

**USE OF DYNAMICALLY SCALED MODELS
FOR STUDIES OF THE
HIGH-ANGLE-OF-ATTACK BEHAVIOR
OF AIRPLANES**

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ABSTRACT

Dynamically scaled, free-flying models are used by the National Aeronautics and Space Administration (NASA) to study the stalling and spinning characteristics of civil and military airplane configurations. Such tests have been conducted for many different designs, and it has been possible to correlate the results predicted by the model tests with flight test results obtained in the investigations. The present paper describes four of the dynamic model testing techniques used at the NASA Langley Research Center, including the scaling laws used in the construction of models and in the interpretation of results. Predictions of stall/spin behavior based on model results have generally been very accurate, and the model tests are regarded as an invaluable precursor to full-scale flight tests. However, aerodynamic scale effects between some models and full-scale airplanes due to differences in test values of Reynolds number have resulted in erroneous predictions for a few configurations. A discussion of these effects is provided, together with the approach used to modify the model so that its behavior more closely matches that of the airplane. Finally, two typical applications of the techniques to the X-29A research airplane and several general aviation research airplanes are presented to illustrate the type of information provided by the tests.

INTRODUCTION

The stalling and spinning behavior of civil and military airplanes has traditionally had a significant impact on the safety and operational utility of such vehicles. Unfortunately, the prediction and analysis of stall/spin characteristics are especially challenging to the airplane designer because of the complex, poorly understood nature of the separated aerodynamic flow fields encountered at high angles of attack. Computational methods are not available for this application, and even experimental methods and testing techniques are questionable for some areas of a stall/spin investigation. Experience has shown that one of the most reliable approaches to predicting stall/spin characteristics is the use of dynamically scaled models which are scaled on the basis of geometric, mass, and time relationships. When these tests are properly conducted and interpreted, the results can be extrapolated with confidence to full-scale conditions.

The NASA Langley Research Center has utilized free-flying models for stall/spin studies since the early 1920's. The continual evolution and improvements in this technology have resulted in four testing techniques which are now used to provide various types of information required for a complete assessment of a specific airplane design. These techniques are the wind-tunnel free-flight test technique, the spin-tunnel test technique, the unpowered drop-model test technique, and the powered radio-controlled model test technique. In the wind-tunnel free-flight technique, the stability and controllability of remotely piloted models are investigated for steady level flight as the angle of attack is increased up to the point of loss of stability or control. Spinning and spin-recovery characteristics are determined in the spin-tunnel testing technique, and large-amplitude spin-entry motions are investigated using the drop-model and powered radio-controlled model test techniques. The models used in all the tests are equipped with extensive flight instrumentation and the flight motions are analyzed with various visual techniques and pilot opinions. In addition to the quantitative motion data provided by the flight tests, the models may also be used in conventional wind-tunnel force tests which measure the aerodynamic characteristics of the configurations. The wind-tunnel data then form the basis for the development of a mathematical model of the airplane which is subsequently used for piloted simulator evaluations of the full-scale airplane and pilot training before flight testing begins.

This paper discusses the overall approach used at Langley for dynamically scaled model tests to evaluate the stall/spin characteristics of airplanes. The scaling laws used to construct the models and the extrapolation of model data to full-scale conditions will also be described.

SCALING PARAMETERS

Dynamic models must be scaled in each of the fundamental units of mass, length, and time in order to provide test results that are directly applicable to the corresponding full-scale airplane (1). Units of length are, of course, scaled from geometric ratios between the model and full-scale airplane; units of mass are scaled from those of the full-scale vehicle on the basis of the relative density factor; and time is scaled on the basis of equal Froude number. As a

result of scaling in this manner, the motions of the model are geometrically similar to those of the full-scale airplane and motion parameters may be obtained by applying the scale factors given in Table 1.

Table 1 Scale Factors For Dynamic Models

	Scale Factor
Linear dimension.....	N
Relative density ($m/\rho l^3$).....	1
Froude number (V^2/lg).....	1
Weight, mass.....	$N^3\sigma^{-1}$
Moment of inertia.....	$N^5\sigma^{-1}$
Linear velocity.....	$N^{1/2}$
Linear acceleration.....	1
Angular velocity.....	$N^{1/2}$
Time.....	$N^{1/2}$
Reynolds number (Vl/ν).....	$N^{1.5}\nu/\nu_0$

Model values are obtained by multiplying airplane values by the following scale factors where N is the ratio of model-to-airplane scale ratio, σ is the ratio of air density to that at sea level (ρ/ρ_0), and ν is the value of kinematic viscosity

Certain limitations of the dynamic model test techniques are apparent upon examination of the factors given in Table 1. For example, the model is tested at a value of Reynolds number considerably less than that of the full-scale airplane for comparable flight conditions. A 1/9-scale dynamic model is typically tested at a value of Reynolds number which is only 1/27 that of the airplane. Although the linear velocities of the model are smaller than full-scale values, the angular velocities of the model are greater than full-scale values. For example, a 1/9-scale model has a flight speed only 1/3 that of the airplane, but it has angular velocities that are three times faster than those of the airplane.

The difference in Reynolds number between model and airplane can be an important factor which requires special attention for stall/spin tests. Large aerodynamic-scale effects caused by differences in Reynolds number may be exhibited by certain configurations, resulting in completely different behavior between the model and airplane. The fact that the angular velocities of the model are much faster than those of the airplane poses special problems with regard to the controllability of the model. Because the human pilot has a certain minimum response time, it has been found that a single, remotely located human pilot cannot satisfactorily control and evaluate the dynamic flight models. The foregoing considerations will be discussed in more detail in later sections of this paper.

The stalling and spinning behavior of airplanes involve complicated balances between the aerodynamic and inertial forces and moments acting on the vehicle. In order to conduct meaningful tests with dynamic models, it is mandatory that the scale factors given in Table 1 be followed in the construction and tests

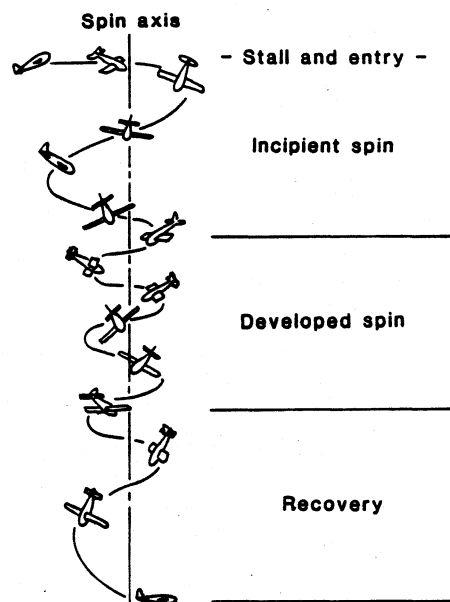


Fig. 1 Phases of stalling and spinning.

of a dynamic model. Simply scaling geometric dimensional characteristics without regard for other parameters (as is usually the case for hobby-type radio-controlled models) can produce erroneous and completely misleading results (2).

MECHANICS OF STALLING AND SPINNING

The stalling and spinning characteristics of airplanes are of primary concern to designers of civil and military aircraft (3). For example, general aviation personal-owner type aircraft require benign, easily controlled motions during stall, with no tendencies to enter dangerous inadvertent spins, particularly near the ground. Civil transports must also exhibit a high degree of stability and controllability for the low-speed conditions associated with the landing and takeoff. High-performance military aircraft must be capable of extended flight at high angles of attack during strenuous maneuvers without unintentional departures, loss of control, or unrecoverable spins.

The use of dynamic models to study the stall and spin includes a consideration of all phases of the airplane motions, as shown in Fig. 1. These phases include the approach to stall, the stall and incipient spin, the developed spin, and the spin recovery. During the approach to stall and stall-departure, some aircraft may exhibit large-amplitude rolling or pitching motions, wing-dropping tendencies, unconventional or ineffective response to control inputs, or directional instabilities. If the motions occur in a rapid and disorienting manner, the pilot may inadvertently lose control of the vehicle and enter the incipient spin phase.

In the incipient spin phase, the airplane's flight path is changing from horizontal to vertical, and the spin rotation is increasing from zero to the rate exhibited in the fully developed spin. If altitude loss is to be kept to a minimum, the pilot must quickly recognize the out-of-control situation and apply the correct control sequence for recovery. If he delays his inputs or applies the wrong control

combinations, the airplane may enter the developed spin phase.

In the developed spin, the attitude, angles, and motions of the airplane are somewhat repeatable from turn to turn, and the flight path is approximately vertical. The spinning motion is sustained by a balance of the aerodynamic and inertial moments acting on the vehicle. The spin consists of a spinning motion about the airplane center of gravity plus translatory motion of the center of gravity; however, it is primarily a rotary motion. The developed spin may be very smooth and steady, or it may be quite oscillatory, violent, and disorienting to the pilot. In addition, the spin may be of the steep spin category, which is characterized by a nose-down attitude and a relatively large spin radius; or the spin may be fast and flat, with a relatively horizontal fuselage attitude and an angle of attack approaching 90° . In most cases, recovery from the flat spin is extremely difficult, since the airplane's aerodynamic controls are ineffective at such high angles of attack.

Spin recovery is accomplished by upsetting the balance of aerodynamic and inertial moments acting on the airplane through movement of the aerodynamic control surfaces. The specific control movements required for a particular airplane depend on certain airplane mass and aerodynamic properties, and the control sequence varies for different types of airplanes (fighters and personal-owner airplanes, for example).

The foregoing motions are very complicated because they involve separated airflow conditions at angles of attack beyond stall. The aerodynamic characteristics of most airplanes become extremely nonlinear and ill-behaved for such conditions, and the prediction and analysis of stall/spin behavior are not amenable to theoretical methods (4). After many experiences and studies in this area, researchers at the Langley Research Center have evolved a series of dynamic-model test techniques to provide the information required for an accurate assessment of airplane characteristics.

DYNAMIC-MODEL TECHNIQUES

Each of the model testing techniques discussed in this paper has a particular area of application within the scope of studies required to adequately define the stall/spin characteristics of a particular airplane design. The advantages and limitations of each technique must be considered in the research planning process, and the appropriate interpretation of the results obtained in each test must be appreciated. The models used in the tests are constructed following the scaling parameters listed in Table 1, and all testing is conducted in atmospheric wind tunnels or outdoors.

Wind-Tunnel Free-Flight Technique

The test setup for the wind-tunnel free-flight test technique is shown in Fig. 2. In this technique, a remotely controlled model is flown without restraint in the 9.14- by 18.28-m open-throat test section of the Langley 30- By 60-Foot Wind Tunnel. A photograph of a typical model undergoing free-flight tests is shown in Fig. 3. The large test section provides the pilots with an unobstructed field of view of the model. The airspeed used for the tests ranges up to about 30 meters per second. Two evaluation pilots are used

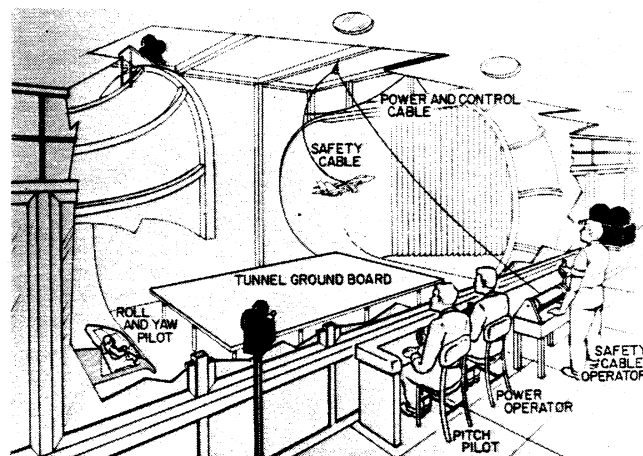


Fig. 2 Setup for wind-tunnel free-flight tests.

during the free-flight tests. One pilot, who controls the longitudinal motions of the model, is located in an enclosed balcony at one side of the test section while the second pilot, who controls the lateral and directional motions of the model, is located in an enclosure at the rear of the test section within the structure of the tunnel flow collector. The model is powered by compressed air, and the level of thrust is controlled by a power operator who is also located in the balcony. The model is flown in 1g level flight, and by careful control of tunnel airspeed, model trim, and model thrust, the models can be flown at specific angles of attack up to stall or loss of control in a single, continuous test sequence. With the use of this technique, instabilities that could seriously affect the maneuvering capability and safety of the full-scale airplane are easily identified and modifications are quickly evaluated (3).

The light, flexible cable attached to the model serves two purposes. The first purpose is to supply the model with compressed air, electric power for



Fig. 3 Model undergoing free-flight tests.

control actuators, and signals for the controls and sensors carried within the model. The second purpose for the cable involves safety. A portion of the cable is made of 1/8-inch steel cable that passes through a pulley above the test section. This part of the flight cable is used to catch the model when the test is terminated or when an uncontrollable motion occurs. The entire flight cable is kept slack during the flight tests by a safety-cable operator who accomplishes this job with a high-speed pneumatic winch.

The models used are rigid, Froude-scaled replicas of the full-scale aircraft. Geometric scales range from 1/10 to 1/20 of the full-scale airplane, resulting in typical wing spans of about 2 meters and typical weights of about 50 kilograms.

In recent years, the control system used by the models has been upgraded to permit simulation of the complex feedback and stabilization logic involved in current systems for high-performance aircraft. A schematic of the control system is shown in Fig. 4. The control actuators are electro-pneumatically operated with rapid response characteristics. The control signals from the pilot stations are transmitted to a digital computer located in the side balcony. Within the computer, a special software program computes the control surface deflections and important high-angle-of-attack elements of the flight control system are represented. Sensors onboard the model are used to measure flight variables and supply appropriate feedback signals for simulation of stability augmentation systems. Typical sensor packages include control-position indicators, linear accelerometers, and angular rate gyros. In addition, some models employ noseboom-mounted vanes for feedback of angle of attack and angle of sideslip.

Data obtained from the flights include oscillograph recordings, motion picture records of model motions, and pilot comments and analysis of the model response characteristics.

Although it is possible for one pilot to fly the model, such an arrangement is not suitable for research purposes because the pilot would have to concentrate intently on keeping the model in flight and at the same time evaluate its flight characteristics in detail. Because the model angular rates are high, considerable piloting skill is required. In addition, when flying a model by remote control, the pilot must control the model with only visual cues since he cannot sense accelerations as he would in an

actual airplane. The lack of acceleration cues can result in delayed pilot inputs, which can be critical in the relatively constrained area of the tunnel test section. In view of these potential piloting difficulties, the piloting task is split between the two pilots so each can concentrate on his particular axis of control.

The wind-tunnel free-flight technique is used to produce valuable information on airplane behavior as angle of attack is increased in 1g level flight. Various phases of a typical investigation would include: (1) an evaluation of vehicle dynamic stability at several angles of attack up to and including loss of control at extreme angles of attack, (2) an evaluation of vehicle response to various control techniques at high angles of attack, and (3) an assessment of the effectiveness of the flight control system feedbacks and augmentation systems.

This technique has several inherent advantages: (1) because the tests are conducted indoors, the test schedule is not subject to weather conditions; (2) since the tests are conducted under controlled conditions, a large number of tests can be conducted in a relatively short period of time; (3) configuration modifications are quickly evaluated; and (4) the models used in the flight tests are also used in conventional wind-tunnel force and moment tests which provide aerodynamic data for use in the analysis of the observed flight motions and the development of mathematical models of the airplane for use in piloted simulators.

The Spin-Tunnel Test Technique

The best known test technique used today to study the spin and spin-recovery characteristics of airplanes is the spin-tunnel test technique. The present Langley Vertical Spin Tunnel, which is the only operational spin tunnel in the United States, has been in operation since 1941 when it replaced a smaller spin tunnel. A cross-sectional view of the tunnel is given in Fig. 5, and a view of the test section is given in Fig. 6. Air is drawn upward by the fan located above the test section. Models are hand-launched with prerotation into the vertically rising airstream, and the tunnel speed is adjusted to permit the model to

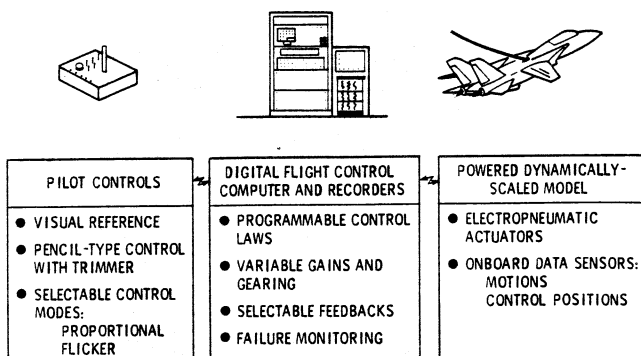


Fig. 4 Sketch of control system layout.

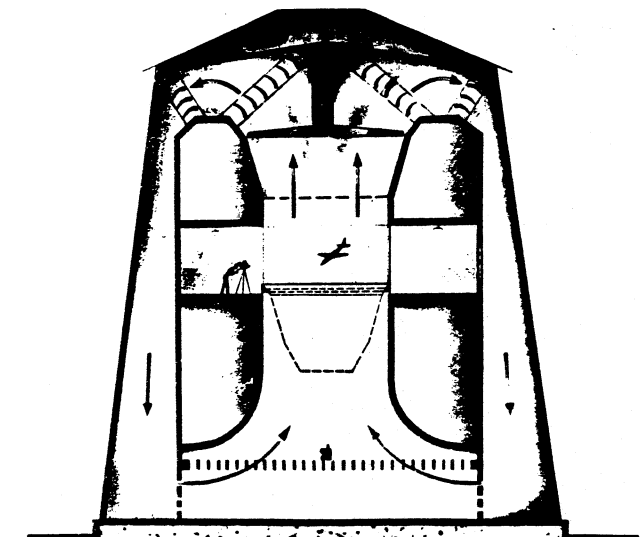


Fig. 5. Cross-sectional view of the Langley Vertical Spin Tunnel.



Fig. 6 Typical spin-tunnel test.

stabilize in the spin before the observers. For studies of spin recovery, the tunnel operator deflects the model control surfaces by remote control and the model dives into a net located at the bottom of the test section. Video records are made of the test results, and the success of the recovery is noted in terms of the number of turns required for recovery following the application of controls.

The models used in spin tunnel tests are typically of about 1/30-scale. In these investigations, a representative program consists of: (1) determination of the various spin modes and spin-recovery characteristics, (2) study of the effect of center-of-gravity location, (3) determination of the effects of external store loadings, and (4) determination of the type and size of parachute required for emergency spin recovery for test airplanes.

In a representative test program, spin and spin-recovery characteristics will be determined for all possible combinations of rudder, elevator, and aileron positions for both left and right spins. In effect, a matrix of results for all control settings is obtained. Based on these results, an analysis is made to determine the most effective combination for recovery, and ineffective or dangerous combinations are also noted. After results have been determined for the basic loading conditions, additional tests are conducted to determine the airplane's probable behavior for anticipated mass distributions and external geometries.

The parachute size required for emergency spin recovery is determined based on the most critical spin results obtained for the basic design. If the parachute is found to be too small for other configurations, the size is adjusted so that the parachute finally recommended for use on the spin demonstration airplane will be sufficient to handle the most critical conditions.

Outdoor Drop-Model Technique

A significant void of information exists between the prestall and stall-departure results produced by the wind-tunnel test technique and the fully-developed spin behavior observed during spin-tunnel tests. The outdoor radio-controlled drop model technique has been developed to supply information on

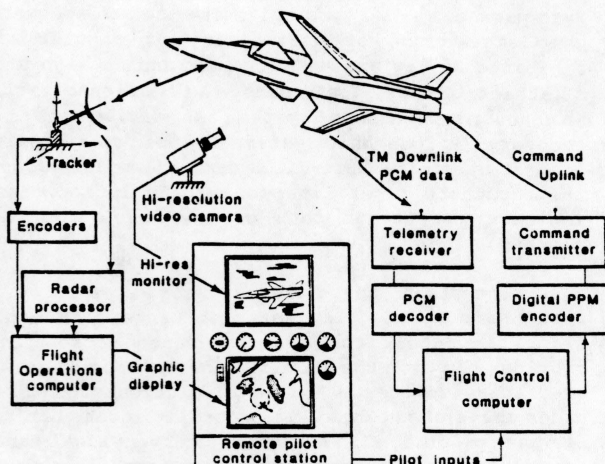


Fig. 7 Sketch of overall drop model operation.

the other phase of stalling and spinning - the spin entry (5). The technique consists of launching an unpowered, dynamically scaled model from a helicopter, assessing the spin resistance of the model via control inputs from remotely located, ground-based pilots, and recovering the model with an onboard parachute system. A sketch of the overall operation is presented in Fig. 7. A photograph of a typical model mounted on the launching rig of the helicopter is shown in Fig. 8.

The models used in the tests must be capable of withstanding the high loads which are incurred on ground impact, even with the parachute recovery system. The models are typically about the same size as the free-flight models described earlier, however their weights are usually higher (up to about 100kg) in order to simulate the relatively heavy high-performance airplanes at high altitudes.

The instrumentation for the drop model provides measurements of air data, model motions, and control surface positions. A noseboom equipped with vanes and an air-driven propeller is used to measure angle of attack, angle of sideslip, and airspeed. Rigid-body



Fig. 8 Drop model on helicopter.

motions are measured with a three-axis linear accelerometer package and two three-axis angular rate gyro packages. Two gyro units are used to account for the large range of variability of angular rates exhibited at low angles of attack and at high angles of attack in fast, flat spins. As mentioned earlier, an onboard parachute system is carried for model recovery. Pyrotechnic systems are used to explosively separate the parachute hatch from the model, to sever the parachute riser lines on ground impact, and to indicate the flight path of the model with smoke markers.

The flight tests are conducted at a large open field near the Langley Research Center. The pilot flies the model from a ground-based cockpit which provides him with the required information on a number of display devices. A high-resolution ground-based video image of the model is centrally located in front of the pilot. In addition, conventional analog instruments presenting parameters such as angle of attack, angle of sideslip, altitude, yaw rate, and normal acceleration are also available. The pilot controls the model with a custom-designed control box capable of simulating the conventional stick and pedal inputs.

The main element of the model control system is a ground-based digital computer which is programmed with the flight control laws. The computer accepts PCM decoded feedback signals from the model downlink telemetry together with the inputs from the pilot, and computes the control surface positions that are then output to the model via uplink telemetry. The computer uses an operating system designed for real-time operations. The system, including input/output delays, is capable of computing a typical modern 3-axis control law set in 3- to 6-milliseconds.

The outdoor drop model technique provides information which cannot be obtained from the other two testing techniques. The indoor free-flight model tests, for example, will identify the existence of deficiencies such as a directional instability and violent departure at stall, but the test is terminated before the model enters the incipient spin. In addition, only 1g conditions are explored with the technique. The drop-model technique can be used to evaluate behavior during the spin entry and accelerated flight conditions, including the effects of control inputs at critical times following the departure. At the other end of the stall/spin spectrum, spin-tunnel tests may identify a potentially dangerous unrecoverable spin, but it may not be possible for the airplane to enter this spin mode from conventional flight - the difference being that models in the vertical spin tunnel are hand-launched with pre-rotation at about 90° angle of attack. The drop-model tests determine the probability of an airplane entering a developed spin in a realistic manner from normal flight conditions.

During a typical investigation with this technique, a complete study will be made of the effects of various types of control inputs to determine the most effective combinations to avoid entry into the developed spin. For example, the spin susceptibility of a configuration when only longitudinal control is applied will be compared with results obtained when all pro-spin controls are applied. Recovery from the spin entry motions is evaluated by applying controls at various stages of the spin entry, such as neutralizing all controls after a certain number of

turns in the spin entry motion. Significant results include: (1) the spin susceptibility of the configuration, (2) control techniques for best recovery, and (3) the most adverse controls for spin-entry conditions. Typically, data obtained from these tests are used in pilot handbooks and procedures prior to full-scale flight tests.

The radio-controlled drop-model technique has several important limitations. The first, and most obvious, limitation is the fact that the tests are conducted out-of-doors. The test schedule is therefore subject to weather conditions, and excessive winds and inclement weather can severely impact a program test schedule. Another limitation is that the technique is relatively expensive. The electronic gear and models must be tolerant of ground impact loads, which are significant, even on the descending parachute system. Because of the higher costs and slow rate at which tests can be conducted, this technique is only used for special cases where the cheaper wind-tunnel methods will not suffice. An example of such an application is when it is necessary to know how easily an airplane may enter a catastrophic spin, or to study recovery from the developing spin.

Powered Radio-Controlled Model Test Technique

NASA facilities and resources are limited, of course, and NASA has therefore been stimulated to develop and validate a relatively inexpensive outdoor free-flight technique which can be used by individuals and industry for indications of airplane behavior at early design stages (6). An example of the models evaluated by NASA is shown in Fig. 9. As a result of

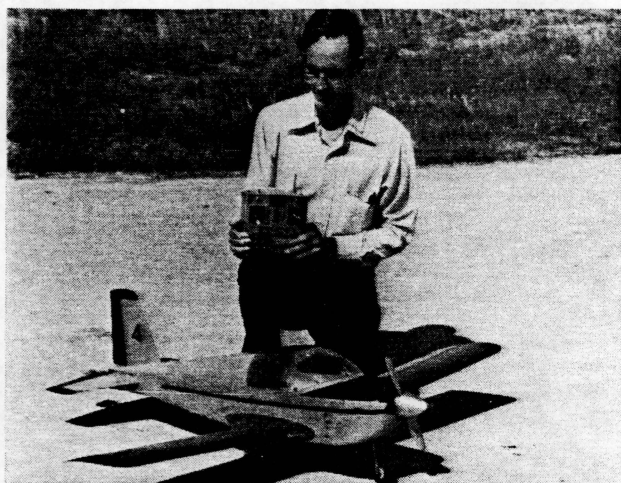


Fig. 9 Powered radio-controlled model.

scaling laws, the models tend to be very heavy and difficult to fly. The technique utilizes low-cost, hobby-type controls and instrumentation; and sensors have been developed to measure control positions, angle of attack, airspeed, and angular rates. The test set-up for these tests is shown in Fig. 10.

AERODYNAMIC SCALE EFFECTS

As a result of the relatively small scale of the models involved in the dynamic tests, the potential existence of aerodynamic scale effects must be

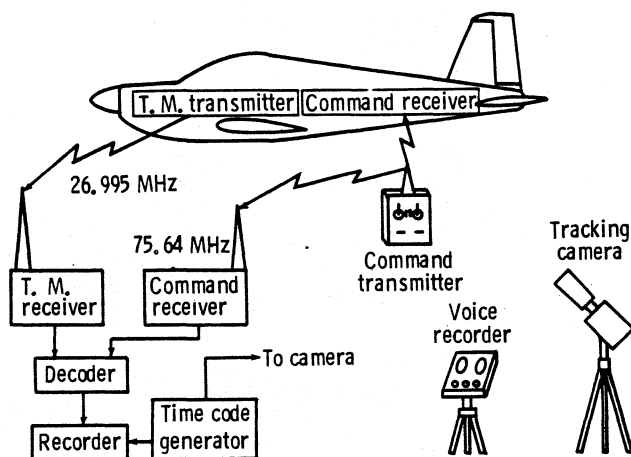


Fig. 10 Test set up for powered models.

considered. In particular, the effects of Reynolds number may result in significant errors in the results predicted by the models.

Military Configurations

One particular Reynolds number effect which has been experienced for military-type airplanes with long fuselage forebodies involves the effects of airflow over the forebody at high angles of attack. Shown in Fig. 11 is a plan view of an airplane in a right spin. The arrows along the nose indicate the relative magnitude and sense of the linear sideward velocities imparted on the fuselage by the rotation. The sketch on the right illustrates the sideslip angle β created at a typical forebody station by the combined sideward- and vertical-velocity vectors. It has been found that sideslip on the fuselage forebodies of current airplanes with long noses can produce large aerodynamic forces, and therefore moments, about the center of gravity of the airplane. If, in the case of a spin to the right (as in Fig. 11) positive (nose-right) yawing moments are produced by the nose, then the moments tend to augment the rotation, and are therefore prospin moments. If, on the other hand, negative (nose-left) values of moment are produced, then the nose is producing an antispin, or damping effect.

The sense of the moment actually produced by the nose configuration is in some cases a strong function of Reynolds number. Shown in Fig. 12 is the variation of yawing moment with Reynolds number for a representative fighter configuration as measured in wind-tunnel tests for an angle of attack of 80° and a sideslip angle of 10° . Recalling Fig. 11, a positive value of sideslip would be produced at the nose for a right spin, and positive values of yawing moment are prospin for that condition. Two values of Reynolds number are of interest: a low value, characteristic of the model tests, and a high value, representative of the full-scale airplane conditions. The values of moment (which at this angle of attack are caused almost exclusively by the nose) tend to be prospin at the low value of Reynolds number, and antispin for the high value. Also shown is a data point indicating the effect of placing a small flow-tripping device, or strake, at a particular point on the nose to cause artificial flow separation. The effect of the strake was to make the aerodynamics of the model more representative of the airplane characteristics.

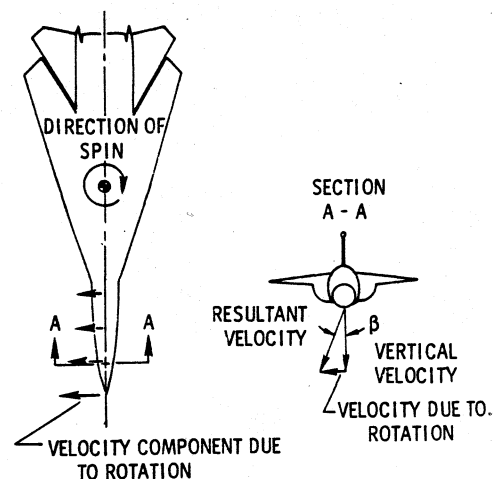


Fig. 11 Plan view of aircraft in flat spin.

It has been found during several past model investigations that this Reynolds number effect existed for some configurations. The basic models exhibited fast, flat unrecoverable spins without corrections for Reynolds number effects. The airplane displayed completely different characteristics, spinning at a relatively steep attitude and recovering easily from the spin. When strakes were added to the model forebody, satisfactory spin characteristics were obtained, and the results agreed closely with full-scale results. Because of concern over the potential existence of such scale effects, a careful assessment of the probable aerodynamic characteristics of each design is made before the model tests are conducted. If such a forebody effect is suspected, conventional wind-tunnel tests are conducted to determine an adequate forebody strake configuration for the dynamic model tests.

General Aviation Configurations

Although the general agreement obtained between results for dynamic models and full-scale general aviation-type airplanes has been good, some airplane designs which utilize high-lift airfoils have exhib-

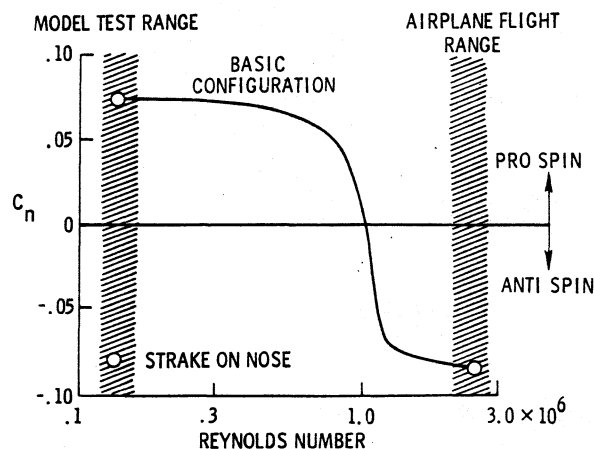


Fig. 12 Effects of Reynolds number for military configuration. $\alpha = 80^\circ$, $\beta = 10^\circ$.

ited serious aerodynamic scale effects. Shown in Fig. 13 are wind-tunnel data for the lifting characteristics of a representative model at relatively low and high values of Reynolds number. The effects of increasing Reynolds number are expected, including an increase in maximum lift and an extension of the angle of attack for maximum lift. These effects cause a distinct difference in the magnitude of the wing-generated propelling moments which drive the spin. This effect can be visualized by analyzing the data of Fig. 13 in terms of the local angle of attack during a spin. If the local angle of attack at the center of gravity is α_0 , the up-going wing will experience an angle of attack of $\alpha_0 - \Delta\alpha$. The down-going wing will experience a value of $\alpha_0 + \Delta\alpha$. If an airplane spins with its center of gravity at an angle of attack of 40° and $\Delta\alpha = 10^\circ$ at representative wing stations, the low Reynolds number data indicate a much lower differential lift on the wing panels than the high Reynolds number data. Thus, the airplane will tend to exhibit a greater tendency to spin at a higher angle of attack.

This Reynolds number effect has been observed for certain configurations in the spin tunnel. Shown in Fig. 14 are results obtained for one such design. The basic airplane employed a NACA 64-series airfoil, which has a relatively sharp leading-edge radius. The results indicate that the model predicted the airplane characteristics quite well. When the airplane was modified to incorporate a full-span high-lift airfoil, the correlation was very poor. The airplane spun at a much higher angle of attack and the spin was unrecoverable; whereas the model spun at a moderate angle of attack and could be recovered from the spin. Exploratory studies have been conducted in an attempt to devise a Reynolds number correction procedure similar to that used for the military forebody application. In these tests, the airfoils of the models have been modified to incorporate a larger leading-edge radius, and thereby higher lift, at the low Reynolds number of the model tests. The results have been encouraging in that the models exhibited spins at higher angles of attack; however, the procedure has not been adequately proven for enough different configurations at this point. The current philosophy used in tests of this type of airplane is to be particularly cautious regarding extrapolation of results for configurations with airfoils having a large leading-edge radius.

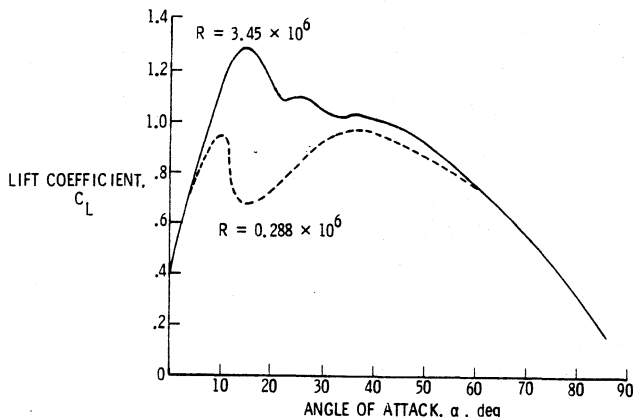


Fig. 13 Effects of Reynolds number for general aviation configuration.

Airfoil	Spin tunnel		Airplane	
	α , deg	Ω , sec/turn	α , deg	Ω , sec/turn
Basic 64 series	45	2.2	46	2.3
Full-span droop	46	2.3	63	2.0

Fig. 14 Effect of airfoil shape on model-flight correlation.

REPRESENTATIVE APPLICATIONS

X-29A Airplane

The X-29A research airplane program is a major effort to evaluate and demonstrate advanced technologies including canards, a swept-forward wing, and an unprecedented level of relaxed static stability. Langley has conducted dynamic model studies of the stall/spin characteristics of the airplane for the past 5 years. All three testing techniques for military configurations have been utilized, and additional conventional tunnel force tests and piloted simulation have also been employed (5,7). A photograph of the 0.22-scale radio-controlled drop model of the X-29A is shown in Fig. 15.

The X-29A investigation provided unique challenges for the dynamic modeling process, since the highly unstable airframe required a very effective flight control simulation in terms of actuator rates and closed-loop computational capability. Using the test instrumentation and flight sensors for stabilization, the free-flight and drop models flew at extreme angles of attack and completely evaluated the design over 3 years before the airplane is even scheduled to begin high-angle-of-attack evaluation flights.

One of the advantages of the swept-forward wing is the fact that the wing tends to stall at the root initially, and the wing tip areas tend to have attached

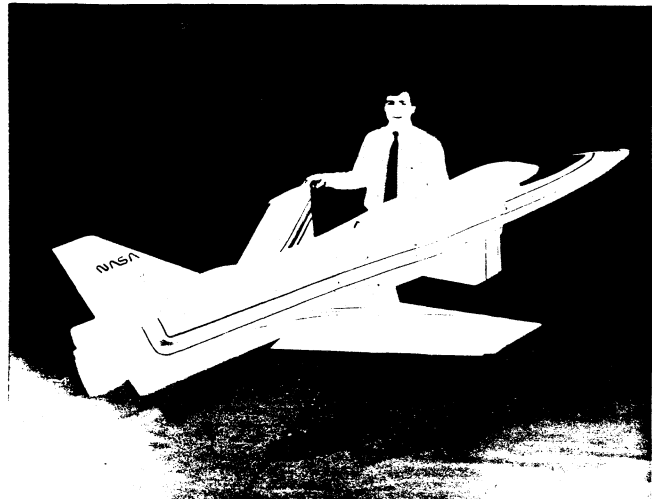


Fig. 15 Drop model of the X-29A airplane.

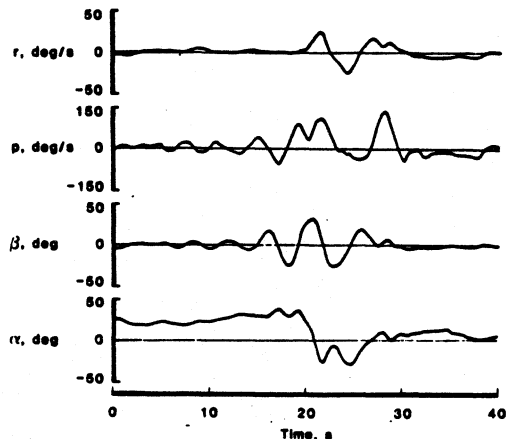


Fig. 16 Time history of wing-rocking motions and snap roll.

flow to higher angles of attack. Thus, many of the problems, such as uncontrollable pitch-up motions and loss of aileron effectiveness, which are characteristic of some swept-back wings, are avoided. The results of preliminary static force tests indicated that the X-29A design would exhibit outstanding stability at high angles of attack with a high level of aileron control effectiveness. These results had been expected, but they only represent part of the considerations required for satisfactory stall/spin behavior.

When the wind-tunnel free-flight model of the X-29A was flown, it exhibited very good stability and control characteristics at moderate angles of attack. As the angle of attack was increased to near that required for maximum lift, however, the model suddenly exhibited large-amplitude oscillations in roll (7). The amplitude of the motions was as large as 35° , and the pilot could not control the motions due to the rapid roll rates encountered. This result, which was completely unexpected, was subsequently shown to be caused by the interaction of strong vortical flows shed by the long pointed fuselage forebody and the wings and tail surfaces. When the drop-model tests were conducted, it was found that the oscillations increased in severity under accelerated flight conditions to the point that the model would exhibit an uncontrollable snap roll. A representative time history of the model motions showing the wing-rocking motions and snap roll is shown in Fig. 16. Recognizing this design deficiency, the researchers devised a high-angle-of-attack control system modification that took advantage of the relatively high level of aileron effectiveness of the X-29A to damp out the lateral motions. With this modification, the model could be flown to much higher angles of attack.

This example of the importance of free-flight model tests for airplane stall/spin assessments provides several examples of the value of the techniques. First, the unacceptable behavior of the configuration at high-angle-of-attack conditions was totally unanticipated. In fact, the existing aerodynamic design codes predicted that the airplane would be dynamically stable at such conditions. Secondly, the rapid identification of the problem led to an effective modification in a timely fashion so it could be included in the design of the flight control system. Finally, the model motions and

aerodynamic data were subsequently used to develop a piloted simulator for pilot training which was of great value to the program.

At the present time, the second X-29A demonstrator is scheduled for high-angle-of-attack flight tests in 1989. The flight program will be entered with an excellent understanding of the expected airplane characteristics.

Light General Aviation Airplanes

The severity of stall/spin accidents within the general aviation community during the 1970's led to an increased effort at Langley to devote resources toward solutions to the problem. The stall and inadvertent spin at low altitudes has, in fact, been the leading cause of fatal accidents in general aviation (6). A broad program was therefore organized at Langley which depended heavily on the use of dynamic model tests to identify the major factors affecting stall/spin behavior for this class of aircraft.

NASA researchers have developed a relatively simple wing leading-edge modification that dramatically increases the inherent spin resistance of typical general aviation designs (8). The modification, shown in Fig. 17, consists of a chord extension of about 3 percent on the outer wing panel, a drooped-nose airfoil design, and an abrupt discontinuity between the outer and inner wing airfoils. This

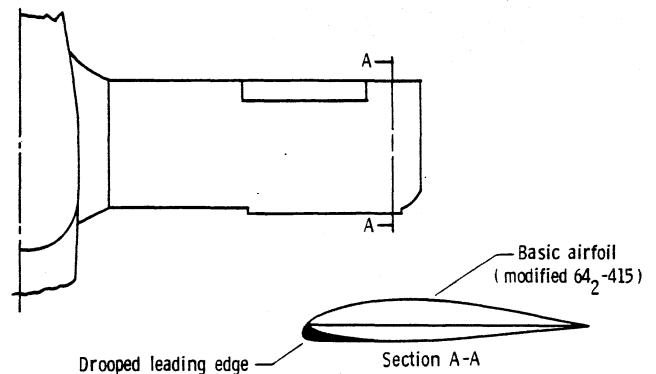


Fig. 17 Wing leading-edge modification.

concept was developed in conventional wind-tunnel tests which indicated that the lifting capability of the outer wing would be extended to very high angles of attack, thereby eliminating the prospin moments generated when a normal wing stalls.

The evaluation process for the concept proceeded into model and flight tests of several different designs intentionally chosen for the wide range of basic wing designs employed. Photographs of the research airplanes are shown in Fig. 18. For the dynamic model tests, powered radio-controlled models were used to dramatically illustrate the effectiveness of the wing modification in preventing spins. The model flights showed that the basic airplane configurations would easily enter a spin when prospin controls were applied by the pilot. The modified models, however, were very reluctant to enter spins, even when the pilot held prolonged prospin controls.

The final full-scale flight evaluations also verified the effectiveness of the modification, and the results correlated very well with the behavior predicted by the model tests. As indicated in Fig. 19, the spin resistance of each design was significantly improved, as evidenced by comparing the frequency with which the airplanes would enter spins for the basic and modified configurations. The basic airplanes entered spins in

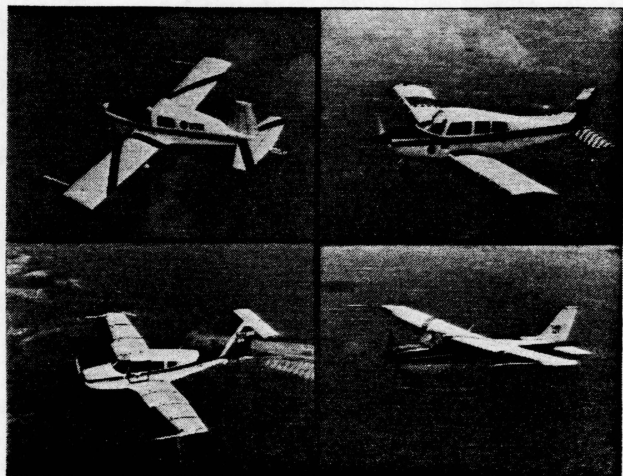


Fig. 18 Stall/spin research airplanes.

almost every spin attempt using normal prospin control inputs; whereas, the modified airplanes very rarely entered spins. In fact, special, unrealistic maneuvers (such as high-power stalls at the peak of vertical climbs) had to be devised by the research pilots in order to force the spins indicated for the modified airplanes in Fig. 19.

Conducting model flight tests before airplane flight tests was invaluable for this program. Not only were the subsequent full-scale characteristics accurately predicted, but geometric variations of the leading-edge concept were quickly and inexpensively evaluated. As a result of the success and potential of the leading-edge modification and the role of the dynamic models, the model techniques are currently being used in cooperative investigations of inherent spin resistance with the U.S. industry.

	Number of spins Attempts	
	Basic airplane	Modified airplane
AA-1X (Yankee)	$\frac{185}{193} = 96\%$	$\frac{0}{31} = 0\%$
C-23X (Sundowner)	$\frac{127}{129} = 98\%$	$\frac{7}{134} = 5\%$
PA-28RX (Arrow)	$\frac{173}{209} = 83\%$	$\frac{13}{244} = 5\%$
C-172X (Skyhawk)	$\frac{97}{164} = 59\%$	$\frac{0}{36} = 0\%$

Fig. 19 Results of flight evaluation.

CONCLUDING REMARKS

In this discussion of dynamic model testing techniques for stall/spin behavior, an effort has been made to indicate the applications, limitations, and most appropriate uses for the various types of techniques and their relative merits. These techniques have proven to be highly reliable predictive tools, and a large amount of significant data can be gathered in a relatively inexpensive, timely fashion. As a result of the value and confidence in the techniques, they are now used for many civil airplane programs and virtually all high-performance military airplane development programs in the United States.

REFERENCES

1. Scherberg, M.; and Rhode, R. V., "Mass Distribution and Performance of Free Flight Models," NACA TN 268, 1927.
2. Wolowicz, C. H.; Bowman, J. S.; and Gilbert, W. P., "Similitude Requirements and Scaling Relationship as Applied to Model Testing," NASA Technical Paper 1435, August 1979.
3. Chambers, J. R., "Overview of Stall/Spin Technology," AIAA Paper 80-1580, August 1980.
4. Chambers, J. R., "High-Angle-of-Attack Aerodynamics: Lessons Learned," AIAA Paper 86-1774, June 1986.
5. Fratello, D. J.; Croom, M. A.; and Nguyen, L. T., "Use of the Updated NASA Langley Radio-Controlled Drop-Model Technique for High-Alpha Studies of the X-29A Configuration," August, 1987.
6. Chambers, J. R., "Summary of NASA Stall/Spin Research for General Aviation Configurations," AIAA Paper 86-2597, September, 1986.
7. Murri, D. G.; Nguyen, L. T.; and Grafton, S. B., "Wind-Tunnel Free-Flight Investigation of a Forward-Swept-Wing Fighter Configuration," NASA Technical Paper 2230, February, 1984.
8. Stough, H. P., III; DiCarlo, D. J.; and Patton, J. M., Jr., "Spin Resistance Evaluation of a Light Airplane," SAE Paper No. 871021, April, 1987.