WIND TUNNEL SPIN TESTING OF DEKO 9 MAGIC AIRCRAFT

Jakub Kulecki
General Electric Company Polska

Summary
This article summarizes wind tunnel spin testing of DEKO 9 Magic aircraft dynamically similar scale model. The article provides basics of theory of stall and spin, describes research methodology and results of testing with conclusions and recommendations.

TABLE OF SYMBOLS

- \(a\) acceleration \([\text{m/s}^2]\)
- \(a'\) speed of sound \([\text{m/s}]\)
- \(b\) wingspan \([\text{m}]\)
- \(B_x, B_y, B_z\) components of forces of inertia \([\text{N}]\)
- \(C_x\) drag coefficient \([\text{ }]\)
- \(C_z\) lift coefficient \([\text{ }]\)
- \(F_x, F_y, F_z\) external force components \([\text{N}]\)
- \(I_x, I_y, I_z\) momentums of inertia \([\text{kgm}^2]\)
- \(L, M, N\) external momentum components \([\text{Nm}]\)
- \(m\) aircraft mass \([\text{kg}]\)
- \(M\) aircraft-to-model density ratio \([\text{ }]\)
- \(Ma\) Mach number \([\text{ }]\)
- \(N\) aircraft-to-model linear dimension scale ratio \([\text{ }]\)
- \(P, Q, R\) angular velocity components \([\text{rad/s}]\)
- \(P_x\) drag \([\text{N}]\)
- \(P_z\) lift \([\text{N}]\)
- \(Q_s\) aircraft weight \([\text{N}]\)
- \(q\) dynamic pressure \([\text{Pa}]\)
- \(R_k\) spin radius \([\text{m}]\)
- \(Re\) Reynolds number \([\text{ }]\)
- \(S\) wing area \([\text{m}^2]\)
- \(U, V, W\) linear velocity components \([\text{m/s}]\)
- \(V_k\) descent speed \([\text{m/s}]\)
- \(\alpha\) angle of attack \([\text{rad}]\)
- \(\alpha_{kr}\) critical angle of attack \([\text{rad}]\)
- \(\delta_H\) eleator deflection \([\text{rad}]\)
- \(\delta_L\) ailerons deflection \([\text{rad}]\)
- \(\delta_V\) rudder deflection \([\text{rad}]\)
1. INTRODUCTION

Spin and stall are a problem since the beginning of aviation – for aircraft designers, but also for pilots and flight instructors. These phenomena are much of interest during aircraft design and flight testing process. Understanding of stall and spin is a crucial part of pilots’ training. Per numbers cited by [21] spin and stall cause 12% of accidents and 25% of disasters in general aviation in the USA. It is worth of saying that 20% of disasters happen with flight instructor on board.

Although general flight mechanics and aerodynamics are same for all the airplanes, it is obvious that specific aircraft behavior is individual and is a function of design features. It applies to stall and spin characteristics as well.

As said above, airplane spin and stall behavior is an item of interest during design process, but it also must be verified during flight testing, which is costly and could be risky. Wind tunnel spin testing before flight tests seems to be safe, cheap and productive method of initial experimental verification of spin behavior of an aircraft.

The subject article is a summary of author’s master thesis (mentor: Prof. Jerzy Maryniak, Ph. D.). Master’s graduation lecture was given in January 2004 at the Faculty of Power and Aeronautical Engineering and earned „very good” score.

Since the original thesis has been written in Polish, all the symbols and designations used in this summary reflect Polish standards. Because of limitations of volume, certain chapters have been significantly shortened; some other, as well as the majority of calculations, have been omitted.

2. PURPOSE OF THE RESEARCH

The purpose of the research is to initially evaluate aircraft spin characteristics and steering effectiveness in a spin based on testing of dynamically similar scaled model. Initial spin recovery capability based on TDPF (Tail Damping Power Factor) methodology was made before wind tunnel testing.

3. STALL PHENOMENON

For better understanding of airplane behavior in stall and spin conditions, let’s briefly remind fundamentals of steady-state horizontal flight aerodynamics and balance of forces. In the steady-state horizontal flight of an airplane weight of the aircraft is balanced by lift, whereas aircraft’s drag is balanced with thrust of the power unit; in this case – piston engine with a propeller.

As known from the basics of a wing section theory, an aerodynamic force appears on a wing as an effect of pressure distribution on the wing section, as shown on Fig. 2. In analysis of the steady-state horizontal flight the aerodynamic force is usually considered after splitting into two components: lift, normal to the horizontal plane, and drag, which is tangent to the flight path and opposite to the engine thrust.
The following equations allow to calculate lift and drag in a steady-state horizontal flight:

\[ P_x = 0.5 \rho V^2 \frac{S}{c} C_x \]
\[ P_z = 0.5 \rho V^2 \frac{S}{c} C_z \]

As shown in the above equations, lift and drag are functions of speed, air density, wing area and wing section geometry; an influence of wing section geometry is embedded in lift and drag coefficients, as shown on Fig. 3.
As shown above, lift and drag coefficients are the function of the angle of attack ($\alpha$). The plots show that exceeding of a certain angle of attack causes significant loss of lift, associated with drag increase. This condition is related to a quantitative change to the wing section airflow, resulting from separation of the boundary layer. The subject angle is called the critical angle of attack. A visualization of airflow separation is shown on Fig. 4.

Airflow separation causes loss of lift and reduces an effective wing area; so increase of the separated flow area might cause significant reduction of the total lift generated on the aircraft. The condition, in which the available lift is insufficient to balance aircraft weight, is called stall.

The stall can be a result of:
- Insufficient aircraft speed; as shown above, lift is a function of $V^2$, so reduction of speed by a half causes four time lift decrease,
- Decrease of lift after exceeding of critical angle of attack,
- Decrease of effective wing area generating lift as an effect of separated flow area increase.

In fact, all the above factors influence each other and act simultaneously.

Stall can be either symmetrical or non-symmetrical, as shown on Fig. 5.
In a symmetrical stall flow separates symmetrically on both airplane wings, resulting equal losses of lift. After loosing a balance between lift and aircraft weight the aircraft will enter a nose-down dive. Non-symmetrical stall occurs when a separated flow area on one wing is greater or increases faster than on the other. Since the separated flow areas are different, one wing provides more lift; a difference in lift generated by wings causes rolling moment, resulting spin initiation.

In general, non-symmetrical stalls are more likely to occur because of wing surface imperfections, variation arising from tolerancing, or foreign objects on wings, such as insects. Thus, flow separation usually occurs on one wing first. Aircraft’s likelihood to enter a nose-down dive or spin is a results of its dynamic characteristics, especially lateral stability.

4. SPIN

Spin is a flight condition beyond a critical angle of attack. Four phases of spin can be distinguished:

1. Spin entry, in which non-symmetrical stall occurs causing a rolling moment,
2. Incipient spin, an initial phase before developing steady spin, usually two to three first turns of spin,
3. Developed spin, when parameters, such as angle of attack, radial speed, spin radius, vertical speed are stabilized,
4. Spin recovery, which is pilot’s action taken to stop aircraft spinning and enter a dive to gain speed necessary to return to the horizontal flight. Phases of spin are shown on Fig. 6.

*Fig. 6. Phases of spin: entry (a), incipient (b), developed spin (c), recovery (d)*

Depending on the angle of attack in general we can distinguish:

- steep spin, with angle of attack below 55°, usually about 45°. This condition is considered desirable and usually can be recovered using standard procedures.
- Flat spin, with angle of attack greater than 55°, usually about 60° to 70°. This condition is characterized by a very stable force equilibrium, making recovery difficult or even impossible. Flat spin occurs as an effect of extremely aft location of aircraft center of gravity, or “flattening” of steep spin resulting from incorrect pilot action, or aircraft damage changing aircraft mass geometry beyond design intent.

The below is a summary of equations of motion for an aircraft in spin. An object of research is an aircraft assumed to be a rigid body having six degrees of freedom. The coordinate system and components of angular and linear speeds are shown on Fig. 7.
It is assumed that “plus” elevator deflection is when elevator is moved upwards (yoke towards pilot), “plus” rudder is when rudder is moved rightwards, “plus” aileron deflection is when the right wing elevator is moved downwards (yoke moved leftwards).

**Fig. 7. Aircraft coordinate system and components of angular and linear speeds**

Since developed spin is observed, the forces and momentums are in balance, so parameters such as vertical and angular velocity, spin radius, period of a single turn, pitch, roll and yaw angle, stabilize. In some cases oscillations may occur.

There are six dynamic equations of motion, one per each degree of freedom:

\[
\begin{align*}
    m \ (QW - RV) &= F_x \\
    m \ (UR - PW) &= F_y \\
    m \ (PV - QU) &= F_z \\
    QR \ (I_z - I_y) &= L \\
    RP \ (I_x - I_y) &= M \\
    PQ \ (I_y - I_x) &= N
\end{align*}
\]

Based on calculations performed in the thesis [13] speed equations are as follows:

\[
\begin{align*}
    U &= V_k \cos \\
    V &= \cdot \Omega \cdot R_k \\
    W &= V_k \sin
\end{align*}
\]
Angular speeds equations are as follows:

\[
P = \Omega \cos \alpha \cos \chi \\
Q = \Omega \cos \alpha \sin \chi \\
R = \Omega \sin \alpha
\]

where \( \chi \) is a yaw angle.
Angular speeds in the steady-state spin are shown on Fig. 8.

![Fig. 8. Angular speeds in the steady-state spin](image)

Based on the equations of force equilibrium lift and drag in the steady-state spin can be described by the following equations:

\[
P_z = m \Omega^2 R_k \\
P_x = Q_s
\]

The equations provided above accurately show the specific of spin: aircraft weight is balanced with drag, whereas lift stays in balance with “inertia forces” related to the rotation of the aircraft. The equilibrium of forces in developed spin is shown on Fig. 9.

Based on the above equations vertical speed in spin can be calculated:

\[
V_k = (2 Q_s / (S C_x))^{0.5}
\]

Spin radius can be calculated as follows:

\[
R_k = (2 m \Omega^2)^{-1} V_k^2 S C_z
\]

Equilibrium of momentum is a quite more sophisticated problem; in developed spin pitch-ing-up aerodynamic momentum is balanced by momentum related to the “forces of inertia” as shown on Fig. 10.
This condition also is shown in the following equations:

\[ 0.5 \Omega^2 \sin 2\alpha \sin \chi (I_z - I_y) + L = 0 \]
\[ 0.5 \Omega^2 \sin 2\alpha \cos \chi (I_z - I_x) + M = 0 \]
\[ 0.5 \Omega^2 \sin^2 \alpha \sin 2\chi (I_y - I_x) + N = 0 \]

The conclusion from the above equations is that instead of taking into account each momentum of inertia, we can focus only on their differences:

\[ I_z - I_y, I_z - I_x, I_y - I_x \]
The fact underlined above will be helpful in modeling of mass properties of a scale model of the aircraft of interest.

Conclusion from the above brief summary of the spin theory is that configuration of spin is a result of airplane aerodynamics and mass geometry. There is one aircraft orientation in spin for certain configuration, in which equilibrium exists. Each aircraft control, such as rudder, elevator, ailerons, flaps, can influence spin characteristics. Rudder is the most influencing control and it is critical for spin recovery.

This article would be incomplete without mentioning spin recovery procedure. There are two general circumstances of spin recovery:
- recovery from incipient spin. The key is to prevent the aircraft from developing spin and equilibrium conditions. Pilot should first of all focus on elimination of flow separations: reduce angle of attack and increase speed,
- recovery from developed spin. In this condition pilot should impact equilibrium using rudder to hamper spinning. After spinning is eliminated, pilot should restore speed sufficient for a horizontal flight.

5. ANALYTIC EVALUATION OF SPIN RECOVERY CAPABILITY

As mentioned above, rudder is a key control for majority of spin recovery techniques. Unfortunately, in majority of aircraft designs fin with rudder are in close vicinity of elevator, which can aerodynamically “shade” the rudder during spin, as shown on Fig. 11. In general it can be assumed that only not shaded part of rudder takes a part in spin recovery. The above always shall be taken into account during aircraft design process.

Fig. 11. Rudder shading in spin with angle of attack of 45°. Gray area is an aerodynamic shade caused by elevator: a) RWD 8, b) TS-8 Bies, c) PZL-104 Wilga 35, d) TS-11 Iskra, e) PZL-130TC Orlik
NACA report [2] provides a simple engineering method for assessment of aircraft controls effectiveness in spin. This method is applicable during preliminary design and can show potential "show stopper" causing a need of complete redesign of aircraft controls. The approach is evaluation of TDPF (Tail Damping Power Factor) coefficient using simple calculations and diagrams created based on wind tunnel tests of over a hundred of scale models.

TDPF analysis has been performed for the DEKO 9 Magic aircraft as a part of subject thesis.

6. SPIN – CERTIFICATION REQUIREMENTS

Requirements for spin recovery are provided in aviation regulations. Since DEKO 9 Magic aircraft was intended for certification in regards to JAR-23 and JAR-VLA, let’s focus on these documents. Both regulations provide requirements for flight testing to assure compliance.

Per JAR-VLA, Section 221 a recovery from single-turn or three second spin – select that taking longer – within not more than one additional turn using standard recovery procedure. Uncontrolled spins must not occur for any steering. Speed or G loading shall not exceed allowable limits for the aircraft [11].

JAR-23 include a list of categories, in which DEKO 9 might be certified:
- Normal: non-aerobatic use, stalls allowed;
- Utility: spins allowed provided compliance assured;
- Aerobatic: no limitations, except those identified during certification testing [10].
In general, JAR-23 requirements are similar to JAR-VLA, with additional requirements for Aerobatic category, requiring recovery from any point of spin up to six turns, or any greater number, if certification is going to include so. Recovery shall be possible within one and a half turn from the first action. In Aerobatic category spin shall be aborted after three turns if spiral dive characteristics appear.

Concluding, the regulations require that during spin allowable speed and G load are not exceeded, and recovery is possible using standard procedures.
7. WIND TUNNEL SPIN TESTING

Spin testing require a wind tunnel with vertical flow. A scale model is hanging in the center of the test space on a thin rope. The rope is attach to the model the way allowing for pitch angle change during the test. In some cases additional rope, attached to the nose of the model, is required for stabilization. Airflow is applied vertically upwards to simulate aircraft descending.

![Figure 13. A frame from the recording of DEKO 9 aircraft model behavior in the wind tunnel test space during a test run. Note rope and attachment arm](image)

The tests have been performed in the vertical wind tunnel of Institute of Aviation Technology and Applied Mechanics, Warsaw University of Technology in 2003. A legacy of wind tunnel testing in this facility include spin testing of PZL-130 Orlik trainer [15], TS-11 Iskra trainer and I-22 Iryda combat trainer [14]. DEKO 9 Magic was the first double-decker that was tested in this vertical wind tunnel.

It is worth of saying that more sophisticated tests include remote control of the wind tunnel test model, or even free-flying models.

8. DEKO 9 MAGIC AIRCRAFT

DEKO 9 magic is a two-seater, double-decker single engine aircraft. The design employs all-metal fabric covered fuselage, wings, stabilizer, fin and rudder. The prototype is powered by the six-cylinder, flat PZL-Franklin 6A-300C1R engine. See Table 1 for detailed technical data.

Mass geometry of the aircraft has been delivered by aircraft’s chief constructor. There are four main weight configurations, shown below.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MTOW with two pilots onboard, both of maximum allowed weight.</td>
</tr>
<tr>
<td>2</td>
<td>MTOW with pilots onboard, and maximum fuel.</td>
</tr>
<tr>
<td>3</td>
<td>With one pilot of maximum allowed weight and maximum fuel.</td>
</tr>
<tr>
<td>4</td>
<td>One pilot onboard of minimum weight and 20 kgs. of fuel.</td>
</tr>
</tbody>
</table>
Table 1. DEKO 9 aircraft technical data. * - target wing span increased due to wing tip redesign in comparison to the prototype

<table>
<thead>
<tr>
<th>Geometrical data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing span</td>
<td>m</td>
</tr>
<tr>
<td>Length</td>
<td>m</td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
</tr>
<tr>
<td>Wing area</td>
<td>m²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight empty</td>
</tr>
<tr>
<td>MTOW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
</tr>
<tr>
<td>Max power</td>
</tr>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td>Propeller</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{NE}$</td>
</tr>
<tr>
<td>Climb at ground level</td>
</tr>
<tr>
<td>Allowable $G$ load</td>
</tr>
</tbody>
</table>

Table 2. DEKO 9 weight configurations. From: [9]

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Aircraft weight [kg]</th>
<th>Center of gravity location [% chord]</th>
<th>Crew weight [kg]</th>
<th>Fuel weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750</td>
<td>23.6</td>
<td>86 + 86</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>750</td>
<td>17.3</td>
<td>79 + 56</td>
<td>77</td>
</tr>
<tr>
<td>3</td>
<td>701</td>
<td>16.1</td>
<td>86</td>
<td>77</td>
</tr>
<tr>
<td>4</td>
<td>614</td>
<td>11.1</td>
<td>56</td>
<td>20</td>
</tr>
</tbody>
</table>

Based on provided data [5] momentums of inertia have been calculated. Table 3 shows momentums of inertia for two extreme configurations from Table 2.
Table 3. DEKO 9 Magic momentums of inertia for two extreme configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$I_x$ [kgm$^2$]</th>
<th>$I_y$ [kgm$^2$]</th>
<th>$I_z$ [kgm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>588.5</td>
<td>1140.5</td>
<td>1390.5</td>
</tr>
<tr>
<td>4</td>
<td>588.3</td>
<td>1055.1</td>
<td>1444.2</td>
</tr>
</tbody>
</table>

9. INITIAL EVALUATION OF DEKO 9 AIRCRAFT SPIN RECOVERY CAPABILITY

Before wind tunnel testing initial spin recovery using TDPF assessment was performed. Fig. 12 shows the TDPF assessment result plot for the DEKO 9 Magic aircraft.

Fig. 14. TDPF assessment for the DEKO 9 Magic aircraft. Original plot from [2]

As shown on Fig. 12 based on the TDPF analysis DEKO 9 aircraft falls into area of recovery using rudder alone, which is a desired result. However, as mentioned above, TDPF analysis is a preliminary assessment only.

10. WIND TUNNEL TEST MODEL DESIGN

Wind tunnel test models dedicated to spin testing require more effort than those dedicated to assessment of basic aerodynamic characteristics. To establish characteristics such as lift, drag and aerodynamic pitching moment it is necessary to model an aerodynamic form of an aircraft only. When preparing a model for spin testing, in addition to the above mass, location of center of gravity and mass distribution shall be modeled as well.

Scale factor of the wind tunnel test model is limited by the size of the wind tunnel test space. The wind tunnel of Institute of Aviation Technology and Applied Mechanics allows for testing of models having wingspan not greater than 350 mm. Scaling of a linear dimension causes a need of scaling of all the dimensional and weight properties to provide dynamic similarity to the baseline.

The proportion of a linear dimension of an aircraft to the model defines a scaling factor $N$:

$$N = \frac{l_s}{l_m}$$
where:
\( l_s \) – linear dimension of an aircraft,
\( l_m \) – linear dimension of a model.

Determination of the scaling factor \( N \) allows for determination of all the dynamic similarity parameters, as shown in Table 4.

**Table 4. Dynamic similarity parameters**

<table>
<thead>
<tr>
<th>No.</th>
<th>Symbol</th>
<th>Definition</th>
<th>Condition of similarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( l )</td>
<td>Linear dimension</td>
<td>( N )</td>
</tr>
<tr>
<td>2</td>
<td>( s )</td>
<td>area</td>
<td>( N^2 )</td>
</tr>
<tr>
<td>3</td>
<td>( V )</td>
<td>volume</td>
<td>( N^3 )</td>
</tr>
<tr>
<td>4</td>
<td>( P )</td>
<td>force</td>
<td>( \frac{M N^3}{N} )</td>
</tr>
<tr>
<td>5</td>
<td>( m )</td>
<td>weight</td>
<td>( \frac{M N^3}{N^3} )</td>
</tr>
<tr>
<td>6</td>
<td>( a )</td>
<td>linear acceleration</td>
<td>const.</td>
</tr>
<tr>
<td>7</td>
<td>( v )</td>
<td>linear velocity</td>
<td>( N^{0.5} )</td>
</tr>
<tr>
<td>8</td>
<td>( t )</td>
<td>time</td>
<td>( N^{1.5} )</td>
</tr>
<tr>
<td>9</td>
<td>( \omega )</td>
<td>angular velocity</td>
<td>( N^{0.5} )</td>
</tr>
<tr>
<td>10</td>
<td>( \varepsilon )</td>
<td>angular acceleration</td>
<td>( N^{-1} )</td>
</tr>
<tr>
<td>11</td>
<td>( n )</td>
<td>speed of revolution (rpm)</td>
<td>( N^{0.5} )</td>
</tr>
<tr>
<td>12</td>
<td>( M' )</td>
<td>moment of force, torque</td>
<td>( MN^4 )</td>
</tr>
<tr>
<td>13</td>
<td>( J )</td>
<td>momentum of inertia</td>
<td>( MN^2 )</td>
</tr>
<tr>
<td>14</td>
<td>( Re )</td>
<td>Reynolds number</td>
<td>( N^{1.5} M^{-1} )</td>
</tr>
<tr>
<td>15</td>
<td>( Ma )</td>
<td>Mach number</td>
<td>( \frac{(a_{m/a_{p}})N^{0.5}}{N} )</td>
</tr>
<tr>
<td>16</td>
<td>( N' )</td>
<td>power</td>
<td>( MN^{3.5} )</td>
</tr>
<tr>
<td>17</td>
<td>( Q/S )</td>
<td>wing area loading</td>
<td>( NM )</td>
</tr>
<tr>
<td>18</td>
<td>( Q/N' )</td>
<td>power loading</td>
<td>( N^{0.5} )</td>
</tr>
</tbody>
</table>

*Fig. 15. Wind tunnel test model. Notice attachment arm*
Based on the available wind tunnel space area and wingspan of the aircraft scaling factor $N = 22$ has been selected. Calculated model wingspan was 316 mm.

Model geometry has been developed based on sections delivered in Autodesk Autocad file format using available model maker materials and technologies. Model design allows for changes of center of gravity locations.

Additional attachment arm is needed to hang the model in the wind tunnel test space, as shown on Fig. 13. Weight of the arm is about 5% of the weight of the model, considered negligible.

The model has been painted white with additional markings allowing for easy identification of model orientation during wind tunnel testing. All the controls have been painted using signal orange paint.

Model design allows for simulation of center of gravity locations between 10% and 30% of chord. Moments of inertia have been measured based on double rope pendulum methodology [15], requiring to measure small oscillations about the main axis of the model, as shown on the figures below:

![Image](https://via.placeholder.com/150)

*Fig. 16. Measurement of momentum of inertia using double rope pendulum: a) $I_x$, b) $I_y$, c) $I_z$*

The summary of moments of inertia is provided below.

<table>
<thead>
<tr>
<th>Axis</th>
<th>$I$ [kgm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>0.001704</td>
</tr>
<tr>
<td>$y$</td>
<td>0.013601</td>
</tr>
<tr>
<td>$z$</td>
<td>0.018425</td>
</tr>
</tbody>
</table>
Table 6. Proportions of differences of momentums of inertia comparison

<table>
<thead>
<tr>
<th>Object</th>
<th>((I_z - I_y) : (I_z - I_x) ) : ((I_y - I_x))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft Configuration 1</td>
<td>1 : 2.41 : 1.41</td>
</tr>
<tr>
<td>Aircraft Configuration 4</td>
<td>1 : 2.19 : 1.19</td>
</tr>
<tr>
<td>Model</td>
<td>1 : 2.39 : 1.37</td>
</tr>
</tbody>
</table>

As shown in Table 6, proportions of differences of momentums of inertia of the model falls within values observed on the aircraft and are close to those observed for Configuration 1.

Author’s efforts to provide rigidity an sufficient strength of the model caused that weight of the model before tests was 0.345 kg. Applied design changes let reduce the weight of the model to 0.280 kg, which reflects a flight at 11600 m, unreachable for the subject aircraft. Excess weight of the model was a major pitfall encountered during the research program and could distort behavior of the model in comparison to the aircraft.

11. MODEL BEHAVIOR AND TEST RESULTS

Initial tests revealed very poor response of the model to rudder deflection. The direction of rotation of the model was not dependent to the rudder. A simple airflow visualization using thin threads has shown that the majority of the rudder of the model is shaded by the stabilizer and elevator as shown below.
Fig. 18. Shading of the rudder of the wind tunnel test model revealed by airflow visualization. At lower angles of attack bottom wings can shade rudder as well

To increase rudder effectiveness the research team has decided to increase rudder area as shown below.

Fig. 19. Increased rudder area configurations: a) baseline, b) configuration I, c) configuration II, d) configuration III

Table 7. Rudder effectiveness after model design changes

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Rudder effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>baseline</td>
<td>none</td>
</tr>
<tr>
<td>I</td>
<td>poor</td>
</tr>
<tr>
<td>II</td>
<td>satisfactory</td>
</tr>
<tr>
<td>III</td>
<td>satisfactory</td>
</tr>
</tbody>
</table>
The research team has decided to continue research using Configuration III, since behavior of the baseline did not allow for completion of test program and data collection. Configuration III was found most practical and most feasible to apply in case that chief constructor decides for a change

12. SUMMARY OF RESULTS

The assessment of spin characteristics was made based on analysis of movies recorded during each test run. Single frames have been extracted for measurement of geometrical characteristics and to be included in the main thesis.

A response for each aircraft control, a variety of center of gravity positions and flow velocities has been evaluated.

As mentioned above, the baseline configuration revealed very poor response to rudder in spin. After modification to Configuration III the response was satisfactory, but not as strong as to ailerons.
An observed response to ailerons was stronger than to rudder. Setting ailerons opposite to the direction of rotation in spin changed spin direction. Deflection of ailerons to pro-spin condition, for some rudder and elevator settings, caused entering a spiral dive.

The model reacted to pro-spin deflections of the elevator. However, in neutral elevator position the model was not likely to enter spin and rather entered a spiral dive. A combined action of rudder and ailerons overwhelmed pro-spin deflection of elevator.

The movement of the center of gravity influenced the angle of attack and angular velocity. Aft positions of center of gravity resulted in flattening of spin, which is consistent with theory.

The influence of the above is shown on the plots.

Fig. 21. Test run recorded on movie frames showing a full turn in a steep spin
<table>
<thead>
<tr>
<th>Run</th>
<th>Configuration</th>
<th>Weight (kg)</th>
<th>Center of gravity (% chord)</th>
<th>dL (deg)</th>
<th>dH (deg)</th>
<th>dV (m/s)</th>
<th>Vk (rad/s)</th>
<th>Direction of rotation</th>
<th>Rk (m)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>baseline</td>
<td>0.28</td>
<td>10</td>
<td>-20</td>
<td>-20</td>
<td>-20</td>
<td>17</td>
<td>left</td>
<td>0.53</td>
<td>autorotation rolI</td>
</tr>
<tr>
<td>2</td>
<td>III</td>
<td>0.28</td>
<td>25</td>
<td>0</td>
<td>-20</td>
<td>20</td>
<td>15</td>
<td>left</td>
<td>0.68</td>
<td>flat spin</td>
</tr>
<tr>
<td>3</td>
<td>III</td>
<td>0.28</td>
<td>12</td>
<td>0</td>
<td>-20</td>
<td>20</td>
<td>17</td>
<td>right</td>
<td>0.2</td>
<td>steep spin</td>
</tr>
<tr>
<td>4</td>
<td>III</td>
<td>0.28</td>
<td>12</td>
<td>-20</td>
<td>-20</td>
<td>20</td>
<td>12</td>
<td>left</td>
<td>1.5</td>
<td>direction of rotation changed</td>
</tr>
<tr>
<td>5</td>
<td>III</td>
<td>0.28</td>
<td>12</td>
<td>-20</td>
<td>-20</td>
<td>20</td>
<td>16</td>
<td>right</td>
<td>1.8</td>
<td>entering spiral dive</td>
</tr>
</tbody>
</table>

**Table 8. Summary of recorded test run results**

---

**Fig. 22. Influence of center of gravity location on spin characteristics**

**Fig. 23. Influence of deflection of ailerons on spin characteristics**
13. CONCLUSIONS AND RECOMMENDATIONS

The research presented in this article provided an early evaluation of aircraft spin behavior. Insufficient effectiveness of rudder could, but does not have to occur during spin testing of the aircraft. The test team proposed a design change, which could be taken into account by chief constructor in future development of the aircraft. It is worth of underlining that proposed change does not require major changes in the structure of the fuselage, as well as does not negatively impact aircraft appearance.

Test results confirmed that location of center of gravity cardinally influences the angle of attack in spin, as expected based on experience. The major lesson learned is that wind tunnel model design should be focused on minimizing weight of the model; excess weight could influence quantitative results of research.

BIBLIOGRAPHY

J. Kulecki

BADANIA KORKOCIĄGOWE W TUNELU AERODYNAMICZNYM SAMOLOTU DEKO 9 MAGIC

Streszczenie

Niniejsza praca przedstawia założenia, przebieg i wyniki badań korkociągowych dynamicznie podobnego modelu samolotu DEKO 9 Magic w pionowym tunelu aerodynamicznym Instytutu Techniki Lotniczej i Mechaniki Stosowanej Politechniki Warszawskiej. Przedstawiono również podstawy aerodynamiki przeciagnięcia i korkociągu.