MODELING OF SPIN MODES OF SUPERSONIC AIRCRAFT IN HORIZONTAL WIND TUNNEL

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Introduction

In order to enhance mission effectiveness of future fighters, new flight regimes at high angles of attack are to be employed. However, the risk of stalling and falling into unrecoverable spin in these flight regimes is extremely high. Degraded controllability and sudden loss of the aircraft airspeed and altitude in spin pose a serious threat to flight safety. As a result, the vehicle's operational envelope may be substantially restricted. This is why the prediction of a new aircraft's spin characteristics and the development of efficient recovery techniques become a very important task for aircraft designers. At the same time, modern spin research techniques, such as flight testing of dynamically-scaled free-flying models in atmosphere or in a vertical wind tunnel and numeric studies by means of various computational methods, require substantial time and budget resources. As a result, these techniques cannot be used during early design phases.

A simple, yet efficient spin test technique has been developed in the Aircraft Aerodynamics and Flight Dynamics Research Division at SibNIA. It enables a quick and affordable experimental examination of an aircraft's spin characteristics by testing a dynamically-scaled model in a conventional (horizontal) wind tunnel. The technique is based on the following two important observations. First, it is well known from flight experience that spin radius r_s is typically much smaller than the altitude loss per one rotation. Therefore, in spin analysis it can be assumed that $r_s=0$ [1]. Secondly, test results obtained on rotating balance in a wind tunnel indicate that the aircraft aerodynamics does not dependent significantly on spin radius [2]. In particular, this fact permit the use of wind tunnel test results obtained on rotating balance for zero radius in spin dynamics modeling and simulation. Hence, it is quite reasonable to suppose that modeling of spin dynamics at $r_s=0$ will also have a small effect on the aircraft's motion parameters compared to a free spin mode. The validity of this solution approach has been confirmed by a good match observed between the experimental data obtained for subsonic light aircraft models tested in the T-203 horizontal wind tunnel at SibNIA and in the T-105 vertical wind tunnel at TsAGI, as well as by comparisons of these experimental results with flight test data.

In the presented paper, the developed technique of spin performance testing in a horizontal wind tunnel is introduced. An example of an advanced highly maneuverable combat aircraft configuration that has a sweptback wing and typical mass and inertia properties is employed. This technique demonstrates a substantial reduction in time and budget required for spin research, together with a significant simplification of the overall spin test process and experimental hardware [3, 4]. The developed technique can be recommended for application beginning from the early stages of an aircraft design cycle.

1 Test technique analysis

Traditionally, in order to describe spin motion of an aircraft, the following parameters are required [5]: spin radius r_s, angular velocity of rotation Ω, spin rate V_h, angle of attack α, and sideslip angle β. The aircraft spin recovery characteristics can be assessed by means of the time delay t_d and the number of the aircraft rotations n_r recordered between the recovery start point and the aircraft rotation stop point. Fig. 1 exhibits an aircraft motion in steady spin. It can be shown that the resulting spin motion may be represented as a sum of the aircraft descent at a constant rate V_h and its rotation about axis *OO'*, where the latter does not coincide with the aircraft's center of gravity (CG).

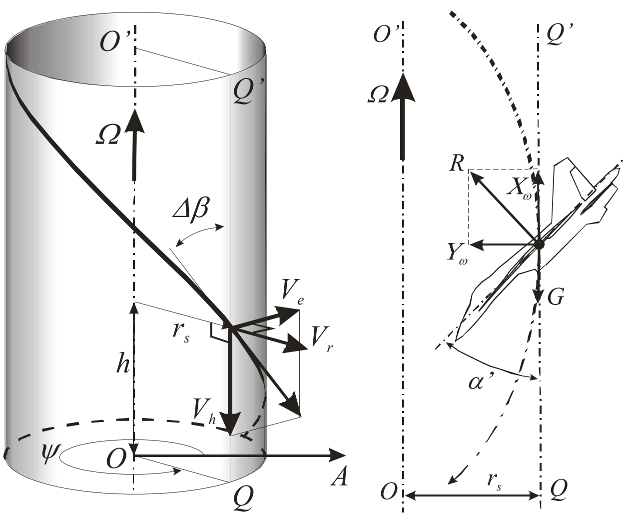


Fig. 1. Aircraft motion in spin

Under the assumption of a negligible effect of spin radius, the aircraft motion can be split onto two components: straight and steady vertical descent and rotation about axis *QQ'* that includes CG. It is therefore becomes possible to reproduce such motion modes in a conventional wind tunnel using the aircraft model and a special support unit, provided that the model can freely rotate about a fixed CG point with three angular degrees of freedom. In order to describe these motion modes mathematically it is sufficient to have only moment equations. Force equations become obsolete because the resulting aerodynamic loads are compensated by reaction forces of the support unit. In case of steady rotation, the system of equations of the aircraft motion in body axes can be written in following dimensionless form [6]:

$$4\overline{\Omega}^2(i_y - i_z)\sin\alpha\sin 2\beta = m_x;$$
$$4\overline{\Omega}^2(i_x - i_z)\cos\alpha\sin 2\beta = m_y; \qquad (1)$$
$$4\overline{\Omega}^2(i_x - i_y)\sin 2\alpha\cos^2\beta = m_z.$$

Here $\overline{\Omega} = \frac{\Omega \cdot l}{2V_h}$ – the model's dimensionless angular velocity of spin rotation;

$i_j = \frac{J_j}{\rho S l^3}$ – the model's dimensionless moments of inertia;

J_j – the model's moments of inertia about body axes;

m_j – the model's aerodynamic moment coefficients;

α, β – angles of attack and side slip.

The system of equations (1) is simple. Nevertheless, its numeric solution is very difficult to obtain, because the aerodynamic moment coefficients depend on many parameters, including unknown values of α, β and $\overline{\Omega}$. However, it is easy to see, that in this case the direction of the gravity force is not essential. Hence, the direction of airflow, be it horizontal or vertical, has no importance neither. In addition, the model motion parameters do not depend on the gravity force. Therefore, it is not necessary to secure weight similarity conditions – it is sufficient to meet the model dynamic scaling requirements only for the moments of inertia [7]:

$$J_M = J_a\left(\frac{\rho_M}{\rho_a}\right)\frac{1}{k^5}; \qquad (2)$$

where J_M, J_a – moments of inertia of the model and the aircraft;

ρ_M, ρ_a – air density for the model and the aircraft;

k – linear scale of the model.

On the other hand, in order to determine the model's steady descent rate in spin, V_h, the following condition must be met:

$$X_\omega = G_M; \qquad (3)$$

where X_ω – the drag force of the rotating model; $G_м$ – the model weight according to dynamic scale requirements:

$$G_м = G_a\left(\frac{\rho_м}{\rho_a}\right)\frac{1}{k^3}. \quad (4)$$

Here G_a – the aircraft weight.

It is obvious that in order to meet condition (3) the drag force of the rotating model is to be measured. It should be noted that real weight of the model may differ from the value determined by equation (4).

Using experimental results of zero-radius spin modeling it is possible to estimate free spin motion parameters, including r_s [8]:

$$r_s = \frac{g}{\Omega_{av}^2 \cdot tg\alpha_{av}}. \quad (7)$$

Here g – gravitational acceleration;

Ω_{av} – average angular velocity of rotation in steady spin;

α_{av} – average angle of attack.

If the parameter r_s is known, an average spiral component of sideslip angle can be calculated:

$$\Delta\beta_{av} = \Omega_{av} \cdot r_s / V_h. \quad (8)$$

It is necessary to note that this component has no effect on the model's aerodynamic characteristics because the actual sideslip angle does not depend on spin radius [8].

2 Test equipment and experimentation process

In order to investigate spin modes of aircraft models in a horizontal wind tunnel a set of special test equipment has been developed in the Aircraft Aerodynamics and Flight Dynamics Research Division of SibNIA. This equipment set includes the following components: 'Shtopor-203' test rig, test experiment control system (CS), and information measurement system (IMS). A sketch of the test rig is presented in Fig. 2. The rig enables a tested model to rotate about the model's CG with three degrees of freedom. It is equipped with transducers for measuring the model angle of attack, sideslip angle and roll angle about the airflow velocity vector. The drag force of the rotating model is measured by means of one-component strain-gauge balance. The envelope of tested angles of attack and sideslip is shown in Fig. 3.

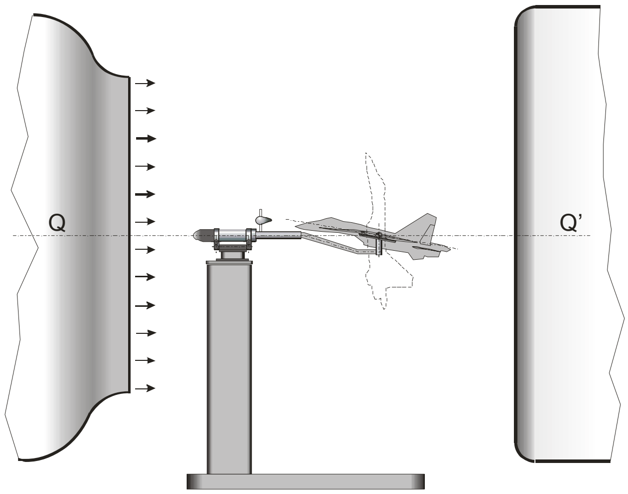


Fig. 2. 'Shtopor-203' test rig

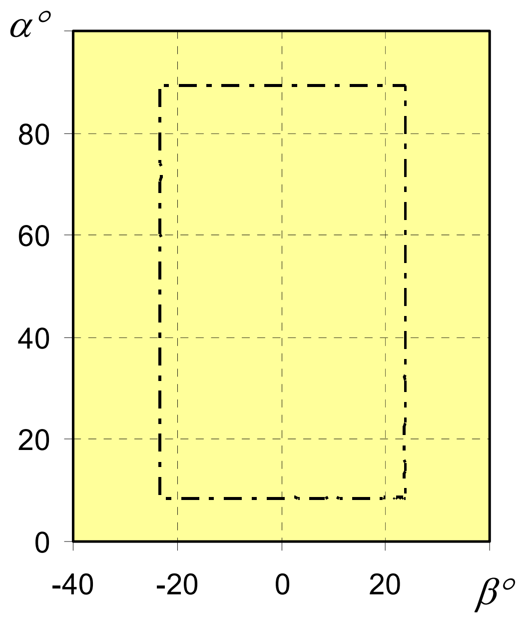


Fig. 3. Envelope of angles of attack and sideslip

The test experiment control system is used for remote deflection of the model's control surfaces according to the test program. The CS hardware is based on Super MAX-66 radio control set and personal computer, equipped with Advantech PCL-836 card. The CS structure is shown in Fig. 4. The source data for CS is a sequence of flight control surface's deflection angles with a given hold time. The experiment control software reads this information from a test plan file and interprets it as commands for the model's servo drives. These commands are passed on to the model via radio channel by means of a transmitter located in the control room of the T-203 wind tunnel and a receiver located inside the tested model.

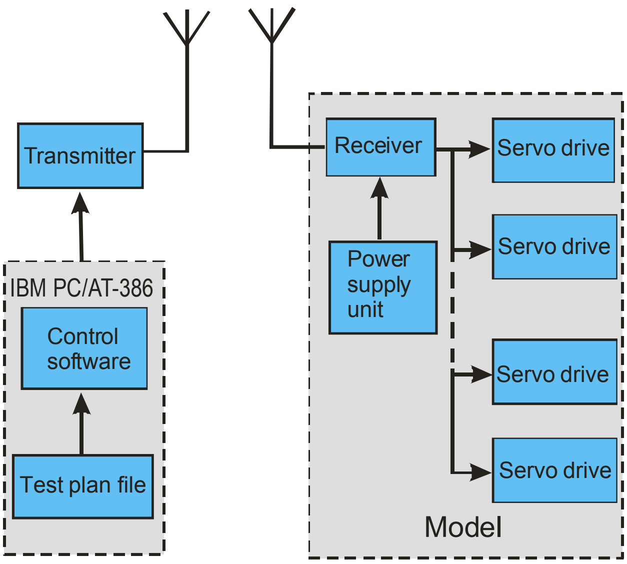


Fig. 4. Experiment control system layout

The model's motion parameters are measured and recorded with the help of IMS – ref. Fig. 5 for IMS structure details. The main component of the system is a Pentium-100 personal computer equipped with Advantech PCL-818HG card. It provides reading, normalization and switching of the signals from the test rig and model transducers, as well as 12-bit AD conversion with a frequency of 100 Hz per channel, and writing data directly to computer's RAM. The information measurement software displays this data on the computer monitor, or writes it down to a test protocol file under the experiment operator's command.

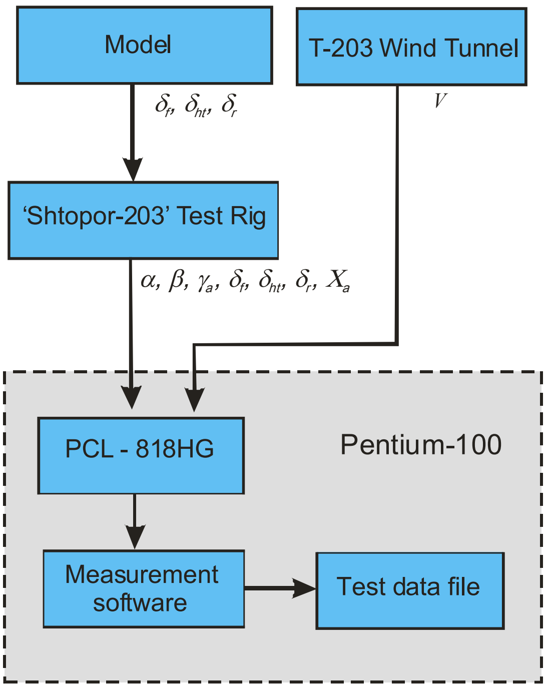


Fig. 5. Information-measurement system layout

The experience of spin research in the T-203 wind tunnel at SibNIA has demonstrated that it is reasonable to split the model's spin analysis process into two stages. During the first stage, a trial test is performed with CS operating in a manual mode. The aim is to identify a subset of the model's flight control configurations that provide acceptable acceleration performance of the model in angular motion, reveal peculiarities in the model behavior, and estimate the number of tests needed in the main program. Then, the positions of the model's flight control surfaces, which provide required rotational acceleration, are written into the test program file and then used by CS to automatically bring the model into a spin mode.

During the second stage, the main part of the test program is performed. Its primary task is to secure a required level of measurement quality and collect statistical data. CS operates in the automatic mode, and after putting model into spin it sets the model's control surfaces according to a tested configuration. To achieve steady spin motion, a time delay of *20 s* or more is used. Then, the operator switches the IMS on to a mode for set-up data registration, and the model's motion parameters are recorded during *6...8 s*. After this, CS deflects the model's flight control surfaces according to a selected recovery technique, and the data recording stops when the transition process is finished. Test results are presented in the form of graphic time-histories $\alpha(t)$, $\beta(t)$, $C_{xa}(t)$, $\gamma_a(t)$, $\Omega(t)$, $\delta_i(t)$. Also shown on these diagrams are the model's flight control configuration parameters, the average airflow velocity, and other test mode information.

3 The model and test program

A typical layout of a dynamically scaled model of a supersonic highly maneuverable combat aircraft is employed as a test article. This model is made of advanced carbon-based composite materials. It is equipped with transducers for measuring the deflection angles of control surfaces, a remote control system with a Super Max-66 receiver, a power supply unit and servos. Special additional mass compartments have been arranged at the wing tips, front and aft parts of the fuselage for adjusting the model's moments of inertia. The model geometric parameters are shown in Table 1, and three plane views and a photo of the model are shown in Fig. 6.

Geometric parameters of the model Table 1

Parameter	Notation	Value
Wing area, m^2	S	*0.191*
Wing span, m	l	*0.817*
Mean aerodynamic chord, m	b_a	*0.258*
Deflection angles, °: - flaperons - horizontal tail - rudder - leading edge	 δ_f δ_{ht} δ_r δ_{le}	 *-25...+35* *-20...+18* *±22.5* *0; 30*

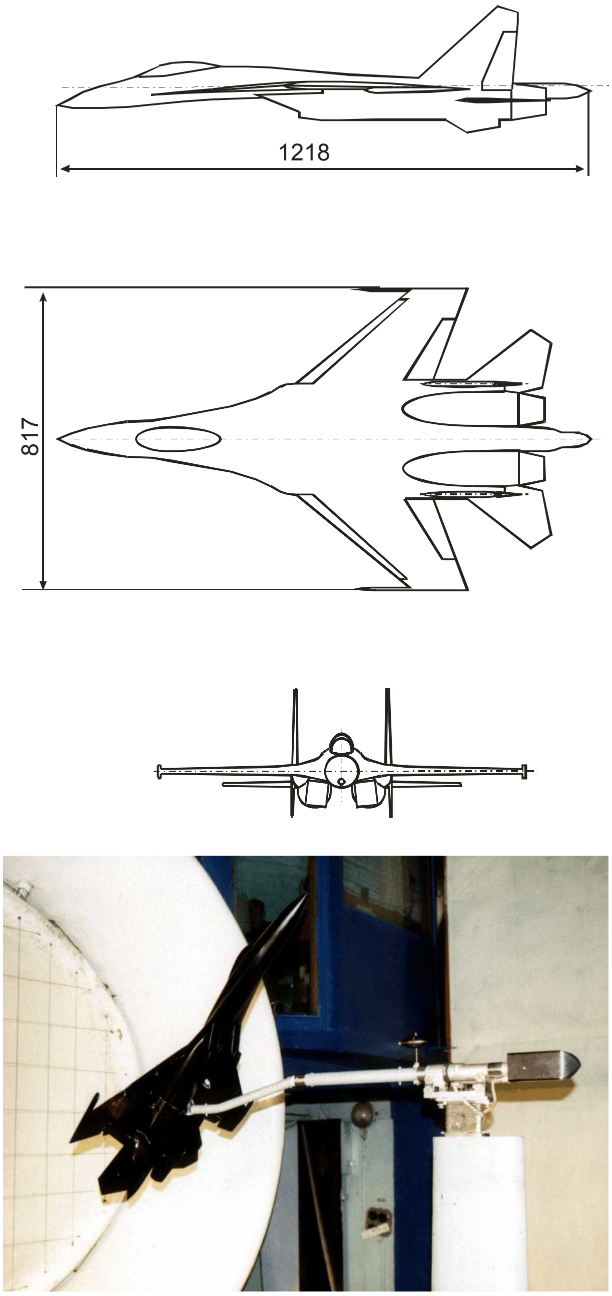


Fig. 6. Tested aircraft model

A special test program has been developed to determinate the model motion parameters in steady spin modes for various combinations of flight control surface positions. Also, the effectiveness of basic recovery techniques has been verified. In some cases differential deflection of horizontal tail surfaces was used to augment the model's lateral controllability. All tested recovery techniques are described in Table 2. The airflow velocity during testing remained constant and equal to $V=15$ m/s that corresponds to Reynolds number $Re=2.6\cdot10^5$.

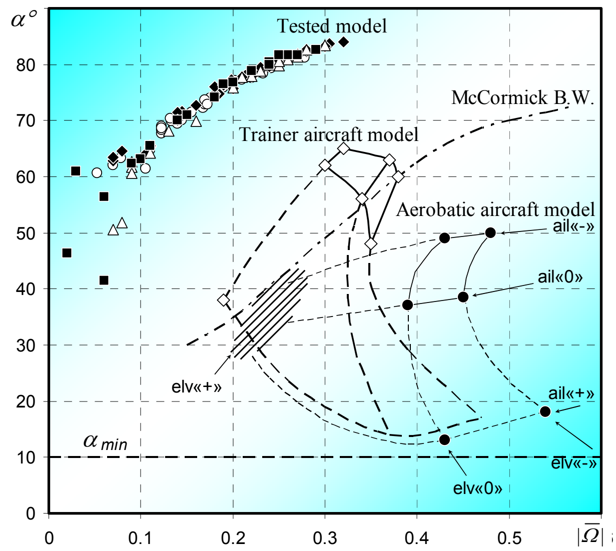
Spin recovery techniques Table 2

Code	Sequence of control inputs
№1	All controls are set to neutral position simultaneously.
№2	Rudder to ‘against spin’ and flaperons to a neutral position are set simultaneously. The horizontal tail surfaces are set to a neutral position with time delay.
№3	Rudder to ‘against spin’ and flaperons to a neutral position are set simultaneously. The horizontal tail surfaces are set to a ‘pitch down’ position with a time delay.
№4	Rudder to ‘against spin’ and flaperons to a ‘pro spin’ position are set simultaneously. The horizontal tail surfaces are set to a ‘pitch down’ position with a time delay.
№4(Mod)	Rudder to ‘against spin’, flaperons and horizontal tail to a ‘pro spin’ position are set simultaneously.

4 Test results

A typical representation of the aircraft motion parameters in the plane $(\alpha, \overline{\Omega})$ for the examined model in steady spin modes is demonstrated in Fig. 7. Test data obtained for two models – a subsonic aerobatic aircraft and a trainer aircraft – are presented for comparison. The dependence $\alpha(\overline{\Omega})$ from Ref. [2] is also depicted in Fig. 7 to compare results of traditional spin investigation techniques obtained for a light general aviation airplane.

First of all, it should be noted that the experimental data obtained for a model of a supersonic aircraft exhibits a monotonous dependence in the plane $(\alpha, \overline{\Omega})$. Spin test results obtained for subsonic aircraft configurations are grouped at nodes of two-dimensional nets. This can be explained by the fact that the effect of aerodynamic moments produced by deflected flight control surfaces in a subsonic configuration is comparable with the effect of the moments produced by inertia forces. So, the spin motion parameters strongly depend on the position of flight control surfaces.



Tested model

$\delta_{le}=0$	$\delta_{le}=30°$	Type of tests
○	◆	Left spin($\Omega<0$)
△	■	Right spin ($\Omega>0$)

Notification	Control surface’s position
«-»	against spin
«0»	neutral position
«+»	pro spin

Fig. 7. Steady spin parameters

A supersonic aircraft configuration has substantially different mass and inertia properties, and typically its inertia force moments dominate over the aerodynamic moments. As a result, the angle of attack in spin does not depend directly on the aircraft configuration, and it can be altered only by changing the aircraft rotational velocity. This observation is confirmed by increased data scattering at low angular velocities. It is necessary to point out that the presented results are in a good match with well-known features of spin behavior observed in flight for various aircraft configurations [5].

The results of the model drag force measurements in steady spin modes are shown in the upper graph of Fig. 8. Also presented here are the balance test data and the dependence

$C_{xa}(\alpha)$ taken from Ref. [7] that correspond to the spin measurement results obtained for various WWII fighter models in the R.A.E. (Great Britain) vertical wind tunnel. A small mismatch of the results can be related to specific properties of an integral configuration of the tested aircraft model. The model's spin descent rate calculated from experimental data is shown in the lower part of Fig. 8. A scale along the right-hand vertical axis corresponds to the aircraft's spin rate. It can be seen that the presented results are in a good agreement regardless of test techniques, tested models and wind tunnel type. Consequently, the spin descent rate does not depend on the spin radius, and it can be determined quite accurately by means of the developed technique.

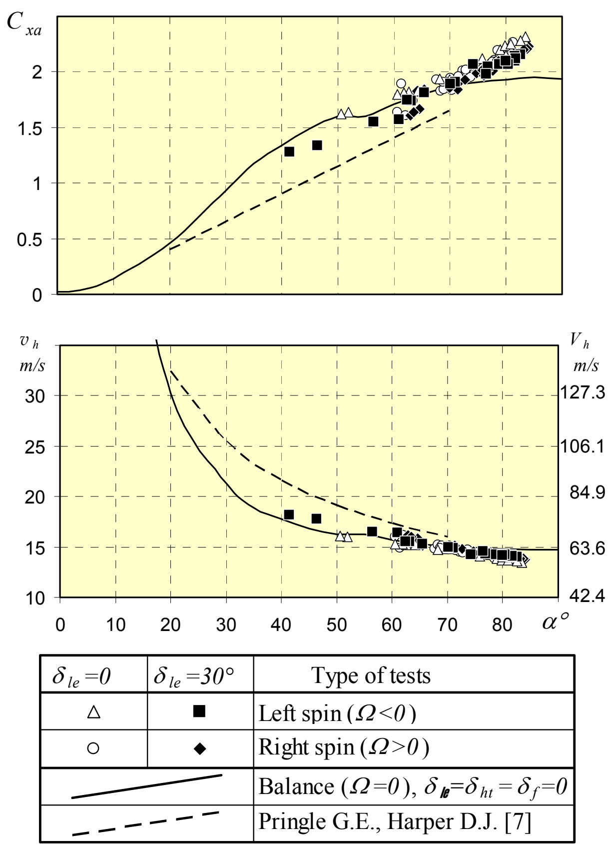


Fig. 8. Model drag coefficient and descent rate vs. angle of attack in spin

A zero radius spin test results can be used to estimate an aircraft's motion parameters in free spin, and these estimates are presented in Fig. 9. It can be noted that in most cases spin radius is less than the wing's semi-span, and as the incidence angle grows the radius decreases to zero. An estimated absolute value of the spiral component of sideslip angle does not exceed $4°$. While the actual sideslip angle does not depend on spin radius [8], the difference between the remaining parameters of the model motion in free spin and zero-radius spin parameters is to be small. Thus, it is possible to neglect them in test practice.

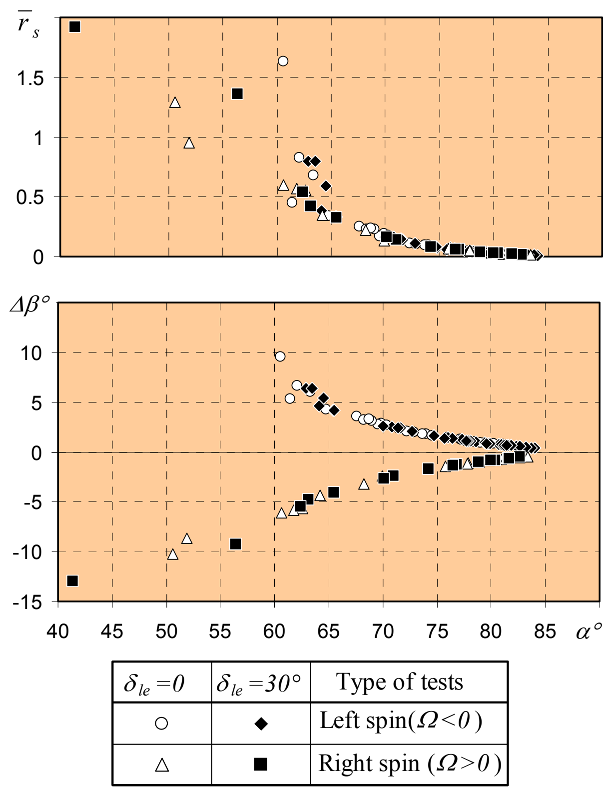
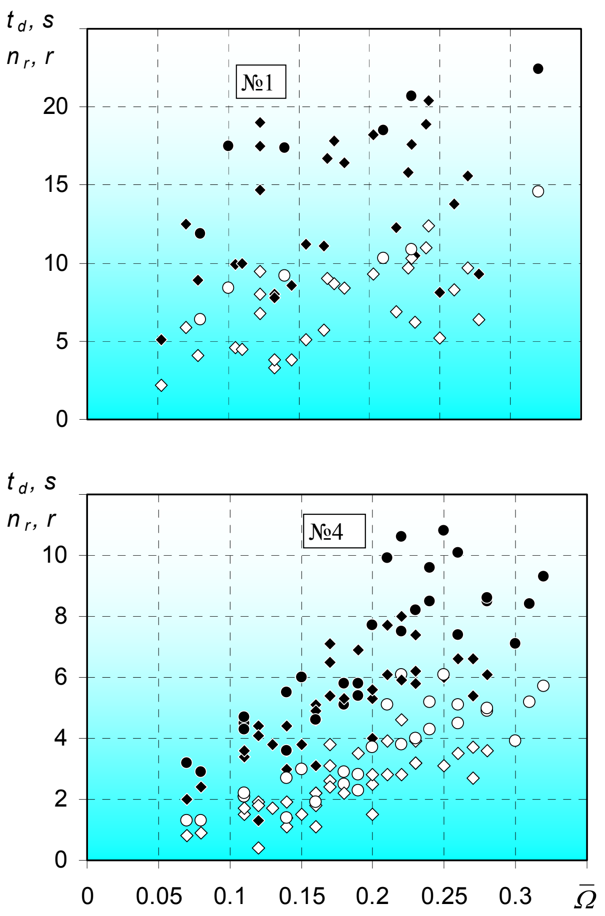


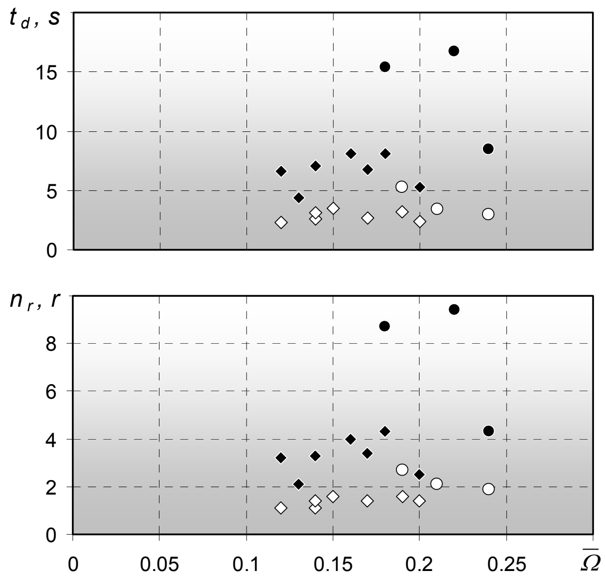
Fig. 9. Free spin motion parameters

The overall goal of an aircraft's spin performance analysis is to develop the most efficient recovery technique. The time delay, t_d, and a corresponding number of rotations in spin, n_r, for each of the tested recovery techniques are shown in Table 2. For the 'weakest' (№1) and 'strongest' (№4) techniques the results of measurements are presented in Fig. 10 in the form of dependencies $t_d(\overline{\Omega})$ and $n_r(\overline{\Omega})$, where $\overline{\Omega}$ relates to a steady spin mode. It follows from the diagram that both techniques are inefficient because of a too large time delay. Nevertheless, experimental data analysis indicates that a strongest effect on the aircraft's spin motion parameters has a differential deflection of the horizontal tail surfaces. Apparently, it is possible to achieve a significant improvement in the aircraft spin recovery performance by using this technique. Shown in Fig. 11 are spin recovery parameters for Technique №4 and its modification, with a differential deflection of the horizontal tail surfaces (ref. Table 2). It can be noted that by applying the modified technique some two rotations are needed to recover from spin, and this is quite acceptable for flight operation.



$\delta_{le}=0$	$\delta_{le}=30°$	Parameter
◆	●	t_d
◇	○	n_r

Fig. 10. Characteristics of standard recovery techniques



$\delta_{le}=0$	$\delta_{le}=30°$	Recovery technique
◆	●	№4
◇	○	№4(Mod)

Fig. 11. Characteristics of enhanced recovery techniques

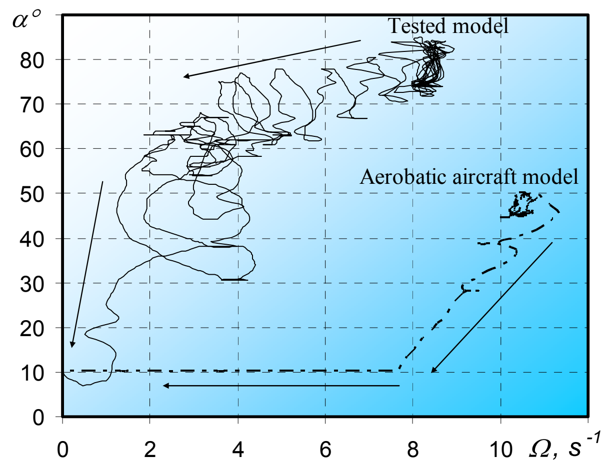


Fig. 12. Recovery process in (α, Ω) plane

Phase trajectories in the plane (α, Ω) are showed in Fig. 12. This diagram demonstrates a principal difference between the spin recovery processes for supersonic and subsonic aircraft. In particular, for a subsonic aerobatic aircraft model the incidence angle during spin recovery decreases faster than the angular velocity does. As a result, the aircraft rotation stops in a sub-critical region of the angle of attack. For a supersonic aircraft, due to its specific inertia properties, the magnitude of aerodynamic moments is not sufficient to overcome the moments of inertia force until the aircraft slows down its rotation. Therefore, first the aircraft has to decrease its angular velocity remaining inside the stall region. And only after the aircraft stops rotating, it becomes possible to decrease the angle of attack.

Conclusion

The analysis of the results described above leads to the following conclusions:

1. Highly reliable experimental estimates of spin characteristics for a supersonic aircraft can be obtained by testing its dynamically-scaled model in a conventional wind tunnel with a horizontal test section.
2. The aircraft descent rate in spin does not depend on spin radius, and it can be determined in a conventional wind tunnel using the developed test technique.
3. It has been demonstrated that in most cases ignoring the effect of spin radius on the aircraft motion parameters does not result in significant deviations from the results observed in free spin modes.
4. It has been discovered that for a supersonic aircraft the inertia forces play a predominant role in steady spin motion.
5. It has been discovered that the angle of differential deflection of the aircraft's horizontal tail surfaces has a strong effect on the aircraft rotational velocity in spin. This property of the examined aircraft configuration can be used to achieve a substantial improvement in the aircraft's spin recovery performance.
6. For a subsonic aircraft, during the spin recovery process, a decrease of the angle of attack occurs first, followed by a decrease in the angular velocity. On the contrary, for a supersonic aircraft, because of its specific inertia properties, a decrease of the angle of attack is not possible until the aircraft slows down its rotation.

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