Recent Experience with Techniques for Prediction of Spin Characteristics of Fighter Aircraft

Joseph R. Chambers* and James S. Bowman Jr.†
NASA Langley Research Center, Hampton, Va.

Spin-tunnel tests and radio-controlled model tests have proven to be useful for prediction of spin characteristics, but these specialized techniques may not be available in early design phases. The present paper discusses other techniques that are more generally available, specifically: 1) conventional wind-tunnel tests, 2) analytical studies, and 3) fixed-base simulation. The techniques and hardware used are described, but the emphasis is placed on the application of the techniques and examples of the type of results that have been obtained. Recent research has indicated that some spin problems (in particular, dangerous flat spins) can be readily analyzed using conventional wind-tunnel equipment and techniques normally employed during routine stability and control investigations. Recent experience with analytical spin prediction methods is discussed using results obtained for a variable-sweep fighter with a long pointed nose. Correlation between theoretical calculations and actual spin characteristics exhibited by a free-flight model of the configuration was quite poor due to large nonrepeatable asymmetric yawing moments created by flow separation on the long pointed nose at high angles of attack. Development and preliminary evaluations of a fixed-base simulator with limited visual and buffet cues for stall/spin studies are also discussed.

Introduction

In recent years there has been an alarming increase in the number of fighter aircraft lost in stall/spin accidents. These accidents have, in general, been related to increased requirements for maneuverability imposed by tactical training and actual combat conditions. The military services have expressed concern over the relatively poor spin-recovery characteristics of contemporary fighter aircraft and have stressed the need for adequate methods by which stall/spin characteristics could be predicted and modified at early design stages.

The analysis of aircraft motions in the stall/spin area is extremely complex, involving phenomena such as aerodynamic interference, flow separation, and nonlinear and time-dependent aerodynamic characteristics. The complexity of the situation has led to the development of several highly specialized test techniques over a period of years by NASA for application to the stall/spin problem. For example, spin-tunnel tests[1] using dynamically scaled models have been conducted at Langley Research Center since 1935, and this test technique has proven to be an unexcelled method of documenting fully developed spin characteristics. Outdoor free-flight tests using radio-controlled models have also been developed to study spin entries. Although these two techniques provide a great deal of information regarding the post-stall behavior of aircraft, they require special facilities and techniques that may not be immediately available to contractors during early design stages. As a result of these limitations, NASA is actively engaged in the development of additional techniques which can be applied using more conventional stability and control techniques and equipment. Three of the more promising techniques are 1) conventional wind-tunnel tests, 2) analytical studies, and 3) fixed-base simulation. These techniques are designed to supply pertinent information leading to an accurate and realistic determination of the stall/spin characteristics of fighter aircraft and should be considered to supplement rather than replace spin-tunnel tests. This paper will discuss the usefulness and shortcomings of these techniques based on recent experience.

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* Aerospace Technologist.

† Aerospace Technologist. Associate Fellow AIAA.

Conventional Wind-Tunnel Tests

Perhaps the most dangerous spinning motion exhibited by an airplane is the fast-flat spin in which the airplane angle of attack approaches 90° (fuselage approximately horizontal) with attendant high rates of rotation. As the angle of attack approaches 90°, conventional aerodynamic control surfaces become relatively ineffective and recovery from the fully developed flat spin may be impossible. Recent research[2] has shown that conventional wind-tunnel tests can be used to determine factors causing a flat spin. In particular, this method has been used to determine the cause and possible cures for a nonrecoverable flat spin exhibited by the sweptwing jet fighter shown in Fig. 1. A number of wind-tunnel test techniques including static force tests, forced-oscillation tests, rotary balance tests, smoke-flow visualization tests, and free-spinning tests were applied to the problem. The results of the tests indicated that the flat-spin tendencies of the airplane were caused by aerodynamic autorotational moments which resulted from aerodynamic interference between the horizontal and vertical tail surfaces.

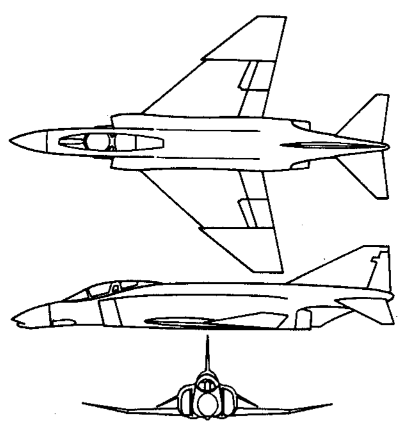

Fig. 1 Three-view sketch of swept-wing fighter configuration.

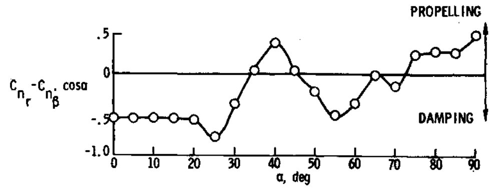

Fig. 2 Variation of aerodynamic damping in yaw with angle of attack.

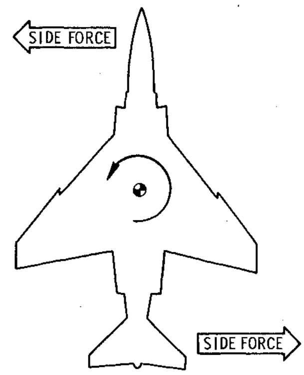

Fig. 4 Assumed relationships between side force and yawing moment during flat spin to left.

Forced-Oscillation Tests

Forced-oscillation tests[3] are normally used to obtain values of dynamic stability derivatives for computer or simulator studies. The derivatives measured by this technique are called oscillatory derivatives, and represent a combination of the damping derivatives with certain linear acceleration derivatives. Forced-oscillation tests are particularly well suited for identification of possible autorotative conditions. For example, shown in Fig. 2 is the variation of the damping-in-yaw parameter $C_{n_r} - C_{n_{\dot\beta}} \cos\alpha$ with angle of attack for the sweptwing fighter as measured during forced-oscillation tests in yaw. Negative values of $C_{n_r} - C_{n_{\dot\beta}} \cos\alpha$ existed for the high angles of attack (about 73° to 90°) associated with the flat spin. The values of the propelling moments were quite large; for example, the magnitude of the propelling moment due to rate of rotation at 90° angle of attack was about equal to the stabilizing values of damping in yaw at 0° angle of attack.

The aerodynamic data measured during the static and forced-oscillation tests were used in a digital computer program which used nonlinear, six-degree-of-freedom equations of motion in an attempt to calculate the developed flat spin exhibited by the airplane. In these equations, the value of $C_{n_r} - C_{n_{\dot\beta}} \cos\alpha$ was multiplied by yaw rate. As might be expected, the propelling values shown in Fig. 2 led to motions of ever-increasing spin rate. Because this result was not the same as that of flight and previous spin-tunnel tests, which showed a steady flat spin, it was concluded that the aerodynamic damping in yaw of the airplane at extremely high angles of attack was nonlinear with respect to rate of rotation.

Rotary-Balance Tests

The rotary-balance test technique[4] consists of using a six-component strain-gage balance to measure aerodynamic characteristics as a model is forced to rotate about a spin axis by a motor-driven sting. The technique is useful in defining nonlinear trends of aerodynamic moments with spin rate. The results obtained from rotary-balance tests of the swept-wing fighter confirmed the nonlinear variation of yawing moment with rate of rotation. Shown in Fig. 3 is the variation of yawing-moment coefficient C_n with nondimensional rate of rotation $\Omega b/2V$ for an angle of attack of 85° during a flat spin to the left. The data were obtained for a condition of wings level and zero spin radius. Negative values of C_n correspond to nose-left yawing moments which for the left spin are propelling or autorotative moments. The data of Fig. 3 show that at low spin rates propelling moments are produced by the rate of spin, whereas at higher rates of rotation the propelling moments become smaller and approach zero and thereby lead to a potential stabilized auto-rotation or steady-spin condition. The equilibrium rate of rotation at 85° angle-of-attack is indicated by these data as being about 0.24.

In order to identify the airframe components producing the propelling moments, the relationship of the yawing moment and side force acting on the airplane during a spin must be analyzed. Figure 4 shows a top view of the airplane during a flat spin to the left. If the fuselage is assumed to produce the propelling moments, a side force to the left, which produces a nose-left (propelling) yawing moment will exist. However, if the tail components are propelling the airplane, the nose-left yawing moments will be produced by a side force to the right. The force-test data obtained for the present configuration indicated that the tail components of the airplane were responsible for the flat-spin tendencies.

After the rear of the airplane was identified as the source of the autorotative tendencies, additional rotary-balance tests were conducted to identify the particular component responsible for the propelling moments. The results of the tests are presented in Fig. 5 which shows the variation of C_n with nondimensional rate of rotation $\Omega b/2V$ for several tail configurations. When the horizontal tail was removed from the complete configuration, the data indicate that positive (nose-right) yawing moments which tended to oppose the yaw rate were produced. This result is opposite to that for the basic configuration. When the vertical tail was removed, with the horizontal tail on, the resulting configuration showed $C_n = 0$ with little variation for values of $\Omega b/2V$ up to about 0.2. This result indicates a condition of zero or neutral damping in yaw. Data showing the effects of inverting the horizontal tail so that it has positive dihedral are presented. These data show a marked improvement over the damping-in-yaw characteristics of the basic configuration. These results indicate the existence of an interference effect between the vertical and horizontal tail surfaces such that propelling moments are produced only when vertical and horizontal tail surfaces are in position on the airplane.

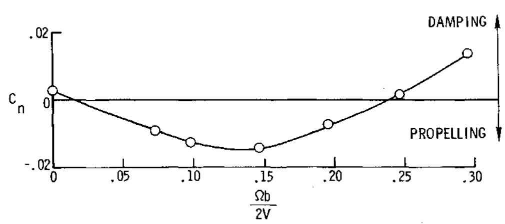

Fig. 3 Variation of yawing moment with rate of rotation; left spin; $\alpha = 85°$.

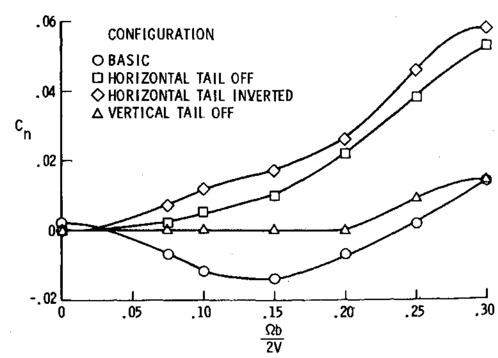

Fig. 5 Variation of yawing-moment coefficient with nondimensional rate of rotation for several tail configurations; $\alpha = 85°$; left spin.

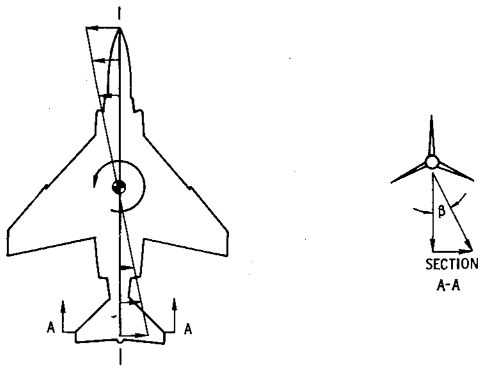

Fig. 6 Sideslip angle generated at tail during flat spin to left.

Static-Force Tests

The forced-oscillation and rotary-balance tests therefore indicated the aerodynamic phenomenon and airframe components responsible for the flat spin. However, these test techniques are somewhat specialized and not widely used; so it is highly desirable to be able to analyze the spin problem in terms of conventional static wind-tunnel data that are easier to obtain and can readily be used to analyze the effects of other variables such as Reynolds number. In order to interpret the results of static-force tests in terms of the effect of tail configuration on the flat spin, the flow conditions at the tail location during a spin must be known.

The sideslip angle generated at the tail during a flat spin to the left is illustrated in Fig. 6. The arrows along the fuselage indicate the relative magnitude and sense of the linear sideward velocities imparted along the fuselage by the rate of rotation during a left spin. The sketch at the right of Fig. 6 is a cross section of the tail during a spin. As can be seen, the airplane rate of descent and the sideward velocity at the tail location produced by the rate of rotation combine vectorially to produce a positive sideslip angle at the tail. With this concept in mind, the variation of static yawing moment with sideslip angle can be examined and the data can be interpreted in a dynamic sense. For example, presented in Fig. 7 is the variation of static yawing moment with angle of sideslip for the basic configuration at 85° angle of attack for several tail configurations. The data show that the basic configuration produced negative (nose-left) yawing moments when subjected to sideslip angles from 0° to approximately 20° or 25°. From the preceding analysis, the nose-left yawing moments may be interpreted as propelling moments for a left spin. It should be noted that the static-force test data exhibited a nonlinear variation with sideslip angle similar to that of the rotary-balance data of Fig. 3.

The data of Fig. 7 indicate trends similar to those exhibited by the rotary-balance data of Fig. 4; that is, removal of

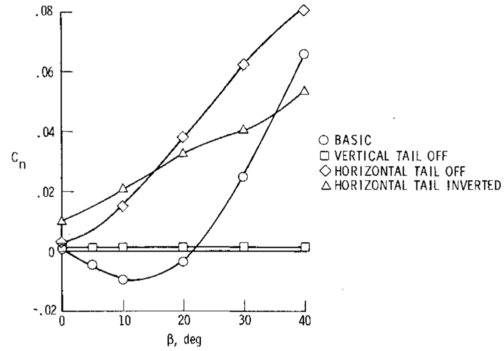

Fig. 7 Variation of yawing-moment coefficient with sideslip angle for several tail configurations; $\alpha = 85°$.

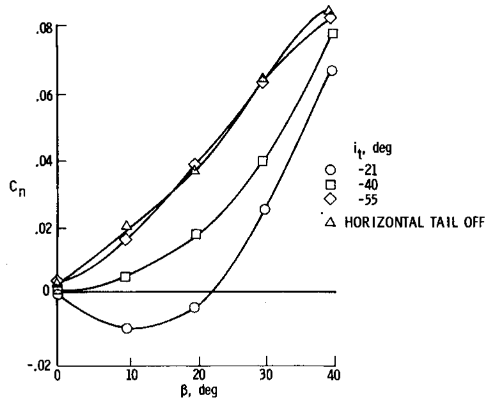

Fig. 8 Effect of horizontal tail incidence angle on yawing-moment characteristics; $\alpha = 85°$.

either the vertical or horizontal tail or inversion of the horizontal tail so that it had positive dihedral produced nose-right or damping moments over the entire range of positive sideslip angles. The results indicate the applicability of static wind-tunnel data for spin analysis when used with suitable interpretation.

Inasmuch as tail geometry was found to have a significant effect on the propelling tendencies, additional static-force tests were conducted to investigate the effects of horizontal tail incidence angle on yawing moment; the results of these tests are presented in Fig. 8. These data show the variation of yawing moment with sideslip angle for horizontal tail incidence angles of 21°, 40°, and 55°, trailing edge up, and data are also presented for the horizontal tails removed. The present physical deflection limit on the airplane is 21°, and the test results indicate that the propelling tendencies are still present. Increasing the deflection angle to 55°, however, appears to be about as effective in eliminating the propelling moment as removing the horizontal tails altogether.

Spin-Tunnel Tests

Tests in the spin tunnel showed that the classical fast-flat spin could be obtained with the horizontal tail either deflected 21° trailing-edge up or neutral, and with the ailerons either neutral or against the spin. Spin recovery from the flat spin with the best possible recovery-control technique (deflection of the rudder to full against the spin, deflection of the ailerons to full with the spin, and deflection of the horizontal tail to 21° trailing-edge up) was unsatisfactory.

A series of tests was conducted on the model to evaluate the effectiveness of deflecting the horizontal tail trailing edge up 30°, 40°, and 55° for recovery. These test results indicated that increasing the trailing-edge-up deflection of the horizontal tail used in the recommended recovery technique to 30° or 40° failed to produce recovery in some cases. When the horizontal tail deflection was increased to 55°, trailing-edge up, a significant improvement was obtained in the recovery characteristics and consistent recoveries from the developed spin were obtained in less than five–six turns. When the horizontal tail deflection was increased to 90°, trailing-edge up, there did not seem to be any further improvement in recovery. These results indicate that a 55° deflection of the stabilator removes most or all of the flow interference caused by the horizontal tail and the resulting recoveries are considered to be marginally acceptable when considering the high rate of rotation of the spin.

The test results also showed that when the basic drooped horizontal tail surfaces were moved rearward a distance approximately equal to $\bar{c}_t$, the model did not exhibit a flat-spin mode. Likewise, when the geometric dihedral was removed from the horizontal tail or when the horizontal tail was inverted so that the dihedral angle was positive, the model

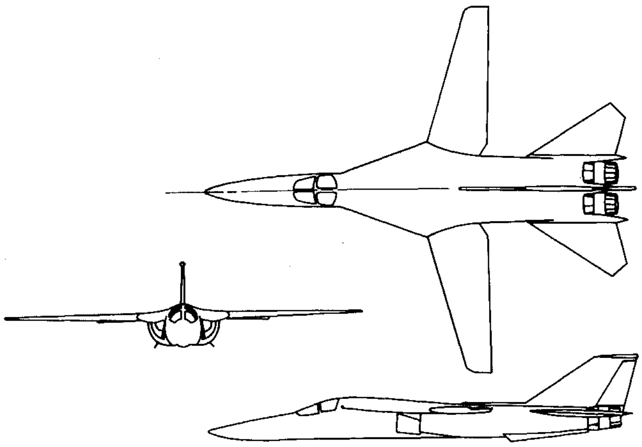

Fig. 9 Three-view sketch of configuration with long pointed nose.

again displayed no flat-spin tendencies. In both cases, even though the model was launched into a flat spin in the tunnel, the flat-spin motion quickly subsided and the model entered a steep oscillatory spin. These results are considered to be quite significant in that recovery from a steep oscillatory spin is usually satisfactory with the recommended control application, whereas no recovery could be effected from the developed flat spin for the basic configuration. These results are a further indication that the autorotational moments caused by the interference effects brought about by the tail configuration were perhaps the most important factor causing the flat spin.

The results of this study indicate that application of conventional wind-tunnel techniques to the stall/spin problem can produce significant information regarding spin characteristics. It should be kept in mind, however, that these tests are somewhat limited in scope and should therefore be restricted to preliminary studies or direct support for actual spin-tunnel tests.

Analytical Studies

One of the most useful spin prediction techniques, if it can properly developed, appears to be a theoretical treatment of the stall/spin problem. The development of a realistic mathematical model of an airplane during a spin would result in a considerable saving in time required to identify and investigate all the possible critical spin conditions during spin tests of an actual airplane. In addition, significant information could be generated regarding the relative effectiveness of various recovery techniques to be used by pilots.

Theoretical studies of airplane spin characteristics (see Refs. 5 and 6, for example) have been conducted for a number of years; however, these studies have concentrated on the effects of various physical and aerodynamic parameters on spin characteristics. As a result, correlation between theory and actual spins and development of the theoretical technique has been somewhat neglected. A program recently conducted at Langley Research Center was directed at this shortcoming by an evaluation of the application of theoretical spin prediction methods to a contemporary fighter configuration shown in Fig. 9.

Theoretical Analysis and Verification

In a recent study of correlation of theory with experiment, spin entries and recoveries from spinning motions were calculated by a high-speed digital computer program which used numerical integration methods to solve nonlinear equations representing six degrees of freedom along and about a body system of axes. Aerodynamic data for the calculations were

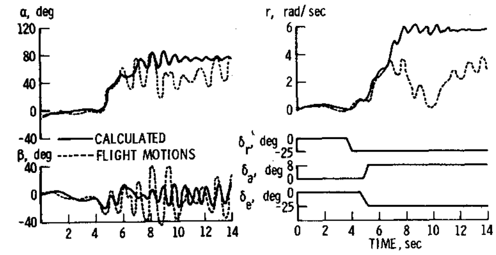

Fig. 10 Comparison of theoretical spin calculations and free-flight model motions for identical control inputs; (time given in model scale).

based on the results of static and forced oscillation tests of a $\frac{1}{9}$-scale model of the airplane. The model used in the wind-tunnel tests had previously been equipped with radio-control instrumentation and was flown into spins following release from a helicopter during a series of outdoor free-flight tests. The aerodynamic characteristics were measured for this model at approximately the same value of Reynolds number as that for the free-flight tests. The static aerodynamic forces and moments were incorporated into the computer program as nonlinear functions of angle of attack and angle of sideslip while the dynamic aerodynamic characteristics were represented by conventional dynamic stability derivatives which were functions of angle of attack.

The calculations were performed by duplicating within the computer program the initial conditions and control input sequencing from flight records obtained during the free-flight tests. Using this procedure, it was possible to compare the spin characteristics exhibited by the model with analytical predictions of spin characteristics based on aerodynamic inputs measured with the same model at the same value of Reynolds number.

Throughout the analytical study, poor correlation existed between the calculated motions and the flight data obtained during the outdoor free-flight tests. For example, shown in Fig. 10 are comparisons of angle of attack, angle of sideslip, and rate of yaw as calculated by the computer program (solid lines) and as obtained from flight recorder traces (dashed lines) for a representative flight. The flight involved prospin control inputs for a right spin (elevator full trailing edge up, ailerons against the spin, and rudder with the spin). The data show extremely poor correlation inasmuch as the magnitudes and variations of angle of attack, angle of sideslip, and yaw rate are markedly different during the spin. In fact, the agreement was so poor that theoretical results predicted a fast-flat spin while the free-flight model exhibited a steeper oscillatory spin of completely different character.

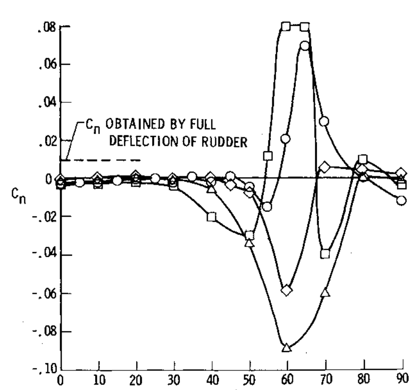

Fig. 11 Variation of static yawing-moment coefficient with angle of attack for several models of the configuration; $\beta = 0°$.

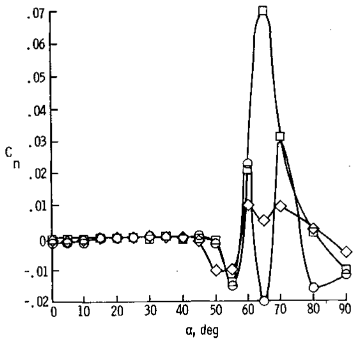

Fig. 12 Variation of yawing-moment coefficient with angle of attack; symbols indicate values obtained in several repeat tests.

In view of the apparent inability of the analytical technique to adequately predict the spin characteristics of the model, additional wind-tunnel tests were undertaken to gain some insight as to possible shortcomings with regard to the theoretical representation of the aerodynamic forces and moments acting on the configuration during a spin.

Wind-Tunnel Tests

The most significant result of the static force tests with regard to the foregoing lack of correlation between calculated and measured spin motions was an indication that large out-of trim yawing moments existed for the present configuration at high angles of attack, and that these yawing moments appeared to be random and nonrepeatable. The large excursions of yawing moment are illustrated in Figs. 11 and 12. Fig. 11 shows the variation of static yawing moment coefficient C_n with angle of attack at zero sideslip and neutral controls as measured during tests of four separate models of the present configuration. As can be seen, the value of C_n remained near zero at low angle of attack, as might be expected. For angles of attack greater than about 30°, however, large excursions of C_n occurred. The magnitudes of these moments are best appreciated by comparison with the value indicated by the dashed line which indicates the magnitude of C_n produced by a full rudder deflection of 7.5° in the normal low-angle-of-attack flight range. The out-of-trim moments near $\alpha = 60°$ are several times as large as the moments produced by full-rudder deflection at low angles of attack, and would be much larger than moments obtained by rudder deflection at $\alpha = 60°$ because of the marked reduction in rudder effectiveness at high angles of attack due to shielding by the fuselage and wing.

An equally important phenomenon exhibited by the configuration was the fact that these large asymmetric yawing moments appeared to be random and nonrepeatable, even for the same model under identical test conditions. A sample of this randomness is presented in Fig. 12, which presents the variation of C_n with angle of attack for $\beta = 0°$ for several repeat tests. The data indicate that for angles of attack above about 40°, separate tests under the same test conditions produced markedly different values of C_n with large excursions in both the sense and magnitude of the asymmetric moment.

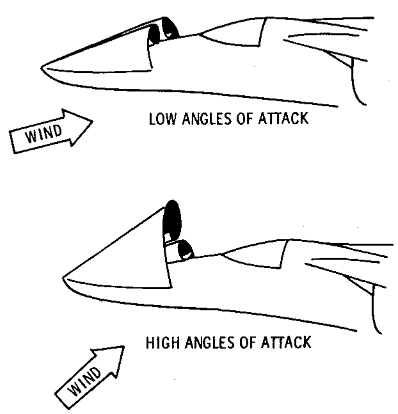

Fig. 13 Sketches of separated vortex sheets on fuselage forebody.

The effect of these large excursions of C_n on spin characteristics was evaluated by means of a series of theoretical calculations in which the asymmetry of C_n was assumed to have the maximum values indicated in Fig. 11 in either a nose-right or a nose-left sense. In these calculations, the airplane was initially in trimmed level flight followed by full prospin control deflections for a right spin (similar to the deflections shown in Fig. 10). When the asymmetric values of C_n were assumed to have the maximum positive (nose right) values indicated in Fig. 11, the results of the calculations indicated a flat-fast spin to the right (the asymmetric values used in the calculations shown in Fig. 10, were also nose right). When the sense of the asymmetry was reversed (that is, in a nose-left sense), the calculations indicated that the airplane would not spin to the right (even with full right prospin controls) but would, instead, perform large-amplitude post-stall gyrations with no continuous rotation. These results show that, depending on the particular asymmetry present, a fast-flat spin or a no-spin condition (and, presumably any type of spin in between) could be obtained from identical initial conditions and control inputs. The large scatter of static yawing moment shown in Figs. 11 and 12 therefore creates a number of possible spin characteristics from identical control inputs and this fact results in a severe limitation of the usefulness of analytical methods for spin studies of this particular configuration. This characteristic is believed to be a major cause of the poor correlation previously shown between the theoretical spin calculations and the free-flight results.

The aerodynamic phenomenon producing the large yawing moments was attributed to asymmetrical shedding of vortex sheets off the long, sharply pointed nose. The flow pattern of such vortices on the fuselage forebody with this type of flow separation is illustrated by the sketch in Fig. 13. Separation of flow from the fuselage forebody at low angles of attack is characterized by two shed vortex sheets. At angles of attack less than 20° for the present configuration, these vortex sheets remain nearly symmetrical above the nose, as depicted by the upper sketch. Because of the symmetry of the vortex sheets, they do not induce asymmetric forces on the forebody for this condition. For angles of attack greater than 20°, however, the vortex sheet pattern becomes asymmetrical, as shown by the lower sketch, with one vortex core moving above and away from the forebody while the remaining vortex sheet moves closer to the nose. The asymmetric vortex pattern creates a large negative pressure area on one side of the nose thereby creating a side force on the nose which, in turn, produces a large yawing moment due to the relatively long distances between the nose and the center of gravity of the airplane.

The random out-of-trim moments result from the fact that some slight geometric or aerodynamic asymmetry establishes the sense of the asymmetric moment. For sharp, high-fineness-ratio noses even very minor asymmetries near the apex of the nose can be very important. For example, experience gathered over a period of years from tests of many models in the Langley spin tunnel has shown that almost all airplane configurations having long sharp pointed noses (including the present configuration) may spin readily in one direction and not in the other until some slight deformation to the nose tip occurs during the tests, after which the ease of achieving a spin in a given direction can reverse; subsequent deformation of the nose may cause this reversal to occur at various times during the course of a test program.

These results indicate that theoretical studies of the spin characteristics of contemporary fighters should be exercised with extreme caution. In particular, the aerodynamic characteristics of configurations having long pointed noses may be poorly defined at spin attitudes yet these aerodynamic phenomena may have a profound influence on the ease and direction of spins exhibited by the airplane.

Simulator Studies

One critical shortcoming of the techniques currently used to predict stall/spin characteristics is that the input of the human pilot has been minimized or entirely eliminated. For example, spin-tunnel tests and outdoor free-flight tests have the pilot located a considerable distance from the model. As a result, the pilot's perspective is unrealistic and the timing of control inputs may be unduly delayed because of the remote location of the pilot and the faster angular velocities of the model caused by dynamic scaling relations. Because of these limitations, the results of these two methods are mainly qualitative and do not provide detailed information regarding controllability at the stall. Recent studies have been conducted to evaluate the possibility of using a ground-based simulator to supply this pertinent information.

A schematic of the hardware used in this technique is shown in Fig. 14. The simulation program uses a fixed-base simulator with limited visual and kinesthetic cues enclosed within a 20-ft-diam sphere. A typical fighter cockpit and instrument display are used and visual cues are provided by a combination of an earth/sky projector and a terrain projector. Two separate projection systems are used because of the difference in angular range available with the present equipment. The earth/sky projector consists of a light source within a program-controlled colored plexiglass sphere resulting in a blue sky/brown earth display which is primarily used for large-angle peripheral cues. A terrain display is used to provide the pilot with a more detailed visual display, including the yawing cues necessary for stall/spin studies. The terrain features are provided by a model which is projected by a three-axis television probe onto the surface of the sphere in front of the pilot. The horizons of the earth/sky display and the terrain features coincide at all times.

Initial evaluation of the simulator revealed that without a visual task research pilots tended to exercise very tight control with almost entire visual scan concentrated on the instrument display. Results obtained tended to be conservative, inasmuch as recovery action from stalls was immediate. In order to present a realistic tactical situation demanding more pilot attention, an additional visual scene consisting of a target airplane was introduced.

In addition to these visual cues, a number of devices were used to provide kinesthetic and aural cues. These devices include: an electromagnetic seat shaker to represent airframe buffet, programed pressurized flight suit and seat cushion to provide g cues, a programed restraining strap to limit movement of the left arm during high g maneuvers, and an engine noise generator to simulate engine flameout and compressor stalls.

All of the simulator equipment is controlled by a real-time digital computer system. The simulated aircraft is represented by six degrees of freedom with nonlinear aerodynamic input while the target airplane can be flown by another pilot or made to follow preprogramed maneuvers.

At this time, it appears that the simulator technique offers considerable promise as a means of predicting controllability of the stall/spin characteristics of an airplane under a combat environment. Modifications to the airframe stability augmentation system or control system are easily evaluated. A readily apparent application of this technique would be the development of a procedures trainer for pilot training. This application is deemed particularly important, inasmuch as current flight restrictions prohibit intentional spinning of most fighter aircraft, thereby depriving the pilot of training for an emergency which may well be difficult to overcome. It should be emphasized, however, that the development of a realistic simulation of stall/spin characteristics is subject to the adequate development of a mathematical model of the airplane to be simulated, and in this regard the technique may be subject to the shortcomings pointed out in the previous section.

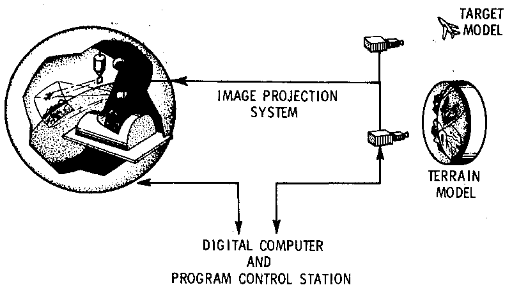

Fig. 14 Sketch of stall/spin simulation system.

Summary

The advantages and shortcomings of several test techniques used to predict the stall/spin characteristics of fighter aircraft have been described. Conventional wind-tunnel tests may provide significant information regarding the factors affecting spin characteristics and appear to be most appropriate for analysis of flat spins. Analytical techniques and simulator studies are very desirable for obtaining quantitative data, but these methods depend on the development of realistic mathematical models of the airplane.

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