Aerodynamic Characteristics of Fighter Configurations During Spin Entries and Developed Spins

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The NASA Langley Research Center is currently conducting a stall/spin research program to define fighter aerodynamics applicable during spin entries and developed spins and to develop analytical methods to use such measured aerodynamics for theoretically calculating these spin motions. Some static, forced-oscillation, and continuous rotation aerodynamic data have been measured for several current fighter models over a large post-stall angle-of-attack range. This paper discusses these aerodynamic data and illustrates both the extremely nonlinear dependence of such data on several variables and the correlation that exists between the three types of measured aerodynamics. The current analytical methods for using these areodynamics to calculate spin entry and developed spin motions are discussed and correlated with experimentally obtained spins.

Introduction

In recent years, a strong interest has been renewed in high-angle-of-attack characteristics of military airplanes. For fighters, this interest is related to the increased requirements for maneuverability imposed in both tactical and actual combat situations. To meet such requirements, current fighters operate at high angles of attack where many configurations experience a severe degradation in stability and control characteristics, resulting in a significant number of stall/spin accidents involving losses of airplanes and aircrews. Moreover, in recognition of the need to operate present-day fighters at increasingly higher angles of attack, many recent fighter designs incorporate both aerodynamic and control system features to permit flight at extreme angles of attack. Thus, the trends with respect to fighter airplane design have emphasized the need for reliable methods for the theoretical prediction of stall/spin characteristics early in the design phase when airframe modifications to a configuration could be implemented more easily. The stall/spin research program at the Langley Research Center currently includes some fundamental research in two areas regarding this need. One research area is to determine what type or combination of types of aerodynamic data measurements are needed to adequately define the complex air flowfield present under spinning conditions and to develop the equipment required to make such measurements. The second research area is to develop and validate the analytical methods which will use such measured aerodynamics for calculating spinning motions.

The Langley approach is depicted in a general way in Fig. 1. This paper will discuss the various elements of this approach, including a brief review of the dynamic model testing and aerodynamic measurement techniques used and a discussion of representative measured aerodynamics that are used in stall/spin studies. The approaches used in combining measured aerodynamics to develop theoretical models for use in predicting stall/spin motions will be described. Calculated results will be presented to illustrate the correlation with measured flight motions, showing the influence of the aerodynamic model selected on the calculated motions.

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Experimental Techniques

The ultimate goal of the Langley stall/spin research program is to provide reliable methods for prediction of stall/spin characteristics. A key factor is the development of experimental methods and equipment both to provide reliable measured aerodynamics and to measure flight motions for validation of theoretical motion-prediction procedures. Langley has developed a unique combination of dynamic model testing methods and other wind tunnel test techniques which are currently used in conducting stall/spin research. These testing techniques are briefly described in the following sections.

Dynamic Model Test Techniques

Langley employs three different dynamic model testing techniques which use free-flying dynamically scaled models to obtain information regarding the entire stall/spin regime. Each of these techniques provides information on the dynamic flight motions of a given configuration over a particular portion of the regime. The spin tunnel test technique identifies developed spin modes and is described in Ref. 1. The free-flight model technique investigates stall/departure characteristics and is described in Ref. 2. The radio-controlled drop model test investigates spin entry and developed spin motions and is described in Ref. 3.

Aerodynamics Test Techniques

Experience has shown that a very comprehensive set of aerodynamics is required to properly represent the extremely

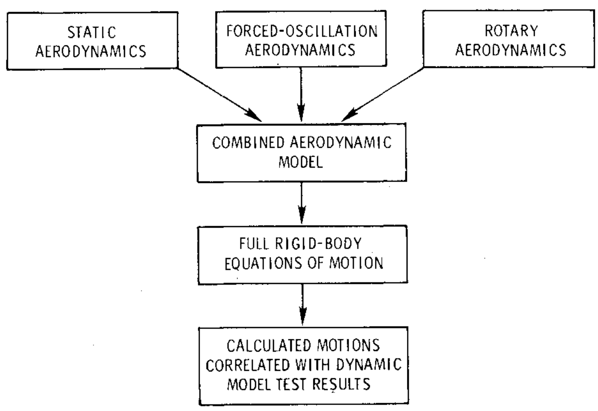

Fig. 1 Approach used for calculation of stall/spin motions and correlation.

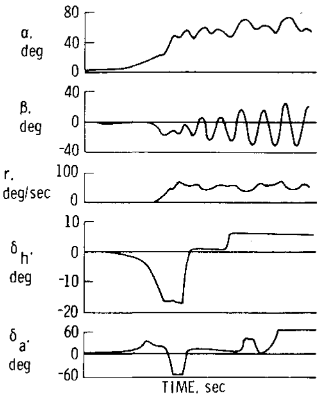

Fig. 2 Sample spin time history.

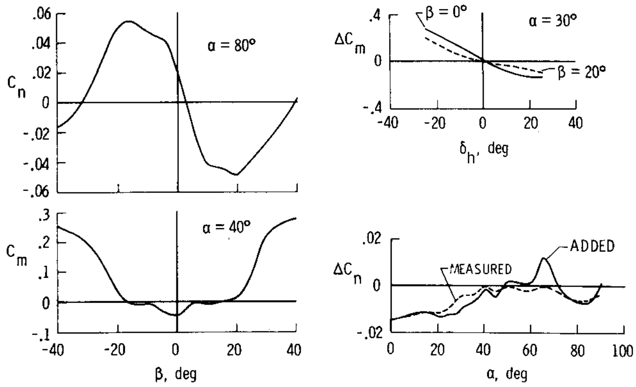

Fig. 3 Representative nonlinearities seen in measured high-angle-of-attack static aerodynamics.

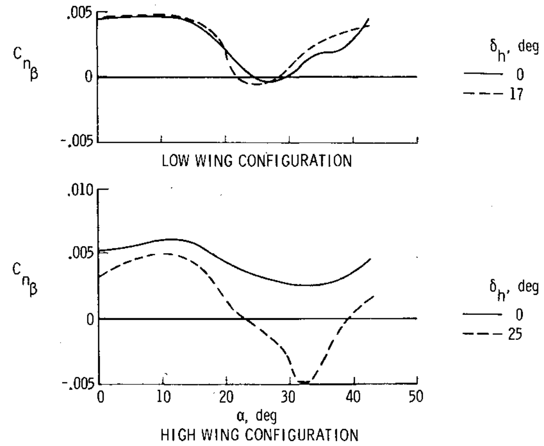

Fig. 4 Effect of longitudinal control deflection on static directional stability.

complex air flowfield present during stall/spin flight conditions. At the present, no one test technique has been devised which can adequately measure these potentially very nonlinear aerodynamics. Some appreciation of the wide range of flight variables encountered in a typical spin can be obtained from the time history shown in Fig. 2. This figure illustrates the nature of the stall/spin motions of one fighter and the magnitude range over which some of the motion parameters can vary. In this flight, the airplane was flown into a high-*g* windup turn during which full aft stick and full aileron were applied. A departure resulted with angle of attack rapidly exceeding 40 deg, sideslip excursions of ± 25 deg, and yaw rates of over 50 deg/s. With controls neutralized, the motion settled into a developed oscillatory spin near $\alpha = 60$ deg. For a configuration having a very flat steady spin, angles of attack approaching 80 to 90 deg can occur with yaw rates in excess of 150 deg/s. Over this wide range of flight conditions at extreme angles of attack, separated-flow phenomena produce very complex flowfields acting on the airplane, including strong vortex flows shed from the airplane nose and such features as wing-body strakes and partially to fully stalled wakes shed by the wings. Three distinctly different wind tunnel test techniques are used at Langley to measure these stall/spin aerodynamics. The following sections describe the methods and types of results obtained from each technique. Finally, some measured results from each technique are presented to show the degree of correlation obtained between the three test techniques.

Static Wind Tunnel Tests

Static wind tunnel tests conducted in stall/spin research efforts must be expanded to measure the steady aerodynamics over a very wide range of angle of attack and sideslip as noted earlier. Results of such tests for a considerable number of current fighter configurations have shown stall/spin aerodynamics to be very configuration dependent and to be very nonlinear functions of both angle of attack and sideslip as noted in Refs. 4-9. Some examples of the nonlinearities which have been measured in static tests are presented in Fig. 3. Shown on the left-hand side of this figure are measured yawing moment and pitching moment variations with sideslip at post-stall angles of attack, indicating that both lateral directional and longitudinal aerodynamics can be strongly influenced by sideslip. On the right-hand side of Fig. 3 are two examples of nonlinearities of aerodynamic control effectiveness. The upper right figure shows the dependence of horizontal tail effectiveness on both tail deflection magnitude and sideslip. The lower right figure shows differences at spin entry and developed spin angles of attack in measured yawing moment increments due to combined rudder and aileron control deflections. The solid line was obtained by adding the increments due to individual control deflections, as is conventionally done, whereas the dashed line represents the increments as measured with both controls deflected simultaneously. The fact that the effectiveness of combined controls is nonadditive is significant in that a number of different control combinations are used in sequence through an entire spin flight and the need to obtain measured aerodynamic data for each control combination used can lead to quite an increase in the wind tunnel test time needed to acquire the data.

Deflection of longitudinal control surfaces is known to dramatically influence static directional stability (Refs. 4 and 9), but the configuration dependence of this effect shown in Fig. 4 is not as well known. For this particular airplane, the static directional stability was unaffected by horizontal tail deflection for the low wing configuration. However, for the same configuration having a high delta wing, deflecting the horizontal tail cause the directional stability to go from highly stable to highly unstable around 30 deg angle of attack.

Forced-Oscillation Tests

The aerodynamic damping of an airplane is measured at Langley using the forced-oscillation method wherein the model is forced to oscillate about a given body axis at a fixed frequency and amplitude while the aerodynamic forces and moments are measured. The aerodynamic damping derivatives have been shown to be strongly and nonlinearly dependent on the oscillation amplitude and frequency as noted in Ref. 5. Figure 5 presents some examples of measured forced-oscillation data to illustrate some of these effects. The upper left plot shows that the damping-in-roll parameter is strongly dependent on both amplitude and frequency to the extent that, for this particular angle of attack, either variable can change the damping from unstable to stable. The other two plots (Fig. 5) show that some damping derivatives have indicated very large abrupt variations in magnitude with angle of attack, and that large unstable values of both damping-in-yaw and damping-in-pitch can occur in the developed spin

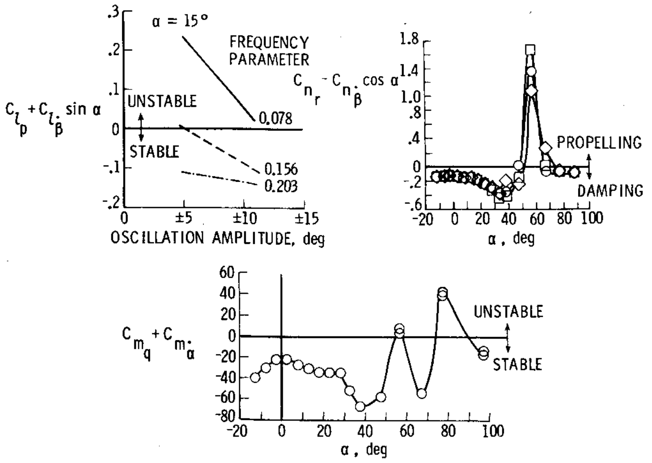

Fig. 5 Representative nonlinearities of measured damping derivatives at high angles of attack.

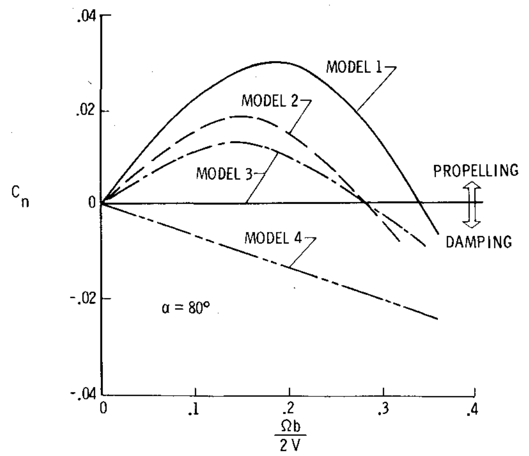

Fig. 6 Example of variations in rotation-balance data typical of fighter airplanes.

angle of attack range. The possibility of such large and relatively abrupt changes in the variation of the damping derivatives with angle of attack requires that tests be conducted with care to insure the data are obtained at small enough increments in angle of attack to avoid overlooking important variations.

Rotary Balance Tests

An important aerodynamic wind tunnel test technique at Langley for stall/spin research is the use of the rotary balance apparatus. This equipment allows the measurement of aerodynamic characteristics in a rotating air flowfield similar to that experienced by an airplane in a steady spin. Results of previous investigations, reported in Refs. 8 and 9, showed this type of data to be necessary due to the nonlinearity of some aerodynamic coefficients with rotation rate. Using this rig, six-component force and moment aerodynamics are measured on a wind tunnel model during 360-deg continuous rotation at a constant angle of attack and sideslip. The rig can provide these measurements for angles of attack of 55 to 90 deg, sideslip angles of ± 10 deg, and nondimensional rotation rates $\Omega b/2V$ of ± 0.3.

An example of several possible variations of yawing moment with rotation rate at spin angles of attack that are typical for current fighter configurations is shown in Fig 6 for controls neutral to illustrate the significance of rotation data. For an airplane rotating to the right (in a right spin), positive values of C_n are propelling and negative values tend to retard (or slow) the rotation. For airplanes 1, 2, and 3, the variation of C_n with rotation rate is unstable (propelling) for small rotation rates and reverses to become stable (slowing) at higher rates. If only forced-oscillation damping derivatives were employed in an aerodynamic model, only the unstable slopes at small rotation rates would be represented and misleading results would be obtained as will be shown later in this paper; this fact emphasizes the importance of properly representing rotary aerodynamics. If a steady equilibrium spin rotating about the airplane's center of gravity did exist at this angle of attack, it would occur at a rotation rate near $C_n = 0$. For such an equilibrium spin, airplane 1 would spin at the highest rotation rate, and airplanes 2 and 3 would spin at the same rotation rate. If the variation in yawing moment with $\Omega b/2V$ were the only difference between airplanes 2 and 3, then airplane 2 would get into the spin more quickly and have a more difficult spin recovery due to its higher values of propelling moments at the lower rotation rates. Airplane 4, in the absence of any other propelling moments, would not be expected to have a steady spin at this angle of attack because it has no aerodynamic propelling moments at any rotation rate.

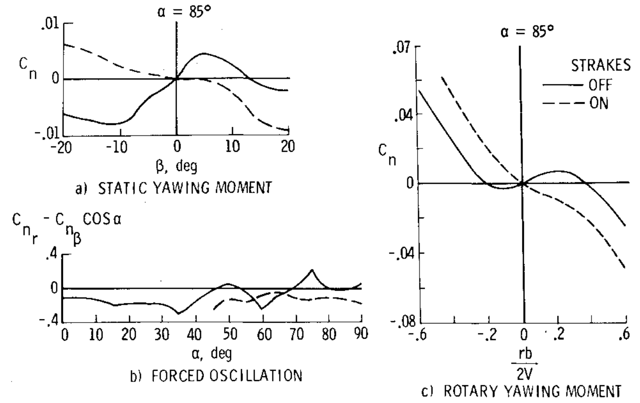

Fig. 7 Correlation of nose strake effects between static, forced-oscillation, and rotating data.

Correlation of Aerodynamic Data

An illustration of the correlation which exists among the three types of aerodynamic data discussed in this paper is shown by the example of nose strake effects presented in Fig. 7. All the data in this figure were measured on the same airplane configuration, of course. In the top left figure, the basic configuration exhibits static directional stability at small sideslips and static instability at greater sideslips. The addition of nose strakes caused the directional stability to go from stable to unstable at low sideslips and to become virtually linear with sideslip. The bottom left figure shows the effects of the same nose strakes on the damping-in-yaw parameter. Here, addition of the nose strakes created a large stable increment in yaw damping at the same angle of attack, as expected. Previous research reported in Ref. 7 explains that an airplane forebody which is statically directionally stabilizing will produce destabilizing damping-in-yaw due to the local sideslip at the nose under rotating conditions. At the right of Fig. 7 are shown the effects of the same nose strakes on the rotary yawing moment data. An extremely strong similarity exists in the overall curve shape between the static data plotted against sideslip and the same rotary balance coefficient plotted against rotation rate for the strakes off. For the strakes on, the same overall curve shape similarity between static and rotary data still exists with both curves becoming virtually linear.

There are two important points to be made regarding the data of Fig. 7. First, the airplane represented here did indeed have a fast flat steady spin at 85 deg angle of attack as indicated by the rotary data. The addition of the nose strakes caused the rotary data to become almost linear with rotation rate but also to have no propelling moments at any rotation rate. This means that the addition of nose strakes for this configuration appeared to be an effective means of breaking up the original steady spin. Subsequent spin tunnel model tests on this configuration verified experimentally that nose strakes did cause the break up of the original spin condition. The second point is that although the significance of the effect was more evident in the rotary data, the potential existence of this effect was predicted by the change in curve shape of the static data. Therefore, it may not be necessary at the design stage to measure aerodynamic data for every configuration variation using the more complicated and time-consuming rotary balance technique, but rather one might conduct rotary tests only on those configurations which show significant changes under static testing.

Theoretical Motion Predictions

As described in the Introduction of this paper, Fig. 1 depicted an overview to the current Langley approach in developing methods for predicting stall/spin motions. Previous sections of this paper have described the dynamic model testing techniques and the static and dynamic aerodynamic measurement techniques. This section will discuss the methods that have been used to utilize these measured aerodynamics in theoretical motion calculations and will present results to show the correlation with experimental motions that has been obtained with different methods. It is emphasized at this point that a final, rigid definition of the proper model to use for stall/spin calculations has not been fully established. However, it is felt that this discussion will provide valuable insight into the importance of certain types of measured aerodynamics for use in stall/spin prediction.

Theoretical Methods

Over the years, a number of efforts have been made to calculate theoretically the spin entry, developed spin, and spin recovery motions of a variety of fighter airplanes. Unfortunately, the majority of those efforts have relied solely on limited conventional static and forced-oscillation data which often did not adequately represent the highly complex air flowfields associated with spinning, especially as regards the aerodynamic nonlinearities with rotation rate. As a result of this lack of proper aerodynamic representation, the theoretically calculated spin motions have very poor correlation with actual flight motions. The credibility of the theoretical techniques was therefore very low.

The overall theoretical technique must incorporate not only the proper measured aerodynamics but the math model which will properly utilize these aerodynamics. Some problems of aerodynamic representation still remain even with the large amount of measured wind tunnel data of all the types and covering all of the nonlinearities discussed in the previous sections. For instance, static wind tunnel data correctly represent only steady, nonrotating conditions. Rotary balance data are valid only for steady spinning conditions. Forced-oscillation data conventionally measured do not account for steady turning flight or for the effects of a rotating air flowfield such as is encountered in spinning. In addition, the conventionally measured forced-oscillation data are usually misused. For instance, the forced-oscillation test technique measures combined derivatives such as $C_{n_r} - C_{n_{\dot\beta}} \cos\alpha$ which are often treated as pure derivatives, C_{n_r} alone. Some past studies, reported in Refs. 10 and 11, have shown the existence of potentially large values of derivatives due to lateral acceleration, $C_{n_{\dot\beta}}$ and $C_{l_{\dot\beta}}$, in the stall/spin entry angle of attack area. Their effects on the airplane spin entry motions could be significant.

Theoretical calculations of an entire spin flight like that shown previously with its large-amplitude, highly coupled motions requires the use of a math model having fully nonlinear, six-degree-of-freedom equations of motion and the capability of storing and utilizing the large amounts of aerodynamic data previously discussed. Table 1 presents the general form of one of the equations of motion (yawing moment) used in stall/spin calculations, showing the inertial terms and the various forms that the aerodynamic terms can take, depending on the type of aerodynamic data available. One of the primary problems with regard to the math model lies in combining and using the three types of aerodynamic data properly in different portions of the overall spin flight. The conventional technique of combining static and forced-oscillation data (referred to as the conventional model in Table 1) has been found to provide a generally valid aerodynamic representation through the stall/departure region where the motions do not contain significant steady rotation rates. In the developed steady spin where the flight path is vertical, the presently used technique combines the rotary and forced-oscillation data in the manner developed in Ref. 12 (referred to as the rotary model in Table 1). This method assumes the aircraft is descending vertically in a developed spin and then separates the airplane angular rates into steady ($\dot\Psi$) and oscillatory components ($\dot\theta$ and $\dot\phi$) such that the steady component determines the proper contribution of the rotary data while the oscillatory component (designated by p_0 and r_0) is applied to the forced-oscillation data to determine aerodynamic damping as shown in Table 1. In the spin entry and oscillatory spin areas, the rotary data must be used differently and with some care due to several limitations. Currently, rotary aerodynamics are measured only for steady rotating conditions, for small sideslips, and where the rotation vector is aligned with the flight path. During the spin entry and oscillatory spins, large sideslips often occur and the angular rates are of a highly oscillatory nature, involving considerable deviation of the total rotation vector from the flight path.

Another limitation is that rotary data measurements have not been made below 50 deg angle of attack. Preliminary theoretical calculations were made in this region by using a compromise approach which employs all three types of aerodynamics. This approach is referred to as the hybrid model (Table 1), wherein static aerodynamics are used to represent the effects of angle of attack and sideslip, forced-oscillation data are employed with oscillatory angular rates to represent oscillatory damping, and rotary effects are represented by an incremental term superimposed on the static data. Use of the rotary data is restricted to conditions where the angle of attack is above 30 deg and where the total rotation vector is fairly closely aligned with the flight path. The new result is that the hybrid model employs the conventional model for normal flight and the initial highly oscillatory phases of the spin entry, then transitions to the use of rotary aerodynamics as the calculated motion approaches a developed spinning condition. The hybrid method thus insures that each type of aerodynamic data is applied to the kinds of motions for which they are most appropriate.

The theoretical methods, including both math model and aerodynamic representation, are continuing to undergo development. As new types of aerodynamic data are generated and math model refinements are made to accommodate and utilize that type of aerodynamics, these theoretical methods should be validated by correlating calculated spin motions with experimental dynamic model test results.

Theoretical Calculations

Langley has measured as comprehensive and complete a set of aerodynamic data as possible on a number of fighter configurations, encompassing all of the nonlinearities and types of data illustrated previously. Theoretical spin motion calculations have been attempted recently on two of those configurations. The primary sources of experimentally measured flight motions for correlation with predictions are the results of helicopter drop-model and spin tunnel tests. Some of the spin motion calculations were initiated in a manner that simulated the spin tunnel model launching

Table 1 Form of yawing moment equation used for stall/spin calculations

$\dot{r} = [(I_X - I_Y)/I_z]pq + (I_{XZ}/I_Z)(\dot{p} - qr)$ + aerodynamic terms

Math model	Aerodynamic data used	Aerodynamic terms (control terms omitted for clarity)
Conventional	Static and forced-oscillation	$C_n(\alpha,\beta,) + C_{n_r}\frac{rb}{2V} + C_{n_p}\frac{pb}{2V}$
Rotary	Rotary and forced-oscillation	$C_n\left(\alpha,\beta,\frac{\Omega b}{2V}\right) + C_{n_r}\frac{r_0 b}{2V} + C_{n_p}\frac{p_0 b}{2V}$
Hybrid[a]	Static and forced-oscillation	$C_n(\alpha,\beta) + C_{n_r}\frac{rb}{2V} + C_{n_p}\frac{pb}{2V}$
	Static, rotary, and forced-oscillation	$C_n(\alpha,\beta) + \Delta C_n\left(\frac{\Omega b}{2V}\right) + C_{n_r}\frac{r_0 b}{2V} + C_{n_p}\frac{p_0 b}{2V}$

[a] Rotary aerodynamics only employed when yawing motion dominates total angular rotation at $\alpha > 30$ deg.

technique with controls pre-set and a higher initial angle of attack and rotation rate than is expected in the developed spin. Other calculations simulated either normal or drop-model spin entry maneuvers beginning with an unstalled trimmed angle of attack and using control inputs to stall the airplane and try to fly through a post-stall/spin entry into a developed spin. Some selected results from these motion calculations are presented here to illustrate the degree of correlation obtained and the influence that the use of different theoretical math models can have on the calculated results. In the process, the inadequacy of using nonmeasured or adjusted aerodynamics for the prediction of spin characteristics will be demonstrated.

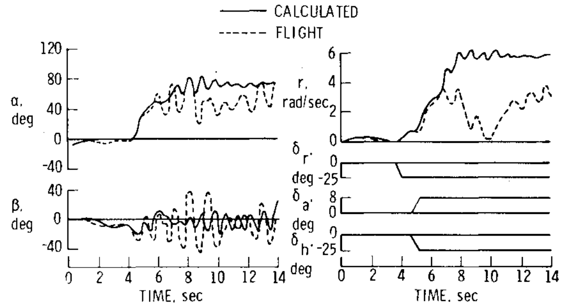

Fig. 8 Comparison of theoretical spin calculations and free-flight model motions.

Stall/Departure

An example of the correlation between calculated and experimentally measured flight motions in the stall/departure area is illustrated in Fig. 8. The flight motions shown were measured using the radio-controlled drop-model technique described earlier. The calculated motions were generated using conventional static and forced-oscillation aerodynamic data inputs. It is evident that the flight motions were predicted well up through the stall and departure. Only when a significant continuous rotation rate had built up at angles of attack beyond the stall did the experimental and calculated motions begin to diverge, thus indicating the need for some other type of aerodynamic representation at this point in the calculated motion. The particular combination of angle of attack and rotation rate which limits use of the conventional math model is, of course, highly configuration dependent. No rotary balance data existed on this configuration, so it could not be determined whether use of rotary data would have allowed a better correlation to be achieved further into this particular spin entry. Langley has conducted relatively comprehensive stall/departure simulations for a range of current aircraft configuration, often with a pilot in the loop, and similar good correlation between predictions and actual flight test results has been obtained using the conventional aerodynamic model.

Steady Developed Spins

Most theoretical calculations of steady developed spin motions in the past have used only conventional static and forced-oscillation data to represent spin aerodynamics. In addition, some of these past investigations made adjustments to selected aerodynamic coefficients to obtain a reasonable correlation with experimental spin results. The aerodynamic models thus obtained were then used as a base for further prediction of various spin characteristics, including spin recoveries. Results to be presented here will illustrate that often the use of a conventional set of measured aerodynamics will not produce realistic spinning motions and that efforts to adjust the aerodynamics to match a known spin condition can produce misleading results when such adjusted aerodynamics are used to predict spin recoveries. Finally, calculated results are presented to illustrate that good correlation can be achieved by use of measured rotary aerodynamics.

An attempt was made to calculate a steady developed spin using a very comprehensive set of measured conventional aerodynamic data for a configuration where spin tunnel tests showed a very steady spin. The calculations were started from a prerotated, high-angle-of-attack condition and resulted in a "runaway" spin of ever-increasing rotation rate, as shown in Fig. 9. Several sets of forced-oscillation data for different frequencies and amplitudes were tried, and all but one of the calculated motions were runaway spins. This type of result was expected for data input sets where the damping-in-yaw was unstable. When stable measured damping-in-yaw values were used, a divergent oscillation occurred such that angle of attack and sideslip exceeded data input limits. No one set of measured static and forced-oscillation data was capable of producing a calculated developed spin of any kind in this configuration.

At this stage, it has been shown that the conventional model does not adequately represent the developed spin air flowfield. Some previous investigations have continued to use the conventional data model, however, by adjusting the aerodynamic inputs until a reasonable simulation of the experimental developed spin is achieved. To illustrate that simulating the developed spin is possible, some adjustments were made to several damping derivatives to force the conventional data model to produce the desired equilibrium steady spin mode. The process by which these modifications are determined, however, results in a nonunique aerodynamic model in that a virtually limitless number of different modifications can be found which will all produce the same steady spin. Calculated results obtained with two such modifications differing only in C_{l_p} and C_{l_r}, are shown in Fig. 10 to give the same steady developed spin, which matches the spin tunnel experimental results. With recovery controls initiated at the same point in the calculated spins, it is obvious that the recovery characteristics predicted are quite different, depending on the changes made to the damping derivatives. One can carry this data modification process one step further, if desired, and try to simulate both the developed spin and the number of recovery turns. Even then, however, the aerodynamic model so developed is still not unique. Obviously, different data sets would give different, and most likely erroneous, spin recovery characteristics if used in attempts to predict effects of control deflections, center of gravity, or inertial loading changes. Recent research at Langley indicates that much more confidence can be placed in the predictive capability of stall/spin aerodynamic models when rotary balance aerodynamics are incorporated to allow spin prediction from measured data which, being measured, would thereby constitute a unique set.

Rotary aerodynamics were measured for the same configuration referred to in Fig. 9 and these data were used with measured forced-oscillation data to form a rotary aerodynamic model. The prerotated spin calculated with this math model is shown in Fig. 11 along with the spin tunnel results and the results of deleting the forced-oscillation data from the model. First, the correlation between the calculated spin and the spin tunnel result is very good. The second calculation without the forced-oscillation data was conducted because it had been conjectured in the past that calculation of a smooth steady spin could be achieved using only the rotary data. It was felt that the inherent damping provided by the rotary data was sufficient in itself by virtue of the rotary data having been measured as a nonlinear function of angle of attack, sideslip, and rotation rate. The calculations show, however, that when the forced-oscillation data are neglected the initial oscillations continue to build up until the oscillations in sideslip exceed the rotary data input limits. Further calculations showed that inclusion of both damping-in-roll and damping-in-pitch were necessary for the developed spin condition to remain stable. These results indicate the necessity of including some type of forced-oscillation derivatives to represent the air flowfield when oscillations are present in the spinning motion. However, instead of being measured in the normal manner, these forced-oscillation data should be measured during oscillations superimposed on a continuous rotation so that the entire flowfield would be representative of that present during the oscillatory spinning motions. An apparatus to do this job is extremely difficult to design both mechanically and with respect to properly analyzing the balance output signals.

Spin Entry

Very little theoretical work has been conducted to investigate the aerodynamic model required for reliable calculation of spin entry motions. To provide some insight into the effects of using the different aerodynamic models described herein, some spin entry calculations were performed using aerodynamics measured on a current lightweight fighter configuration. The calculated motions covered flight from below stall through a stall/departure and into the initial phase of an oscillatory spin. Calculations were made for a conventional aerodynamic model, for a rotary aerodynamic model used unrestricted for $\alpha \geq 40$ deg, and for the hybrid model described earlier with restricted use of rotary data above $\alpha = 40$ deg. The results of the calculations for the conventional and the hybrid models are presented in Fig. 12. Calculations with the conventional model could not be continued beyond the point shown in Fig. 12 since the violent motions obtained exceeded the limits of the aerodynamic inputs used. When the rotary model involving unrestricted use of rotary data above $\alpha = 40$ deg was employed, the calculated results (not shown) produced oscillatory motions similar to

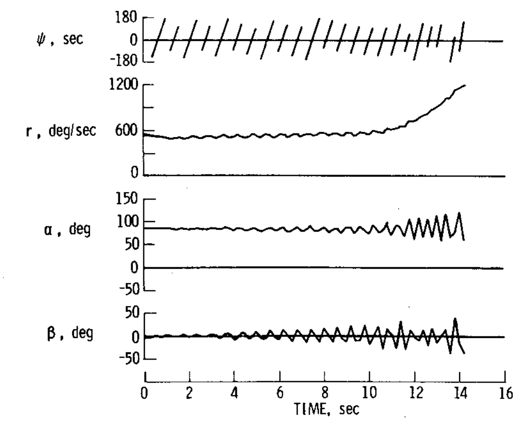

Fig. 9 Prerotated flat spin attempts using conventional static and forced-oscillation data system.

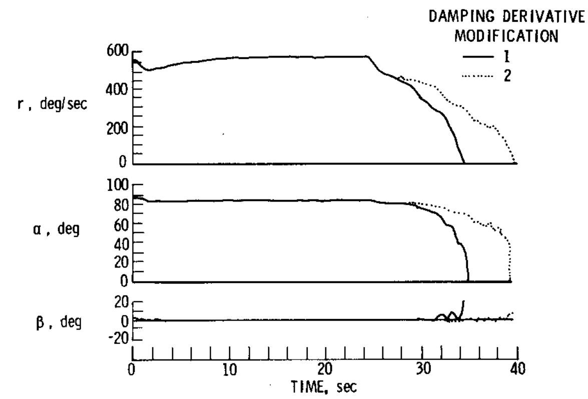

Fig. 10 Prerotated flat spins and recoveries using two different sets of modified damping data. Recovery controls applied at $T = 25$ s.

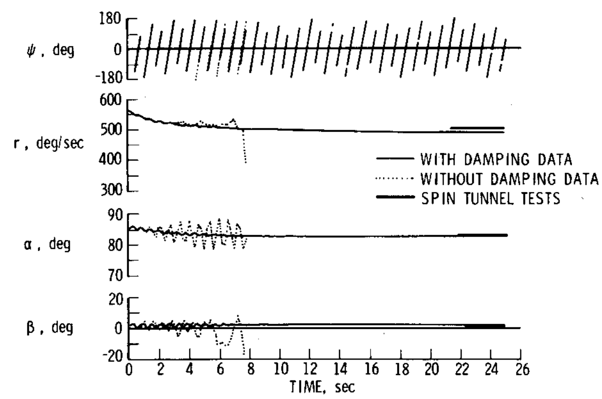

Fig. 11 Prerotated flat spins calculated using the rotation-balance data system with and without forced-oscillation damping data.

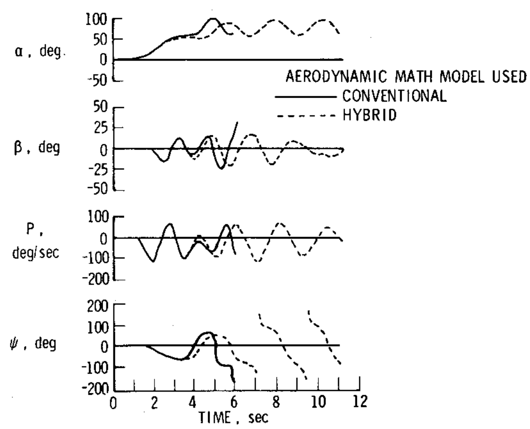

Fig. 12 Inertially coupled departure and spin entry calculations.

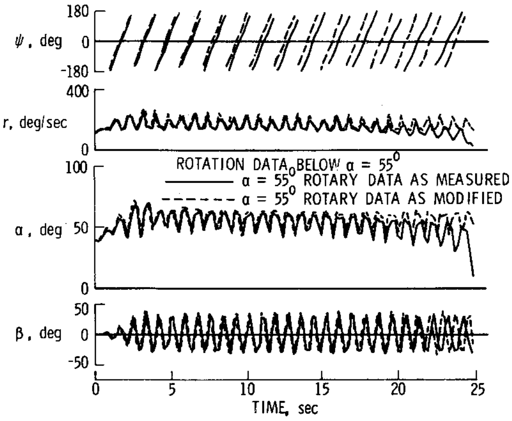

Fig. 13 Prerotated oscillatory spins using the hybrid data system incorporating rotation-balance yawing moment data.

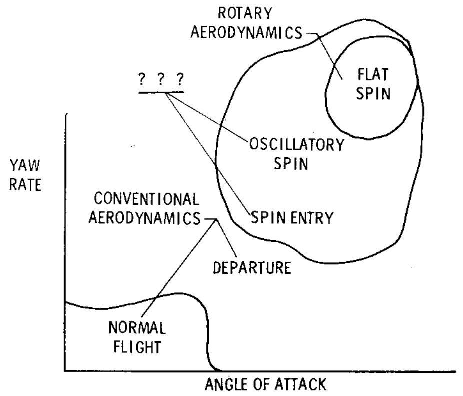

Fig. 14 Regions of application of aerodynamic models for stall/spin motion prediction.

those of the hybrid model but the oscillations were divergent. When the hybrid model was used, the motions obtained constitute a spin entry evolving into a stable oscillatory spin. Spin tunnel results for a configuration similar to that studied here indicate this configuration does exhibit a highly oscillatory spin mode similar to that calculated. These calculations show that while a complete spin entry motion could not be calculated without incorporating rotary aerodynamics at some point during the entry motion, both the aerodynamic representation and the math model should be properly assessed. It should be stressed here that these results only constitute a brief study of one aircraft configuration and that a further and more detailed study of several configurations must be accomplished before one can begin to make general comments regarding the required aerodynamic model for calculating spin entry motions.

Oscillatory Spin

Analytical research into predicting oscillatory spin motions is currently highly constrained by the lack of measured aerodynamics that are directly applicable for use in theoretical models. Rotary data cannot be measured at low enough angles of attack or large enough sideslips, and there is currently no testing apparatus available which allows measurement of forced-oscillation data on a model undergoing oscillatory motions superimposed over steady rotating conditions. However, as a first step in approximating these conditions, an effort has been made to combine the available measured aerodynamics into a hybrid model to assess the potential for calculating oscillatory spins.

The same configuration referred to in the section on steady developed spins was observed in both the spin tunnel and in drop-model testing to exhibit an oscillatory spin. Attempts to calculate this oscillatory spin motion using the conventional aerodynamic model were unsuccessful in that all efforts produced violently unstable motions showing no equilibrium oscillatory spin of any kind. No measured rotary aerodynamics were available on this model below 55 deg angle of attack. However, two hybrid models were generated with different approximations of lower angle of attack rotary effects. First, the rotary effects present at 55 deg angle of attack were held constant for excursions in angle of attack down to 30 deg. Second, the rotary aerodynamic yawing moments below $\alpha = 55$ deg were modified to better approximate the correlation between the effects of rotation rate and static data sideslip effects shown earlier in this paper. The results of calculations attempted with both models are shown in Fig. 13. The main result to be noted is that inclusion of rotary effects allowed calculation of a sustained oscillatory spinning motion to be achieved; this calculated motion compared fairly well with the drop-model results. The motion with the first aerodynamic model, however, is seen to be slowly divergent whereas the motion obtained with the second model appears stable. Obviously the equilibrium oscillatory spin under study was only marginally stable. Again, as was stated for the spin entry, the purpose of the oscillatory spin calculations was to explore the suitability of the different types of aerodynamics for predicting oscillatory spin motions.

Concluding Remarks

This paper has presented a summary of recent research results in two areas related to the prediction of fighter stall/spin characteristics—measured aerodynamics and theoretical calculations. Measured aerodynamic results obtained from these different test techniques have been presented to emphasize the highly nonlinear dependence such aerodynamics exhibit with respect to several variables, and the resultant need for using large, comprehensive aerodynamic models in stall/spin motion prediction. Some results have been presented to point out the degree of correlation which can exist between the three wind tunnel aerodynamic test techniques in showing the influence of important configuration changes. Although previous investigators have at times employed simple conventional static and forced-oscillation aerodynamic models for overall stall/spin calculations, results presented herein have illustrated that this is not a reliable approach; in fact, for the cases presented, the conventional data system was incapable of calculating equilibrium developed spins of any kind. In the developed spin area, results were presented to point out the shortcomings of making adjustments in measured aerodynamics to force a correlation with experimental results; any adjustment from measured aerodynamics results in a nonunique set of data inputs resulting in questionable predictive capability.

Results presented in this paper illustrate that very good correlation has been obtained with motion calculations in the stall/departure region using conventional measured aerodynamics. Use of rotary aerodynamics produced a calculated steady spin which correlated well with experimental results. Calculated results for both the spin entry region and the oscillatory spin region illustrate the importance of incorporating rotary aerodynamics in some manner. To summarize these results, Fig. 14 depicts the various stall/spin regions located on a plot of yaw rate vs angle of attack and points out the types of aerodynamic models that have been found necessary for motion predictions in each region. As is noted, there still exists a degree of uncertainty as to the proper aerodynamic model for performing reliable predictions in the spin entry and oscillatory spin regions.

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