frequent inadvertent type of spin experienced is the erect spin which in many instances cannot be terminated by the pilot. Inverted spins (negative angle-of-attack, p and r of opposite signs) on the other hand are less frequently experienced and in almost all instances can be terminated by releasing the controls. The fact that a pilot is prone to become disoriented and apply pro-spin control deflection during an inverted spin and thereby maintain this type of spin is considered a training problem. This study, therefore, was restricted to investigating the erect spin.

There are various combinations of initial flight conditions and control manipulations which may result in an aircraft entering an erect spin. Only 1 g stall entries are presented in this paper, that is, the aircraft was trimmed initially in 1 g wings level flight at an angle-of-attack 2° below the stall angle-of-attack.

It is realized that designers of aircraft limit the authorities of their control deflections for various reasons; in particular, rudder excursions. In some instances, placing limits on the control travel may reduce effectively the chances of inadvertently entering a spin. The major purpose of this study was, however, not to determine techniques for preventing the spin but rather to determine the influence that various quantities (other than control travel authorities) have on the spin. Throughout this study, therefore, large incremental control deflections were assumed to be available for initiating spin entries. That is, −25° of elevator deflection (stick back) and −30° of right rudder deflection (right pedal depressed) were applied as a ramp function over a 1-sec time interval, starting at a time equal to 0 sec. Over the same time period, 60° of total lateral control deflection were applied. As shown in Fig. 2, these control deflections were then held constant throughout the computed time history. Normally, lateral stick and rudder pedal displacements to the right (coordinated controls) were applied; a large number of cases, however, were also examined for right lateral stick displacement and left rudder deflection (crossed controls).

Throughout this study, the propulsion thrust was reduced to zero as a step function when an angle-of-attack of 20° was attained during the initial entry maneuver.

Presentation of Results

The results of the study to determine the influence of the aerodynamic quantities on the spinning motion of aircraft are summarized on Tables 1–5. [The bases of judgement (ratings) are given in the previous section]. These tables also identify the type of spin and the mass distribution for which the subject aerodynamic characteristics were investigated, and note the values that were assigned to the aerodynamic characteristics.

Discussion

The following observations are presented in conjunction with the ratings presented in Tables 1–5.

Static Aerodynamic Stability and Control Characteristics

1) The yawing moment due to deflection of the lateral control has an appreciable influence on the spin. A negative value for the $C_{n_{\delta_a}}/C_{l_{\delta_a}}$ ratio very effectively promotes flat spins. The greater the negative value the more rapidly the flat spin is attained.

2) The static stability characteristic that has the greatest influence on the spin is the rolling moment due to sideslip. For all types of spins and mass distribution, a critical value exists for the effective dihedral, $(-C_{l_\beta})$; below which spin equilibrium cannot be established or maintained. For example, a divergent oscillatory motion is generated when the critical value is reached for aircraft capable of entering a steep or flat spin having their mass heavily concentrated in the fuselage. This motion eventually drives the vehicle into

Table 1 Influence of the lateral control characteristics on different type of spins

	$[(I_x - I_y)/mb^2]\ 10^4$	−200	−1700	−200	−1700
		Type of spin			
Value assigned to variable	Variable	Steep moderate spin rate	Steep slow spin rate oscillatory	Very slow developing high angle-of-attack spin	Slow developing flat spin
−1, 0, 1 x base	$C_{n_{\delta_a}}$	Appreciable	Appreciable	Appreciable	Appreciable

Table 2 Influence of static stability characteristics on different type of spins

	$[(I_x - I_y)/mb^2]\ 10^4$	−200	−1700	−200	−1700
		Type of spin			
Value assigned to variable	Variable	Steep, moderate spin rate	Steep, slow spin rate, oscillatory	Flat, very fast spin rate	Flat, fast spin rate
$\frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ $\frac{3}{4}$, 1, 2 x Base	$C_l(\beta)$	Appreciable	Appreciable	Appreciable	Appreciable
$\frac{1}{2}$, 1, 2[a] x Base	$C_m(\alpha)$	Significant	Significant	Significant	Significant
$\frac{1}{2}$, 1, 2 x Base	$C_n(\beta)$	Insignificant	Insignificant	Significant	Significant
$\alpha_{C_{n\beta}=0}$ = 20, 33, 40	$\alpha_{C_{n\beta}=0}$	Insignificant	Insignificant	Insignificant	Insignificant

[a] Above 1-g trim α and α TRIM MAX.

the unstalled angle-of-attack region. As the value is progressively decreased below the critical value, the vehicle correspondingly becomes unstalled in less time. The magnitude of the effective dihedral required to maintain a flat spin is greater than that required for maintaining a steep spin. Also, the amount of effective dihedral required to maintain or establish any type of spin increases as the mass becomes more concentrated in the fuselage. The effective dihedral also has a slight effect on r and α for values above the critical value when the mass is heavily concentrated in the fuselage and this effect becomes more significant as the mass becomes less concentrated in the fuselage.

3) The pitching moment characteristics have a significant but not an appreciable influence on the spin (with the possible exception noted below). This conclusion is valid whether the C_m vs α relationship is varied throughout the angle-of-attack range (over-all spring constant) or just above the maximum static trimmed angle-of-attack (local spring constant). For all types of spins and mass distributions, the direct effect of increasing the spring constant is to decrease the amplitude and required decay time of the initial spin entry oscillation, and to slightly depress the resulting spin angle-of-attack and to significantly increase the spin rate. Aircraft capable of entering a steep or flat spin will do so regardless of the magnitude of the spring constant. This is the case even when the spring constant is increased to a value which is considerably beyond the value attainable with an aircraft. Aircraft that are capable of entering a steep spin and have a very low spring constant (small nose-down moment at a high α) may slowly transition into a flat spin. This situation will occur, if a vehicle oscillates about a mean angle-of-attack which is above the angle that would be realized in a steep spin and if the aerodynamic characteristics at this higher angle-of-attack are different (mainly a more negative value for $C_{n_{\delta_a}}$ or C_{l_β}) than those experienced at the steep spin angle-of-attack. The very low nose-down pitching moment at a relatively high angle of attack, that is required to induce this effect, might only be encountered with a delta winged configuration or with an improperly designed T-tail configuration.

4) The yawing moment due to sideslip characteristics (absolute magnitude and variation with angle-of-attack) do not play an important role in steep spins. The magnitude of the moment is significant, however, during flat spins since a progressive increase in the values of r and α is realized with increasing directional instability.

Dynamic Aerodynamic Characteristics

As shown on the tables, the dynamic derivatives (i.e., the damping, cross, and acceleration derivatives) do not have an appreciable influence on the spin during the time period which would be of interest to the pilot.

Acceleration derivatives

The influence of the acceleration derivatives ($C_{m_{\dot\alpha}}, C_{n_{\dot\beta}}, C_{l_{\dot\beta}}$) on the spin is insignificant for all types of spins and mass distributions. Only very slight effects may be detected on the motion during the incipient phase of the spin.

Cross derivatives

The influence of the cross derivative C_{n_p} on the spin is insignificant for all types of spins and mass distributions. 2) The influence of the cross derivative C_{l_r} is also insignificant except for aircraft that are capable of entering a fast flat spin and have their mass slightly more distributed along the fuselage than the wing reference axis (inertia parameter = −200). In this instance, increasing the value

Table 3 Influence of the acceleration derivatives on different type of spins

	$[(I_x - I_y)/mb^2]\ 10^4$	−200	−1700	−200	−1700
		Type of spin			
Value assigned to derivative	Derivative	Steep, moderate spin, rate	Steep, slow spin rate, oscillatory	Flat, very fast spin rate	Flat, fast spin rate
Base −0.2 0	$C_{m_{\dot\alpha}}$	Insignificant	Insignificant	Insignificant	Insignificant
−0.2 0	$C_{n_{\dot\beta}}$	Insignificant	Insignificant	Insignificant	Insignificant
−0.2 0	$C_{l_{\dot\beta}}$	Insignificant	Insignificant	Insignificant	Insignificant

Table 4 Influence of the cross derivatives on differen type of spins

	$[(I_x - I_y)/mb^2]\ 10^4$	-200	-1700	-200	-1700
		Type of spin			
Value assigned to derivative	Derivative	Steep, moderate spin rate	Steep, slow spin rate, oscillatory	Flat, very fast spin rate	Flat, fast spin rate
2, 1, 0, −2 x Base	C_{n_p}	Insignificant	Insignificant	Insignificant	Insignificant
2, 1, 0 x Base	C_{l_r}	Insignificant	Insignificant	Significant*	Insignificant*

Table 5 Influence of the damping derivatives on different type of spins

	$[(I_x - I_y)/mb^2]\ 10^4$	-200	-1700	-200	-1700
		Type of spin			
Value assigned to derivative	Derivative	Steep, moderate spin rate	Steep, slow spin rate, oscillatory	Flat, very fast spin rate	Flat, fast spin rate
2, 1, 0 x Base	C_{m_q}	Insignificant	Significant	Insignificant	Insignificant*
2, 1, 0 x Base	C_{l_p}	Insignificant	Insignificant	Significant	Significant
2, 1, 0 x Base	C_{n_r}	Insignificant	Insignificant	Significant	Insignificant*

of C_{l_r} results in a low-frequency oscillatory spin and lower values of α, β, p, q, and r.

Damping derivatives

1) For steep spins, the damping derivatives (C_{m_q}, C_{l_p}, and C_{n_r}) play an insignificant role except for C_{m_q}, which has a significant affect when the mass of the vehicle is heavily concentrated in the fuselage. In this instance, a large effect on the frequency of the oscillations in α, β, and angular rates is noted. 2) For flat spins, the damping derivative C_{l_p} has a significant effect. For the inertia parameter of -200, an increase in C_{l_p} has a significant effect on the magnitude of α, q, and r. For the inertia parameter of -1700, as C_{l_p} decreases a highly oscillatory spin is generated as reflected in the time histories of p and β.

General

As noted on the tables, certain ratings for the rotary derivatives have been starred for the following reason: Although the influence of the derivatives C_{m_q}, C_{l_r}, and C_{n_r} on the spin is insignificant for vehicles that are capable of entering a flat spin and have their mass heavily concentrated in the fuselage, this is not the case when zero values are assigned to these derivatives. A zero value for any of these derivatives will trigger a radical change in the spin behavior. The vehicle will transition from a flat spin into a divergent oscillatory motion which eventually kicks the vehicle out of the spin. A zero value for the derivative C_{m_q} has the greatest influence on the spin in that its effect begins during the incipient spin phase and the over-all spinning motion is terminated in a relatively short period of time. In this respect, the derivative C_{l_r} ranks next in importance with C_{n_r} being the least important. In fact, the effect on the spin of having C_{n_r} equal to zero would only be of academic interest to the pilot since he obviously would have elected to eject before the vehicle entered (after 21,000 ft of altitude and 48 turns) the recovery dive. In this instance, however, the aircraft would have recovered from the spin and dived into the earth after the pilot left the vehicle; a situation that may have been observed on occasion.

It should also be noted that these aerodynamic terms may not be neglected (effectively assigning a zero value to these derivatives) during an analytical design study and zero values should only be employed on the bases of conclusive experimental information.

For an inertia parameter value of -200, assigning zero values to the derivatives C_{m_q} and C_{n_r} will not produce the radical change in spin characteristics observed for the heavily fuselage loaded configuration. A zero value for C_{l_r} will have this effect but, in this instance, is truly academic in that the recovery is realized after a 21,000 ft altitude loss and 71 turns.

Concluding Remarks

The aerodynamic characteristics that must be accurately determined in order to compute the full-scale spinning motions of an aircraft have been identified. It was found that the yawing moment characteristics associated with the lateral control and the effective dihedral are the two most important aerodynamic parameters involved in the spin phenomenon; whereas the influence of the acceleration derivatives $C_{m_{\dot{\alpha}}}$, $C_{n_{\dot{\beta}}}$, and $C_{l_{\dot{\beta}}}$ as well as the cross derivative C_{n_p} on the spin are insignificant. The remaining dynamic aerodynamic derivatives may in some instances have a significant influence on the spin motion depending on the type of spin and the magnitude of the inertial coupling term.

The insight into the spin mechanism that was obtained in achieving the study objective allows one to: 1) appreciate the aerodynamic characteristics responsible for the spin characteristics exhibited by a new design. 2) identify aerodynamic fixes that are most likely to act as antispin devices. 3) conceive of automatic control techniques for spin prevention or spin recovery.

Reference

[1] Bihrle, W., Jr. and Heyman, A. C., "The Spin Behavior of Aircraft," GAEC Rept. 394-68-1, Dec. 1967, Grumman Aircraft Engineering Corp., Bethpage, N.Y.