

EXPERIMENTAL INVESTIGATION OF PROPELLER AERODYNAMIC DERIVATIVES

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Abstract: Whirl flutter is a specific type of flutter instability, for which the experimental validation of the analytical results is required. One of the key issues is the solution of propeller aerodynamic forces for which aerodynamic derivatives are used. Paper describes the mechanical concept of the used demonstrator that represents a sting-mounted nacelle with a motor and propeller and the methodology of the assessment of the derivatives. The main focus is paid on the wind tunnel test including the list of the tested variants, methodology of testing and the data assessment. Finally, the examples of the results are provided.

Keywords: Whirl Flutter, Propeller Aerodynamic Derivative, W-STING Demonstrator

1. Introduction

Whirl flutter is a specific kind of aeroelastic flutter instability, which may appear on turboprop aircraft owing to the effect of rotating parts. It is driven by motion-induced unsteady aerodynamic propeller forces and moments acting in the propeller plane. It may cause unstable vibration, which can lead to a failure of an engine installation or a whole wing. Due to the unreliable analytical solution of propeller aerodynamic forces that are based on a propeller aerodynamic derivatives, experimental investigation is required. This paper takes up the previous work on the subject by the author (Čečrdle, 2023).

2. Theoretical Background

The principle of whirl flutter phenomenon is described on the simple mechanical system with two degrees-of-freedom with a flexible engine mounting and a rigid propeller (see figure 1). This system has two independent mode shapes. Considering propeller rotation, the gyroscopic effect causes both independent mode shapes to merge into the whirl motion. A propeller axis shows an elliptical movement. The orientation is backward relative to the propeller rotation for the mode with the lower frequency (backward whirl mode) and forward relative to the propeller rotation for the mode with the higher frequency (forward whirl mode). The gyroscopic motion results in unsteady aerodynamic forces, which may under specific conditions induce whirl flutter instability. Considering small angles, the equations of motion become:

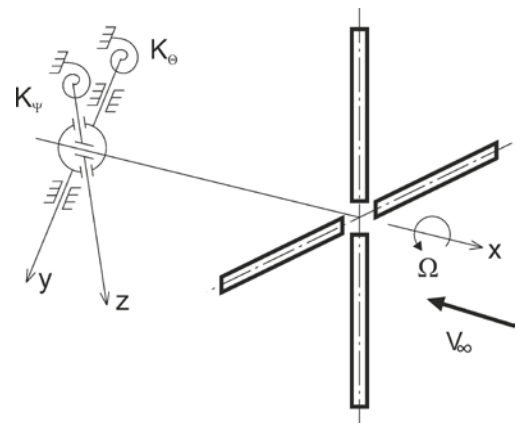


Fig. 1: Gyroscopic system with propeller

$$J_Y \ddot{\Theta} + (K_\theta \gamma_\theta / \omega) \dot{\Theta} + J_X \Omega \dot{\Psi} + K_\theta \Theta = M_{YP} - aP_Z$$

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$$J_Z \ddot{\Psi} + (K_\Psi \gamma_\Psi / \omega) \dot{\Psi} + J_X \Omega \dot{\Theta} + K_\Psi \Psi = M_{ZP} + aP_Y \quad (1)$$

Propeller aerodynamic forces and moments (right-hand side of eqn. 1) are determined using aerodynamic derivatives. Neglecting the aerodynamic inertia terms, the equations for the propeller's dimensionless forces and moments may be expressed as follows:

$$\begin{aligned} P_Y &= qS \left(c_{y\Psi} \Psi^* + c_{y\Theta} \Theta^* + c_{yq} (\dot{\Theta}^* D/2V) \right) & P_Z &= qS \left(c_{z\Psi} \Psi^* + c_{z\Theta} \Theta^* + c_{zr} (\dot{\Psi}^* D/2V) \right) \\ M_{YP} &= qSD \left(c_{m\Psi} \Psi^* + c_{mq} (\dot{\Theta}^* D/2V) \right) & M_{ZP} &= qSD \left(c_{n\Theta} \Theta^* + c_{nr} (\dot{\Psi}^* D/2V) \right) \end{aligned} \quad (2)$$

Where q is a dynamic pressure, S is a propeller disc area, D is a propeller diameter, Θ^* and Ψ^* are effective pitch and yaw angles, respectively. The aerodynamic derivatives (c-terms) are the following:

$$\begin{aligned} c_{y\Theta} &= \partial c_y / \partial \Theta^* & c_{y\Psi} &= \partial c_y / \partial \Psi^* & c_{yq} &= \partial c_y / \partial (\dot{\Theta} D/2V) & c_{yr} &= \partial c_y / \partial (\dot{\Psi} D/2V) \\ c_{z\Theta} &= \partial c_z / \partial \Theta^* & c_{z\Psi} &= \partial c_z / \partial \Psi^* & c_{zq} &= \partial c_z / \partial (\dot{\Theta} D/2V) & c_{zr} &= \partial c_z / \partial (\dot{\Psi} D/2V) \\ c_{m\Theta} &= \partial c_m / \partial \Theta^* & c_{m\Psi} &= \partial c_m / \partial \Psi^* & c_{mq} &= \partial c_m / \partial (\dot{\Theta} D/2V) & c_{mr} &= \partial c_m / \partial (\dot{\Psi} D/2V) \\ c_{n\Theta} &= \partial c_n / \partial \Theta^* & c_{n\Psi} &= \partial c_n / \partial \Psi^* & c_{nq} &= \partial c_n / \partial (\dot{\Theta} D/2V) & c_{nr} &= \partial c_n / \partial (\dot{\Psi} D/2V) \end{aligned} \quad (3)$$

Considering the symmetry (or antisymmetry), we can reduce the number of derivatives as follows:

$$c_{z\Psi} = c_{y\Theta}; c_{m\Psi} = -c_{n\Theta}; c_{mq} = c_{nr}; c_{zr} = c_{yq}; c_{z\Theta} = -c_{y\Psi}; c_{n\Psi} = c_{m\Theta}; c_{mr} = -c_{nq}; c_{yr} = -c_{zq} \quad (4)$$

In addition, we can neglect the negligible derivatives: $c_{mr} = -c_{nq} = 0$ and $c_{yr} = -c_{zq} = 0$. Finally, we obtain six independent derivatives: $c_{z\Theta}$, $c_{m\Theta}$, $c_{z\Psi}$, $c_{m\Psi}$, c_{mq} and c_{zr} . The first four ones may be investigated experimentally. The explanation of subscripts and other quantities can be found in sections 3 and 4.

3. Demonstrator Concept and Methodology of Measurement

Aeroelastic demonstrator for investigation of a propeller aerodynamic derivatives represents a sting-mounted nacelle with a motor and propeller. The demonstrator includes two degrees-of-freedom (engine pitch and yaw). Both pivots can be independently moved in the direction of the propeller axis. For the measurement, just a single degree-of-freedom is used while the other one is mechanically blocked. The propeller is powered by an electric motor with a nominal power of 15 kW. The power is sufficient to provide the measurement with the propeller in the thrust mode. The demonstrator sensor instrumentation includes measurements of both pitch (Θ) and yaw (Ψ) deformation angles using strain-gauge sensors and the measurement of both pitch ($K_\Theta \Theta$) and yaw ($K_\Psi \Psi$) pivot moments using a balance cell. Propeller and motor-related quantities include the propeller Ω , torque (M_k) and the immediate power (P) that are evaluated by a servo amplifier. The propeller thrust (T) is measured by a single component balance cell. Wind-tunnel related quantities include the angle of manipulator (Θ_m), airflow velocity (V) and dynamic pressure (q).

The static equations for the engine and propeller pitch and yaw deflection may be (from eqn. 1) expressed using the total moment-related derivatives (denoted by *) as:

$$k^2 \Theta = \kappa (c_{m\Theta}^* \Theta + c_{m\Psi}^* \Psi) \quad k^2 \Psi = \kappa (c_{n\Psi}^* \Psi + c_{n\Theta}^* \Theta) \quad (5)$$

Note that the relations $c_{m\Theta}^* = c_{n\Psi}^*$ and $c_{m\Psi}^* = -c_{n\Theta}^*$ given by eqn. 4 were used in the latter equation.

For determination of $c_{m\Theta}$ and $c_{z\Theta}$ derivatives, the pitch-only arrangement of the demonstrator is used. Hence, for $\Psi = 0$, the total pitching moment coefficient (c_m^*) may be expressed as:

$$c_m^* = (K_\Theta \Theta / qSD) \quad (6)$$

Where $K_\Theta \Theta$ is the measured pitch pivot moment. The measurement is performed varying the pitch angle by the wind tunnel manipulator and the moment is evaluated with respect to the pitch angle (Θ). The slope of the measured curves is the reference pitch moment due to the pitch angle derivative ($c_{m\Theta}^*$). To separate the force and moment contributions to the total pitch moment, two configurations varying the distance between the gimbal axis and the propeller plane (a) are measured. The equations are:

$$c_{m\Theta 1}^* = c_{m\Theta} - (a_1/D) c_{z\Theta} \quad c_{m\Theta 2}^* = c_{m\Theta} - (a_2/D) c_{z\Theta} \quad (7)$$

And the final expressions for aerodynamic derivatives become:

$$c_{m\theta} = (1/(a_2 - a_1))(a_2 c_{m\theta 1}^* - a_1 c_{m\theta 2}^*) \quad c_{z\theta} = (D/(a_2 - a_1))(c_{m\theta 1}^* - c_{m\theta 2}^*) \quad (8)$$

For determination of $c_{m\psi}$ and $c_{z\psi}$ derivatives, the yaw-only arrangement of the demonstrator is used. Hence, the total yawing moment coefficient (c_n^{**}) may be expressed as:

$$c_n^{**} = (K_\psi \Psi / qSD) = (c_{n\psi}^* \Psi + c_{n\theta}^* \Theta) \quad (9)$$

Where $K_\psi \Psi$ is the measured yaw pivot moment. The measurement is performed varying the pitch angle by the wind tunnel manipulator and the moment is evaluated with respect to this pitch angle (Θ). The slope of the measured curves (c_n^{**}) and eqn. (9) are used to obtain the reference yaw moment due to pitch angle derivative ($c_{n\theta}^*$) that is:

$$c_{n\theta}^* = (c_n^{**} - c_{n\psi}^* (\Psi/\Theta)) \quad (10)$$

The yaw-to-pitch angle ratio (Ψ/Θ) is constant just for a given blade angle and dynamic pressure. The reference yaw moment due to yaw angle derivative ($c_{n\psi}^*$) is obtained using the antisymmetry (eqn. (4)) as $c_{n\psi}^* = c_{m\theta}^*$. Similarly, we use $c_{n\theta}^* = -c_{m\psi}^*$ to obtain the reference pitch moment due to yaw angle derivative ($c_{m\psi}^*$). Separation of ($c_{m\psi}^*$) to its components ($c_{m\psi}$) and ($c_{z\psi}$), i.e., the separation of force and moment contributions is carried out similarly as is mentioned above. The final expressions for aerodynamic derivatives are:



Fig. 2: Wind tunnel test arrangement.

$$c_{m\psi} = (1/(a_2 - a_1))(a_1 c_{n\theta 2}^* - a_2 c_{n\theta 1}^*) \quad c_{z\psi} = (D/(a_2 - a_1))(c_{n\theta 2}^* - c_{n\theta 1}^*) \quad (11)$$

4. Test Arrangement, Measured Configurations and Results

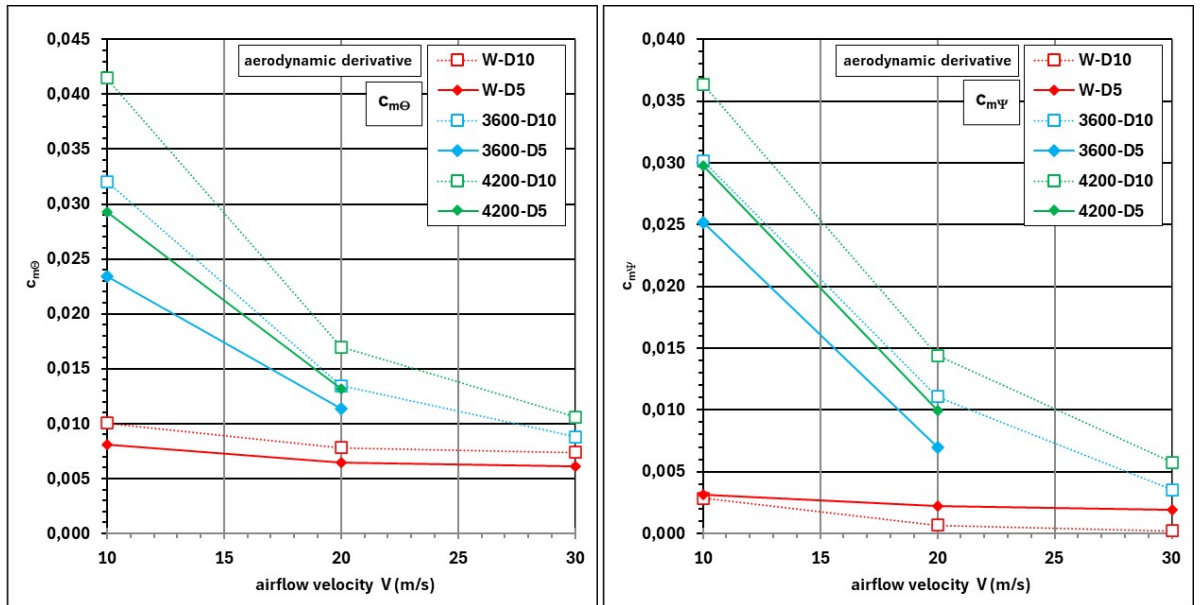


Fig. 3: Evaluated aerodynamic derivatives $c_{m\theta}$ (a) and $c_{m\psi}$ (b).

With respect to the above-described methodology of aerodynamic derivatives assessment, the test plan included four basic groups of measurements: 1) Pitch degree-of-freedom active, front pivot station, 2) Yaw degree-of-freedom active, front pivot station, 3) Pitch degree-of-freedom active, rear pivot station and 4) Yaw degree-of-freedom active, rear pivot station. In the above-mentioned four groups, changes of

secondary parameters were realized. The tested variants included a single choice of both yaw and pitch stiffness, a single choice of propeller's blade, two choices of blades' angle-of-attack, three choices of the propeller revolutions and 3 airflow velocities. The choices of parameters described form 54 variants in total. The wind tunnel test arrangement is documented in figure 2.

The final results include the following aerodynamic derivatives: 1) Pitch force due to pitch angle ($c_{z\Theta}$) and yaw force due to yaw angle ($-c_{y\Psi}$), 2) Pitch moment due to pitch angle ($c_{m\Theta}$) and yaw moment due to yaw angle ($c_{n\Psi}$), 3) Pitch force due to yaw angle ($c_{z\Psi}$) and yaw force due to pitch angle ($c_{y\Theta}$) and 4) Pitch moment due to yaw angle ($c_{m\Psi}$) and yaw moment due to pitch angle ($-c_{n\Theta}$).

As an example, $c_{m\Theta}$ and $c_{m\Psi}$ derivatives are presented in figure 3. The curves represent the measured variants in terms of the propeller revolutions (windmilling, 3600 rpm and 4200 rpm) and the blades' angle of attack (5 and 10 deg.).

Figure 4 demonstrate the evaluation of derivatives using the slopes of the pitch or yaw moment coefficients. The presented curves represent the blade angle of attack of 5 and 10 deg. and the states of front and rear hinge station and the pitch and yaw degree-of-freedom active (FP, RP, FY, RY).

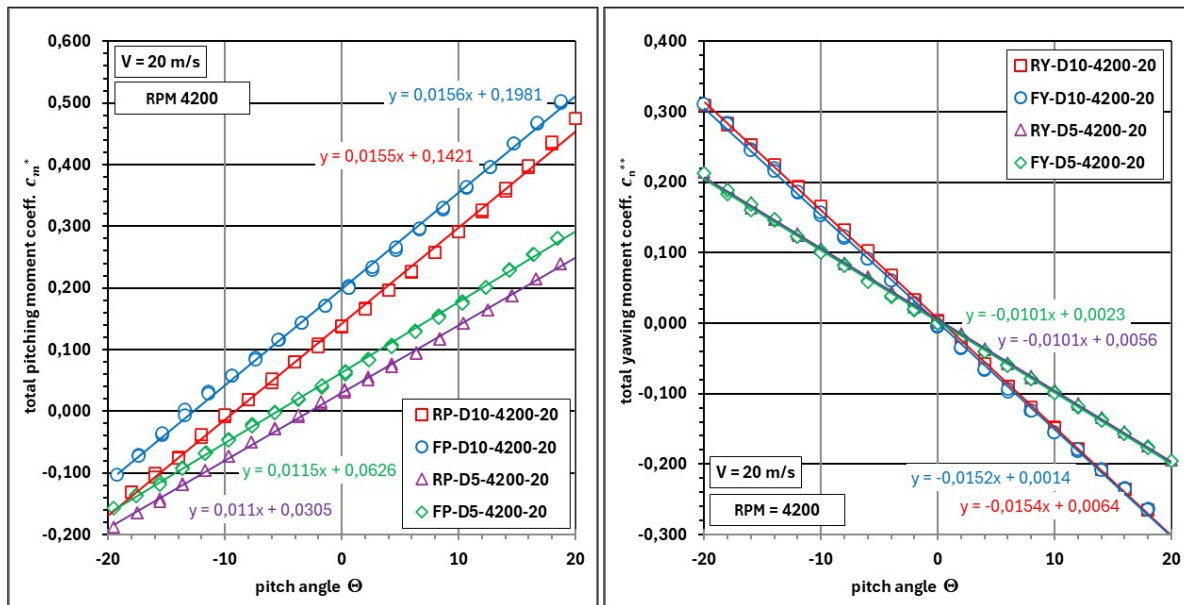


Fig. 4: Measured total pitching (a) and yawing (b) moment coefficient over pitch angle.

5. Conclusion

The paper deals with the experimental assessment of a propeller aerodynamic derivatives. A broad testing campaign in the 3m-diameter wind tunnel was accomplished. In general, the test results are in accordance with the expectations. In the future, the experimental results will be compared to the analytical results given by various analytical models and computational tools, and the experimental data will be utilised for verification and update of these tools.

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