ESTIMATION OF SPIN CHARACTERISTICS OF AEROBATIC AIRCRAFT BY MEANS OF SPIN MODES MODELING IN A HORIZONTAL WIND TUNNEL

N.P.Sohi, Y.A.Prudnikov, Y.N.Temlyakov
Federal State Unitary Enterprise «Siberian Aeronautical Research Institute»
21 Polzunova Str., Novosibirsk, Russia 630051
E-mail: sibnia@online.nsk.ru

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Abstract

Spin is a strictly prohibited, critical regime of flight for the most types of flying vehicles. Getting an aircraft into a spin mode is very undesirable because of its poor controllability and abrupt speed and altitude losses. This phenomenon significantly restricts the operational flight envelopes of aircraft. Therefore, the prediction of aircraft spin behavior and the development of effective recovery techniques are very important tasks for enhancing flight safety.

The spin problem is especially significant for sport aircraft. Spin is a mandatory figure in aerobatic flying, and is often included into various air display sequences and training exercises. In this case, it is important not only to have a controllable entry to and safe recovery from a spin, but also to produce a spectacular external impression of the figure itself. Therefore, it would be quite desirable, beginning from the design phase, to know what kind of influence various design factors can make on the aircraft's spin motion characteristics.

Currently, among modern methods of aircraft spin research the following ones are most widely used:

- *testing of dynamically scaled models in free flight*
- *experimental testing of models in vertical wind tunnels*
- *mathematical modeling and computer simulation of spin based on experimental data.*

Reconstruction of the aircraft spin motion by means of dynamically scaled models, through their testing in free flight or in vertical wind tunnels, are non-trivial tasks; they require from the researcher special skills and, sometimes, even a kind of art. In order to use effectively computational modeling and simulation for spin investigation, it is required to obtain a large volume of experimental data from the balance tests conducted in a wind tunnel and on various test rigs for a broad range of the model's angles of attack and sideslip. All these factors substantially restrict the application of the above-listed methods in the early design phases of the vehicle's life cycle. Thus, ordinary wind tunnel studies performed at early design stages require enhancement.

A simple yet efficient spin testing technique has been developed at the Aerodynamic Division of SibNIA. This technique enables an experimental estimation of the aircraft's spin characteristics by means of dynamically scaled models. The model has three angular degrees of freedom, and is capable of free rotation about its fixed center of gravity in a horizontal-test-section wind tunnel. This method is based on the assumption that the spin radius has insignificant influence on the aircraft aerodynamic characteristics. The realization of the proposed spin mode modeling method allows to significantly simplify the experiment, accelerate experimental data processing, and, to a large extent, automate the process. As a result, considerable budget savings can be achieved that makes it attractive for use during the early design stages.

In the presented paper, some features of this technique and related experimental technology are discussed. A brief description of both test the equipment and the model is also given. A comparison with some traditional spin investigation methods is made. The effect of some layout modifications, such as drooped ailerons and inertia control, on steady spin characteristics of the Sukhoi-26 aircraft model has been estimated, based on the wind tunnel test results obtained by means of the developed technique.

1 The test technique analysis

It is well known, that spin is an involuntary, poorly controlled motion of the aircraft along a near-to-vertical spiral-like trajectory at post-stall angles of attack. If we assume that the air density change due to altitude loss is negligible, then within a short period of time after the mode began it is possible to consider the aircraft motion as stationary and describe it by means of some characteristic parameters. Traditionally, for this aim the following notions are used: the spin radius r_s, the angular velocity Ω, the descent rate V, the height loss per one rotation h_r, the angle of attack α, and the sideslip angle β. The recovery characteristics are estimated by means of the delay period t_d, measured from the moment of controls reversal to the moment of spin stop, and a corresponding number of rotations, n_r. Fig.1 exhibits the aircraft's steady spin motion. As it follows from the figure, the resultant motion consists of the rotation about the spin axis OO', which does not cross the aircraft's center of gravity. Another motion component is ordinary diving at a descent rate V. On the other hand, it is possible to assume, that the aircraft rotates about the axis QQ' passed through its center of gravity, which moves along the spiral trajectory. As such, the aircraft weight is balanced by the vertical component X_a of the full aerodynamic force R_a and its horizontal component Y_a, resulting in the motion along a spiral of the radius r_s.

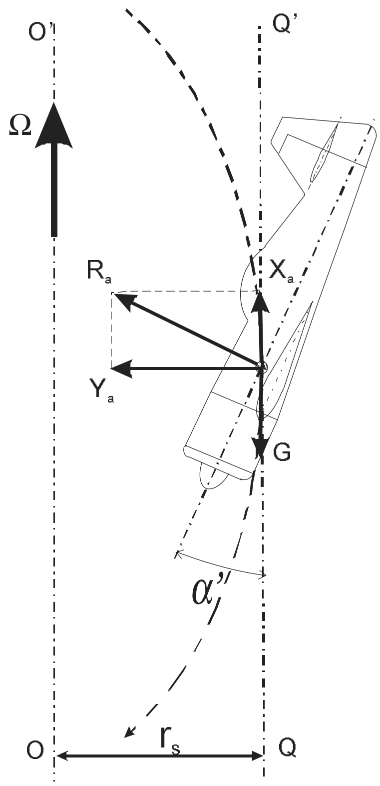

Fig.1

In a general case, the spin radius is significantly less than the height loss per one rotation. So, in a simplified analysis it is often assumed that $r_s=0$. Computational methods of spin investigation also use experimental data, obtained for a model rotating about the center of gravity [3, 4]. Results obtained from the wind tunnel tests equipped with rotating balances can serve as a substantiation of the validity for such an approach [5]. These results indicate that the aerodynamic characteristics of various aircraft layouts have a minor dependence on the spin radius.

It follows from Fig.1 that by neglecting spin radius effects it is possible to consider the aircraft motion as consisting of its rotation about the axis QQ', which passes through its center of gravity, and the aircraft is moving not along the spiral trajectory, but straight. It is quite easy to reproduce such motion in a wind tunnel by means of a model and a special support device with a hinge. The hinge is needed to provide the model with a three-degree-of-freedom rotation capability about a fixed center of gravity. For a mathematical description of such motion it is enough to use the three equations, out of six equations of the aircraft spatial motion, which characterize the equilibrium condition between the moments of aerodynamic and inertial forces. The remaining three force equations are reduced to an equality relation of the resultant aerodynamic load and the rig support force. Therefore, for the main body coordinate system it is possible to write [1]:

$$
\begin{aligned}
(J_z - J_y)\,\omega_y\,\omega_z &= M_x;\\
(J_x - J_z)\,\omega_x\,\omega_z &= M_y;\\
(J_y - J_x)\,\omega_x\,\omega_y &= M_z.
\end{aligned}
\tag{1}
$$

Here J_x, J_y, J_z - denote the inertia moments about the body axes;

ω_x, ω_y, ω_z - are the projections of the angular velocity vector on the body axes.

Let Ω be the angular velocity about the axis coinciding with the velocity direction. Then, for the body axes, we have:

$$
\begin{aligned}
\omega_x &= \Omega\cos\alpha\cos\beta;\\
\omega_y &= -\,\Omega\sin\alpha\cos\beta;\\
\omega_z &= \Omega\sin\beta.
\end{aligned}
\tag{2}
$$

In Eqs. (2) α and β - are the angles of attack and sideslip, respectively.

Taking into account (2), the system (1) becomes:

$$
\begin{aligned}
&\frac{1}{2}\Omega^2(J_y - J_z)\sin\alpha\sin 2\beta = M_x;\\
&\frac{1}{2}\Omega^2(J_z - J_x)\cos\alpha\sin 2\beta = M_y;\\
&\frac{1}{2}\Omega^2(J_y - J_x)\sin 2\alpha\cos^2\beta = M_z.
\end{aligned}
\tag{3}
$$

Reducing it to a non-dimensional form, we obtain:

$$
\begin{aligned}
&4\overline{\Omega}^2(i_y - i_z)\sin\alpha\sin 2\beta = m_x;\\
&4\overline{\Omega}^2(i_z - i_x)\cos\alpha\sin 2\beta = m_y;\\
&4\overline{\Omega}^2(i_y - i_x)\sin 2\alpha\cos^2\beta = m_z.
\end{aligned}
\tag{4}
$$

Here $\overline{\Omega} = \dfrac{\Omega l}{2V}$ - is the non-dimensional angular spin rate;

$i_j = \dfrac{J_j}{\rho S l^3}$ - are the non-dimensional moments of inertia of the model;

m_j - are the coefficients of aerodynamic moments.

Unknown variables in Eqs. (4) are the aircraft angles of attack α and sideslip β and the rate of rotation $\overline{\Omega}$. A solution to Eqs. (4) in the analytical and/or numerical form is very difficult to obtain. This is because the aerodynamic moment coefficients m_x, m_y, m_z in the right parts of the equations depend on many parameters, as well as on the variables α, β, and $\overline{\Omega}$. The model configuration, which is determined by the deflection angles of elevator δ_e, rudder δ_r, and ailerons δ_a, and the Reynolds number, makes search for available solutions much more complex. Nevertheless, it is easy to observe that now the aircraft motion parameters are not dependent on the gravity force direction, and they are fully determined by the aerodynamic and inertia characteristics of the model. Hence, in this case the airflow direction, horizontal or vertical, is not significant. For the same reason, it is not necessary to secure the weight similarity, but only sufficient to provide the similarity of the moments of inertia between the model and the full-scale aircraft:

$$
J_m = J_f\left(\frac{\rho_m}{\rho_f}\right)\frac{1}{k^5}. \tag{5}
$$

where J_m, J_f - are the moments of inertia of a model and a full-scale aircraft;

ρ_m, ρ_f - the air density for a model and a full-scale aircraft;

k - the linear model scale.

On the other hand, in order to transfer the obtained model results to a full-scale aircraft condition it is necessary to know the model weight determined by the similarity conditions:

$$
G_m = G_f\left(\frac{\rho_m}{\rho_f}\right)\frac{1}{k^3}\;. \tag{6}
$$

The condition providing the possibility of the transfer is the equality between the drag force and the determined model weight, which can differ from the actual one:

$$X_a = G_m. \quad (7)$$

This condition is automatically fulfilled in spin testing in a vertical wind tunnel by means of the flow velocity adjustment providing a zero model descent rate. It should be artificially fulfilled in testing in the horizontal-section wind tunnel. To do this, the drag force of the spinning model should be measured.

Thus, it is quite possible to simulate simplified spin motion modes in an ordinary wind tunnel that has a horizontal work section. Then all motion parameters, except for the radius, can be determined by direct measurements. But the question about the validity of obtained results still has no answer. Obviously, the immobility of the center of gravity entails motion parameters changing as large as a free spin radius differs from zero. However, small dependence of the aerodynamic characteristics from r_s allows to suggest that deviations will not be too large and the model's behavior in qualitative terms remains the same.

2 The test equipment and technology of experiment

In order to investigate the spin modes in a horizontal-section wind tunnel, verify the outlined assumptions and advance the technique further, a unique set of experimental equipment has been developed at the Aerodynamics Division of SibNIA. The equipment includes an experimental rig, a control system and data measuring systems. The diagrams of the test rig versions are shown in Fig. 2. The test rig consists of a supporting strut, a collector unit and a cantilever curvilinear sting with a hinge unit located at the end. Two potentiometers used as transducers for measuring the angles of attack and sideslip are mounted inside the hinge. Two additional transducers are built into a collector unit for measuring bank angles. The drag force is measured by a one-component strain-gauge balance. In the wind tunnel air stream the rig is placed ahead of the model and provides it with free rotation in pitch, yaw and about the airflow velocity vector. The areas (α, β) restricting the angular model position are depicted in Fig. 3.

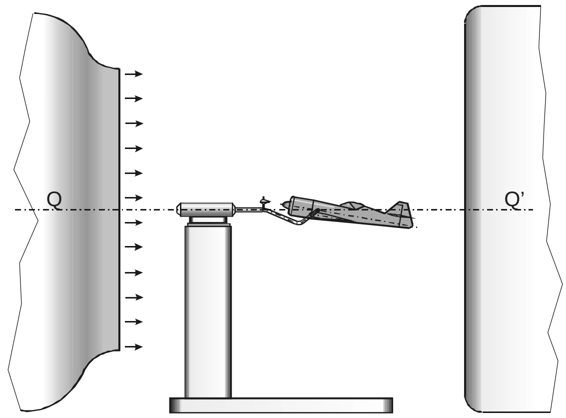

Fig.2

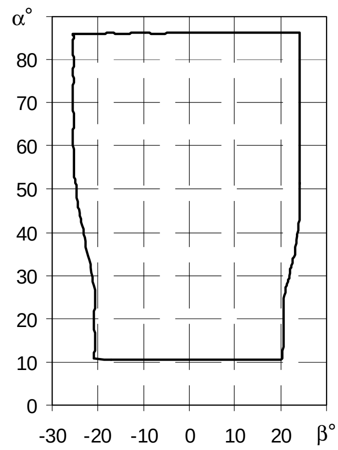

Fig.3

The control system is intended for program control of deflections of the control surfaces. The system includes a radio control equipment set Super MAX-66 used for remotely controlled airplane models, a personal computer IBM PC/AT-386 and control software. The diagram of the control system is shown in Fig. 4. A desired sequence of each control surface deflection angle due to time is specified in the experiment control file before testing. Control software uses this information to generate commands for the model servos. The commands are transmitted via the radio control channel by means of a transmitter, located in the wind tunnel control room, and a receiver embedded into the model. The developed control system provides independent proportional control inputs for each control surface and enables to adjust the model to any required configuration without airflow stop. So, a high degree of experiment automation and broad possibilities to imitate aircraft control system properties are enabled. For example, it is possible to model a dropped aileron mode by means of independent deflection of the right and left ailerons. Also, it is quite easy to provide controls reversal modes at various rates to model the rate of the aircraft control system drives.

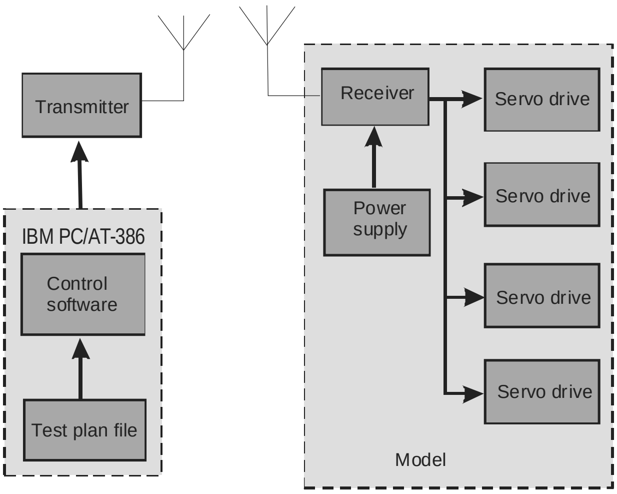

Fig.4

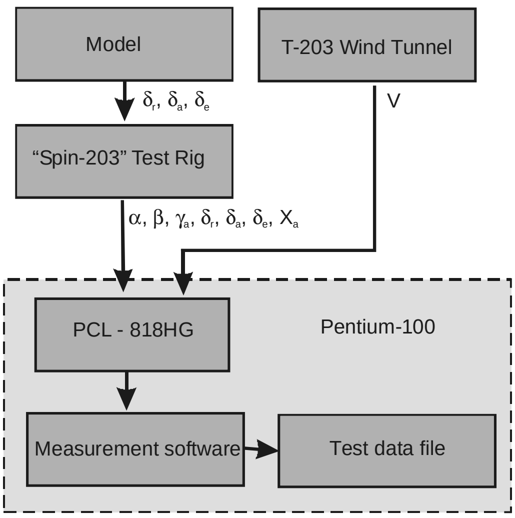

Fig. 5

The model motion parameters are measured and recorded during an experiment with the help of the data measuring system – ref. Fig.5. The core of the system consists of the Advantech PCL-818HG multifunction input-output card and a Pentium-100 personal computer. All transducer signals from the rig and model are directed to the analog ports of the card. The flow velocity signal is entered through a digital port; a strain-gauge balance signal is preliminary normalized in an amplifier. The card operates under the control of special measurement software. All analog signals are sequentially switched to an analog-digital converter for transferring to the digital form. When the experiment operator issues a command, the process of data recording begins in the computer's RAM memory. Then the information is recorded to the hard disk in the protocol form with some additional service flags attached. For each channel a transfer frequency $f=100$ *Hz* is provided by an external generator.

The experimentation process includes preliminary orientation of the supporting strut in the direction of the velocity vector, accelerating the airflow and entering the model into spin by means of the programmed sequence of controls reversal. Then the control surfaces are deflected to a test configuration, and when spin achieves a steady mode, the operator issues a command to start data recording. After 4...8 model revolutions the controls are set to a recovery position, the measurement system records the transition process and finishes data registration. The test results were are presented on plots of $\alpha(t)$, $\beta(t)$, $C_{xa}(t)$, $\Omega(t)$, $\delta_e(t)$, $\delta_r(t)$, $\delta_a(t)$ time-histories with the average flow velocity fixed for the time interval containing 6...8 model rotations. An example of a flat spin mode chart is shown in Fig. 6. It should be noted that all the time-histories in the above-described process are generated on-line, while traditional spin investigation techniques in free flight or in vertical wind tunnels require many hours of elaborate work to interpret a recorded movie of the spin process.

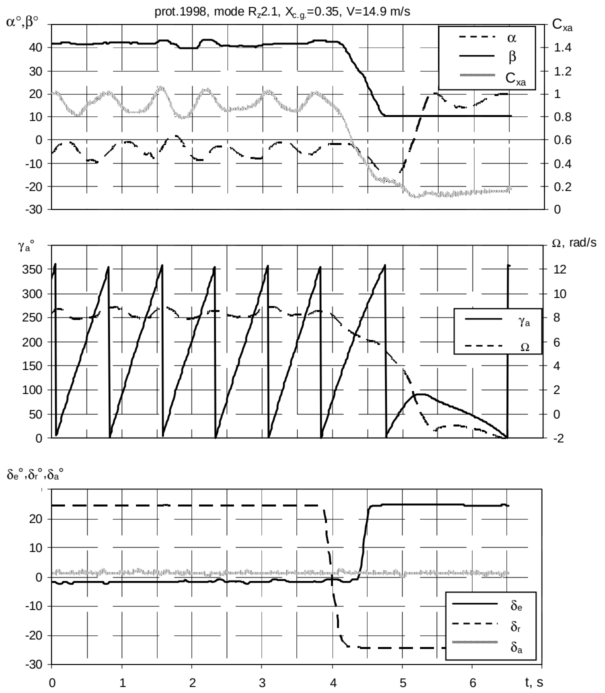

Fig.6

3 The model and test program

A new dynamically similar model of the Su-26 sport aircraft has been developed as an object for spin examination. It photo is shown in Fig. 7. This model, made of modern carbon-based materials, is equipped with transducers for measuring controls deflection angles and a remote control system including the Super Max-66 receiver, a power supply and servos. At the wing tips, nose and aft parts of the fuselage special mass compartments are arranged for inertia moment adjustments. Geometric parameters of the model are given in Table 1.

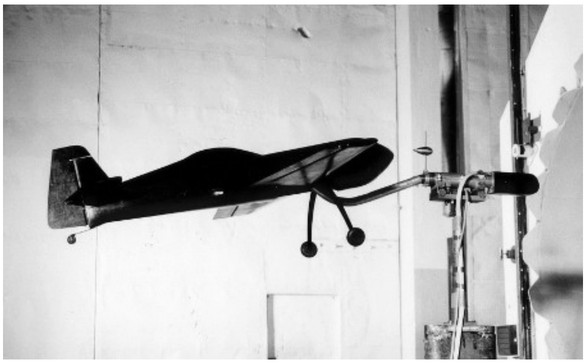

Fig. 7

Table 1

№	Parameter	Notation	Value
1	Scale	M	1:6
2	Wing area	S	0.33 m^2
3	Wing span	l	1.3 m
4	Mean aerodynamic chord of wing	b_a	0.261 m
5	Deflection range of ailerons, elevator and rudder	$\delta_{a\ max}$ $\delta_{e\ max}$ $\delta_{r\ max}$	±25° ±25° ±25°

A special test program has been developed to identify the influence of the inertia moments and dropped ailerons on the aircraft's spin characteristics. Adjustment of the inertia moments is performed by loading wing and fuselage mass compartments with masses in various combinations. The measured inertia characteristics for all variants of the model loads required to satisfy dynamic similarity criteria are shown in Table 2.

Table 2

Inertia moment	Required value, kG·m^2	Measured value, kG·m^2			
		Var. 1	Var. 2	Var. 3	Var. 4
J_x	0.1	0.110	0.149	0.101	0.145
J_y	0.261	0.271	0.315	0.296	0.336
J_z	0.185	0.168	0.179	0.198	0.191

The variant 1 corresponds to the original model's tune, wing tips where loaded in variant 2, mass compartments in nose and aft parts of the fuselage – in variant 3, and both wing and fuselage compartments – in variant 4.

Obviously, information about the effect of the inertia moments on the aircraft's spin characteristics is useful to have in design. For a ready-to-fly aircraft it is much more important to know how the spin parameters will change if the aircraft is modified. For instance, it is possible to improve the lift properties of the Su-26 aircraft's layout by means of dropped ailerons. Link length adjustments in the roll control channel are enough for it. A disadvantage of this approach is a decrease of the available roll control moments, but it can not be avoided without more essential structure alteration. So, changes in spin characteristics may become a strong argument for installing dropped ailerons on the aircraft.

The effect of dropped ailerons was imitated in the model by means of the control system. Together with the ailerons drop at the angle δ_a=+5°, the deflection range decrease to $\delta_{a\ left}=\delta_{a\ right}$=-15°...+25° was imitated too. The inertia moments correspond to the initial loading option.

In Ref. [8] it has been demonstrated that a zero radius spin parameters do not depend on the Reynolds number range accessed in wind tunnel tests. It permits to simplify the test technique further, canceling the condition (7) directly during tests. So, only the drag force X_a for a constant flow velocity $V=15\ m/s$ related to the Reynolds number $Re=2.6\cdot10^5$ was measured. The descent rate was calculated according to the condition (7) later, during a secondary data processing. Tests for all model's configurations and mass distributions were carried out five times each. Time-histories of the motion parameters recorded during tests were plotted, and statistical analysis was performed.

4 Test results

The applicability of the proposed approach to spin modes investigation can be demonstrated by comparing these results with the data obtained in the T-105 TsAGI vertical wind tunnel for another model of the Su-26. Such comparisons are shown in Fig. 8 in the form of plots where the horizontal axes correspond to the data obtained in the T-105 of TsAGI, and the vertical axes correspond to the same parameters but registered in the T-203 wind tunnel of SibNIA. If the two results are matching a dot is placed on the diagonal plotted by a dashed line. The boundaries of the confidence interval are shown by doted lines. It means that data variations within these limits are not significant under the Fisher's F-criterion given the confidence level $p=0.95$. Therefore, in spite of the difference in test conditions, there exist spin modes, where effects of the spin radius are negligible. Moreover, the majority of the observed statistically significant differences prove to be within boundaries of the confidence interval.

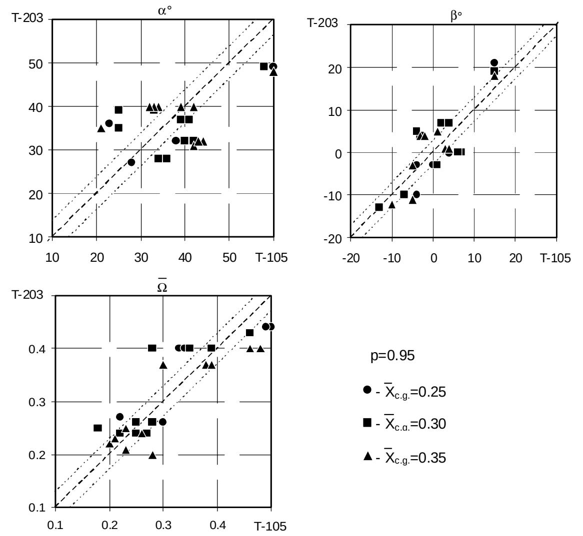

Fig.8

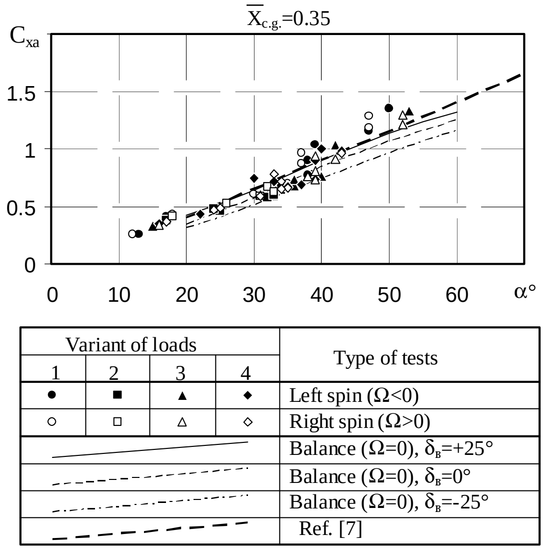

Fig. 9

As was noted above, estimation of the descent rate can be performed by the condition (7). But a direct comparison of the descent rates for various models is not correct because of the scale difference. Therefore, measurement data for the drag force of the spinning model, obtained in the presented study, are shown in Fig. 9. A thick dashed line, which represents a $C_{ya}(\alpha)$ function taken from Ref. [7], is based on the large number of tests conducted in the vertical R.A.E. wind tunnel (Great Britain) with the WWII fighter models. The same relationships, obtained in the balance tests of the Su-26 aircraft model for a broad range of the angles of attack and sideslip and, hence, corresponded to a zero angular velocity, are depicted by thin lines. It is seen that the agreement between the presented results is quite good, regardless of the test technique and wind tunnel differences.

Presented materials permit to suggest that the proposed approach to spin mode investigation is quite acceptable, at least for classical aircraft layouts equipped with non-swept wings. Therefore, the influence of some layout modifications, such as drooped ailerons and inertia control, on spin characteristics of aircraft can be estimated in a horizontal wind tunnel with a high level of confidence.

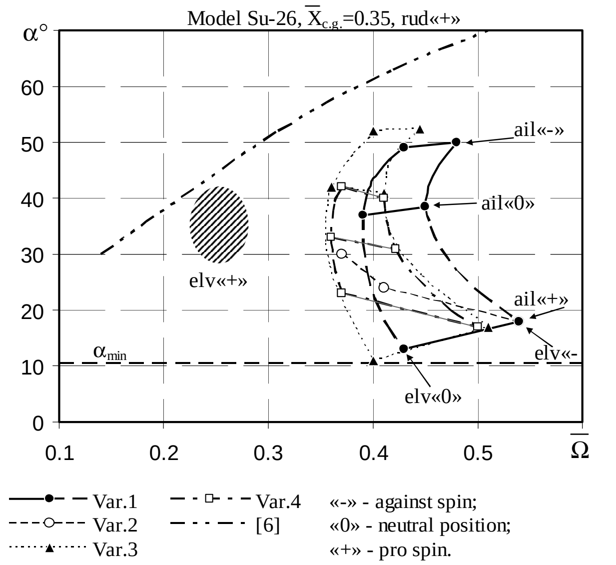

Fig.10

The results of testing the Su-26 aircraft model with dropped ailerons and changed inertia moments are presented in the plane *(α, $\overline{\Omega}$)* in Fig.10 as a net diagram. Junctions in the net reflect the average motion parameters in a steady spin for a corresponding model configuration. The aircraft configurations with elevator deflected to "pro spin" position (to pitch up) are shown separately by a shaded area, because they have very closed average motion parameters and practically are not susceptible to inertia variations and dropping ailerons. Also, it has been revealed that spin modes for investigated layout do not occur if rudder is set to a neutral position, so, it is assumed in all presented discussions that rudder is deflected to "pro spin" position.

It is necessary to note that not always and not every configuration creates rotation on high angles of attack. For example, in the variant 1 of the model loading, if elevator is set to a "pitch up" position and ailerons are deflected to an "against-spin" position, then model rotates at a minimum accessible angle of attack $\alpha_{min}\approx+10.6°$, firmly leaning upon the support unit limiters. Certainly, such motion was not considered as spin. But it was sufficient to make a small ailerons drop *($\delta_a=+5°$)*, and this configuration began to demonstrate a stable rotation with an angular velocity $\overline{\Omega}=0.26$ at the angles of attack $\alpha\approx +34°...+42°$. On the contrary, in the configurations, which earlier demonstrated a stable spin, the drop of ailerons did not lead to a statistically significant divergence in the motion parameters. Thus, the revealed effect proves to be rather qualitative, then quantitative.

It was noted above that variations of the inertia moments practically do not affect spin modes with a low rotation rate (the configurations with elevator in a "pitch up" position). In all remaining cases the model's response was quite noticeable. This can be seen from the net diagram deformations. The wing tips loading (Var.2) has lead to the elimination of some regimes and related junctions of the net. The effect of the fuselage compartments loading (Var.3) consists of an increase in the angle of attack range and some reduction in the rotation rate. Alterations of the motion parameters for both wing and fuselage compartments loading cases can be viewed as a superposition of the effects of Var.2 and Var.3.

It also can be seen that the wing tips loading, for instance, implemented by passing from Var.1 to Var.2 or from Var.3 to Var.4, is resulted in a reduction of the accessible spin modes area and, hence, it is not favorable for sport aircraft. Here it is needed to make reservation though, that improvements in spin characteristics for sport aircraft means something different compared to other types of flying vehicle.

It is quite natural that good spin characteristics often mean a higher degree of resistance to a departure and entry to a spin, a low rotation rate at small angles of attack, and a recovery to normal flight modes without a time delay and by applying a simple piloting technique. But for sport aircraft it is necessary to point out that modern aerobatic sequences and exercise complexes are packed with various spin rotations and that visual appearance of these of figures is evaluated by air display referees. Given these circumstances, the following qualities have a special value: quick and controllable entry to a spin and recovery from it, easy descent, and a spectacular execution of spins. Therefore, aircraft spins with a near-to-horizontal position of the fuselage and a high rotation rate, inherent to a flat spin, are more preferable.

The results of the presented study indicate that it is possible to achieve such effects by means of decreasing the mass distribution along the wing span. And again, taking to account an expansion of the list of possible spin modes due to dropped ailerons and favorable effects of the design layout on the lift properties, these measures can be recommended as an additional method of improving spin characteristics in sport aircraft.

In conclusion it is worth to draw the reader's attention to the results presented in Ref. [6], which also are shown in Fig.10. In that study, a comparison between some traditional techniques of spin investigation was made using an example of a light one-engine aircraft, which is similar to the Su-26 aircraft layout. A good agreement between the data sets obtained in the presented study and in the referred study was observed for low spin rotation rates. This can serve as an additional evidence of the validity of the proposed experimentation approach. Taking to account the revealed effects, it is possible to suggest that the results mismatch observed at higher angular velocities are due to differences in the inertia characteristics.

5. Conclusion

The paper considers a possibility of estimation of the spin characteristics for sport aircraft using spin modes modeling in a wind tunnel with a horizontal test section. The analysis of the obtained results allows to draw the following conclusions:

1. The possibility of spin mode investigation by means of simulation of simplified spin motion in the flow of a standard wind tunnel with a horizontal test section has been confirmed.
2. It has been demonstrated that ignoring the spin radius effects on the aircraft motion parameters does not lead in most cases to significant deviations from the parameters observed in free spin modes.
3. The influence of dropped ailerons and inertia control on steady spin motion parameters has been estimated by means of spin modes modeling on a dynamically scaled Su-26 sport aircraft model in the T-203 SibNIA low-speed wind tunnel.
4. The analysis of variations of steady spin parameters due to inertia moment control permits to recommend a decrease of the J_x moment as one of possible measures aimed to improve sport aircraft spin characteristics.
5. The simplicity of implementation, favorable effects on the aircraft lift properties and expansion of a list of possible configurations for spin allow to recommend dropped ailerons as an additional affordable measure for improving sport aircraft piloting characteristics.

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