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MECHANICAL CONCEPT OF WHIRL FLUTTER AEROELASTIC DEMONSTRATOR

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Abstract: *This paper deals with the design of the whirl flutter aeroelastic demonstrator. It gives a theoretical background of the whirl flutter phenomenon. The main part is focused on the new aeroelastic demonstrator "W-WING", designed at the VZLU. The demonstrator represents wing and engine nacelle of a twin turboprop commuter aircraft. It enables changes of the main structural parameters influencing whirl flutter stability characteristics. Moreover, it includes thrusting propeller. The demonstrator is intended for experimental investigations at the VZLU 3m-diameter low-speed wind tunnel. The results will be used for validation of analytical methods and software tools as well as in the frame of research projects.*

Keywords: Aeroelasticity, Whirl Flutter, Aeroelastic experiment, W-WING 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 (propeller or gas turbine engine rotor). Rotating mass generates additional forces and moments and increases the number of degrees-of-freedom. Rotating propeller also causes aerodynamic interference effect with a nacelle and a wing. Whirl flutter instability 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.

The complicated physical principle of the whirl flutter requires the experimental validation of the analytically gained results, especially due to the unreliable analytical solution of the propeller aerodynamic forces. Further, a structural damping is a key parameter, to which whirl flutter is extremely sensitive and which needs to be validated. Therefore, the aeroelastic models are used. This paper takes up the previous work on the subject by authors (Čečrdle & Maleček, 2010) and summarizes the new achievements in the aeroelastic demonstrator development process.

2. Theoretical Background

The principle of whirl flutter phenomenon is described on the simple mechanical system with two degrees-of-freedom, where an engine flexible mounting is represented by two rotational springs (stiffness $\boldsymbol{K_\Psi}$, $\boldsymbol{K_\Theta}$), while a propeller is considered rigid (see figure 1). This system has two independent mode shapes (yaw and pitch) with angular frequencies $\boldsymbol{\omega_\Psi}$ and $\boldsymbol{\omega_\Theta}$. Considering a propeller rotation with the angular velocity $\boldsymbol{\Omega}$, the gyroscopic effect causes both independent mode shapes merge into the whirl motion. A propeller axis shows an elliptical movement with a trajectory dependent on both angular frequencies $\boldsymbol{\omega_\Psi}$ and $\boldsymbol{\omega_\Theta}$. The orientation of the gyroscopic movement 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 changes of the propeller blades' angles of attack. It causes generating of unsteady aerodynamic forces, which may under specific conditions induce whirl flutter

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instability. The critical flutter state is defined as the neutral stability with no damping of the system and the corresponding air velocity ($\boldsymbol{V_\infty = V_{FL}}$) is called critical flutter speed. If the air velocity is lower than flutter speed ($\boldsymbol{V_\infty < V_{FL}}$), the system is stable and the gyroscopic motion is damped. If the airspeed exceeds the flutter speed ($\boldsymbol{V_\infty > V_{FL}}$), the system becomes unstable and gyroscopic motion divergent.

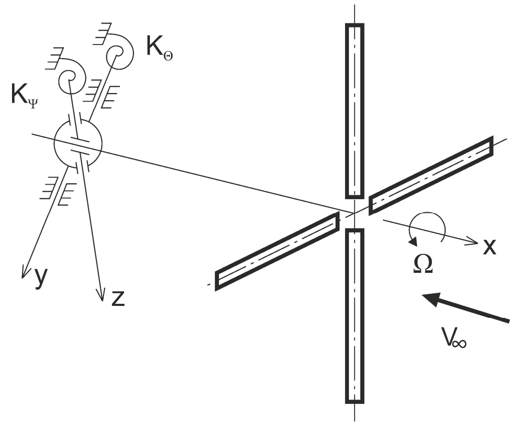

Fig. 1: Gyroscopic system with propeller

The analytical solution is focused on a determination of the aerodynamic forces caused by the gyroscopic motion on each of propeller blades. Presented equations of motion were derived for the gyroscopic system shown in figure 1 using Lagrange's approach. The kinematical scheme is shown in figure 2. Three angles ($\boldsymbol{\varphi}$, $\boldsymbol{\Theta}$, $\boldsymbol{\Psi}$) are independent generalised coordinates, the propeller angular velocity is constant ($\boldsymbol{\varphi = \Omega\, t}$). The rotating part is assumed cyclically symmetric with respect to both mass and aerodynamics. Non-uniform mass moments of inertia of an engine with respect to pitch and yaw axes ($\boldsymbol{J_Z \neq J_Y}$) are considered. Considering small angles, the equations of motion become:

$$
\begin{aligned}
J_Y\ddot{\Theta} + \frac{K_\Theta\gamma_\Theta}{\omega}\dot{\Theta} + J_X\Omega\dot{\Psi} + K_\Theta\Theta &= M_{Y,P} - a.P_Z \\
J_Z\ddot{\Psi} + \frac{K_\Psi\gamma_\Psi}{\omega}\dot{\Psi} - J_X\Omega\dot{\Theta} + K_\Psi\Psi &= M_{Z,P} + a.P_Y
\end{aligned}
\tag{1}
$$

Propeller aerodynamic forces are determined using aerodynamic derivatives (Ribner, 1945; Houbolt & Reed, 1962). Seeking for the critical (flutter) state assuming the harmonic motion has a character of an eigenvalue problem. The whirl flutter matrix equation then has a following form:

$$
\left(-\omega^2[M] + j\omega\left([D] + [G] + q_\infty F_P \frac{D_P^2}{V_\infty}\left[D^A\right]\right) + \left([K] + q_\infty F_P D_P\left[K^A\right]\right)\right)\begin{bmatrix}\overline{\Theta} \\ \overline{\Psi}\end{bmatrix} = \{0\} \tag{2}
$$

The critical state emerges when the angular velocity $\boldsymbol{\omega}$ is real. The critical state can be reached by increasing either $\boldsymbol{V_\infty}$ or $\boldsymbol{\Omega}$. The increase of the propeller advance ratio ($\boldsymbol{V_\infty / (\Omega R)}$) has destabilizing effect. Structural damping is a significant stabilization factor. On the contrary, the influence of the propeller thrust is negligible. The most critical state is $\boldsymbol{\omega_\Theta = \omega_\Psi}$, when the trajectory of the gyroscopic motion is circular. Considering the rigid propeller blades, the whirl flutter inherently appears at the backward gyroscopic mode.

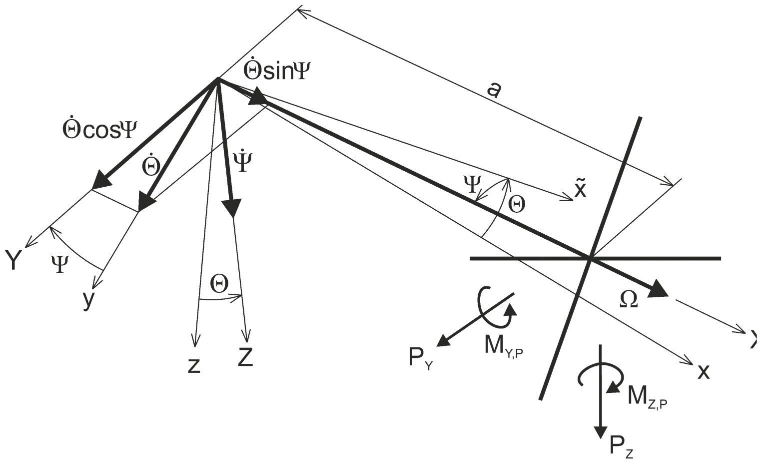

Fig. 2: Kinematical scheme of gyroscopic system

The described model with a rigid propeller is applicable to conventional propellers, for which the propeller blade frequencies are much higher compared to the nacelle pitch and yaw frequencies. In case of the large multi-bladed propellers of heavy turboprop aircraft, the consideration of a rigid propeller appears too conservative and the blade flexibility must also be modelled.

3. Experimental Research on Whirl Flutter

The first experimental investigations of whirl flutter characteristics were accomplished by Houbolt & Reed (1962) on the simple model of a propeller in the windmilling mode. Further investigations were conducted by Bland & Bennet (1963), who measured the propeller forces and stability of the propeller-nacelle component model. The comparison of the experimental results with theory demonstrated that the theoretical aerodynamic derivatives underestimate the whirl flutter speed. Another broad experimental campaign was conducted following the accidents of two L-188C Electra II airliners in the frame of the accident cause investigation (Abbott, Kelly & Hampton, 1963).

4. W-WING Whirl Flutter Aeroelastic Demonstrator

"W-WING" (Whirl-Wing) is the new whirl flutter demonstrator designed and developed by the Aeronautical Research and Test Institute (VZLU), Prague, Czech Republic. The demonstrator was adapted from the former aeroelastic model of the L-610 commuter aircraft, which was used for assessment of the flutter and the aeroelastic dynamic response issues during the development of the aircraft. The starboard wing including the nacelle was later utilised as the research demonstrator.

The wing with span of 2.56 m is fixed at the root to the pylon and attached in a wind tunnel. The wing structure is modular. The wing stiffness is modelled by the duralumin spar with the variable H-cross-section; the aileron stiffness is modelled by the spar with a variable rectangular cross-section. The inertial characteristics are modelled by lead weights. The aerodynamic shape is covered by the modular balsa and plastic foil segments.

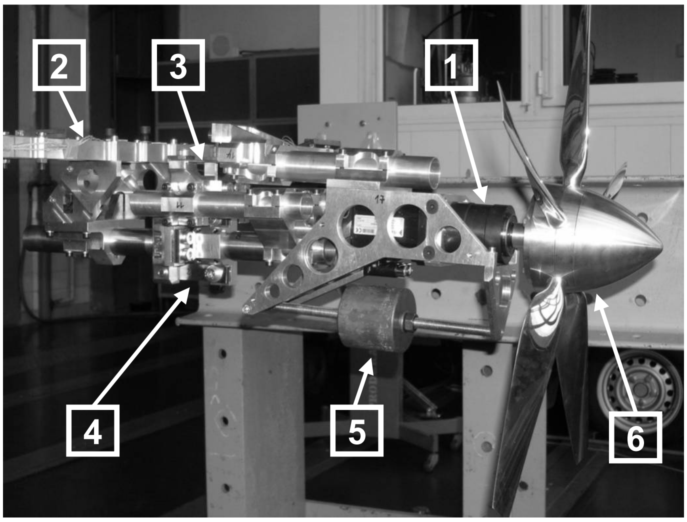

Fig. 3: W-WING demonstrator uncoated nacelle with motor and propeller (1 - motor; 2 - wing spar; 3 - pitch attachment; 4 - yaw attachment; 5 - massbalancing weight; 6 - propeller)

The nacelle structure is replaceable. The W-WING demonstrator represents the new nacelle structure (it does not represent any specific type of aircraft). The demonstrator is capable of simulating changes of all the important parameters influencing the whirl flutter. The nacelle model has two degrees of freedom - engine pitch and yaw. The stiffness parameters in both pitch and yaw are modelled by means of cross spring pivots with changeable spring leaves (stiffness constants are independently adjustable by replacing these spring leaves). Both pivots can be independently moved in the direction of the propeller axis within the range of 0.15 m to adjust the pivot points of both vibration modes. The centre of the gravity of the nacelle can be adjusted by means of the movable balance weight with a nominal mass of 4.22 kg. The plastic nacelle cowling is manufactured using the 3D print technology. The gyroscopic effect of the rotating mass is simulated by the mass of the propeller blades. Two sets of blades made of duralumin and steel are available. The propeller diameter is 0.7 m. It represents a geometrically scaled-down real 5-blade Avia V-518 propeller. The propeller blades' angle of attack is adjustable at the standstill by means of the special tool.

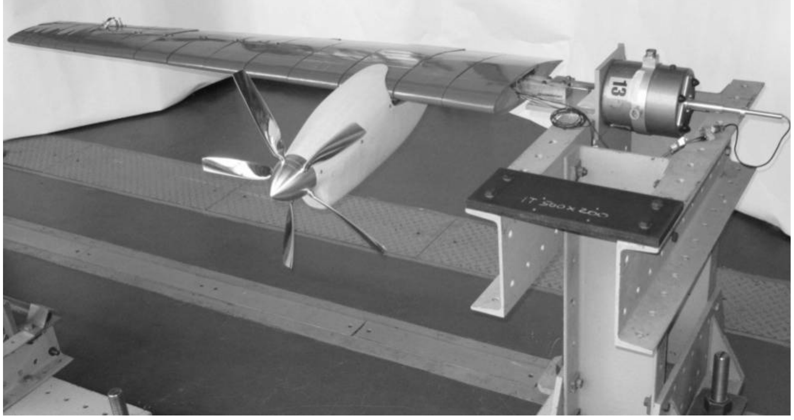

Fig. 4: W-WING demonstrator

Contrary to the most of former experimental applications, the W-WING demonstrator’s propeller is powered by an electric motor. Its nominal power is 597 W and nominal revolutions are 3000 rpm. Although the propeller thrust influence on the whirl flutter stability is low, the powered propeller solution was chosen to obtain wider options in the combination of the wind-flow velocity and the propeller revolutions. The demonstrator may be excited either by the wind flow turbulence or aerodynamically by means of the aileron deflection using various excitation signals (harmonic, swept sine, impulse). The system is controlled by the special in-house SW tool prepared in the LabVIEW v2012 environment. It provides acquisition of measured quantities from the strain gauges, accelerometers and the propulsion system, and also the safeguard preventing the destruction of the demonstrator by turning off the motor and the aerodynamic excitation, provided the response is exceeding the preselected limits.

5. Conclusion and Outlook

The paper deals with the mechanical concept of the new aeroelastic demonstrator for whirl flutter simulation (W-WING). The demonstrator represents wing and engine with the thrusting propeller of a turboprop commuter aircraft. The demonstrator's concept allows adjusting of all main parameters influencing whirl flutter. The W-WING demonstrator underwent the functionality tests and tests of the structural parameters. A broad testing campaign in the VZLU 3m-diameter wind tunnel is planned. The test schedule includes the measurement up to wind flow velocity of 45 $m \cdot s^{-1}$. In the first phase of testing, the influence of pitch and yaw stiffness and mass balance weight station will be primarily evaluated. The second phase will be focused mainly on the influence of the different sets of propeller blades (gyroscopic effect) and their angle of attack. The experimental results will be subsequently utilized for verification of the analytical methods and tools used for the certification of turboprop aircraft.

In parallel with the demonstrator hardware, the analytical model for FE flutter calculations was prepared. The model was used for preliminary analytical studies. First, the parametric calculations using optimization-based approach (Čečrdle, 2012) to find the stability margins and to predict the flutter behaviour of the system during the wind tunnel tests were performed. The stations of both hinges and balance weight were kept at the centre of their ranges, while both vertical and lateral stiffness as well as the propeller revolutions became parameters. The example of results is shown in the figure 5. It shows the stability margin (expressed in terms of required stiffness for the neutral stability) for a fixed propeller revolutions and variable wind flow velocity. Next, the influence of both engine attachment hinge points as well as balance weight stations was evaluated.

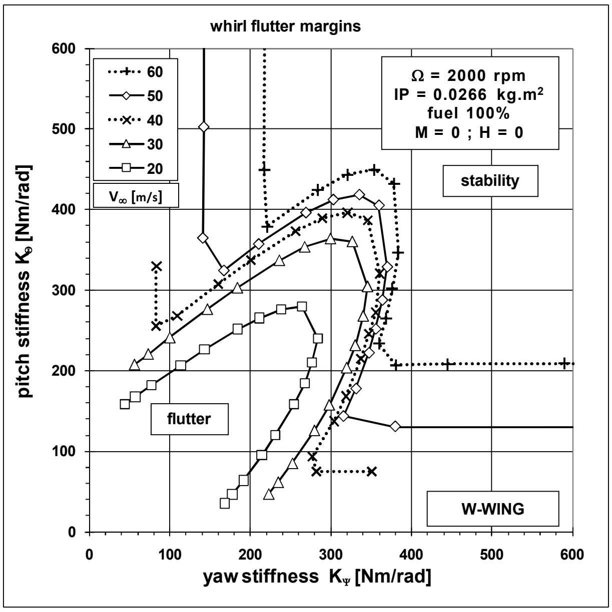

Fig. 5: W-WING analytical results example - required stiffness for neutral stability

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