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NEW DESIGN AND UPGRADE OF WHIRL FLUTTER AEROELASTIC DEMONSTRATOR

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Abstract: *W-WING is aeroelastic demonstrator representing a half-wing with the nacelle, engine, and propeller. It was adapted from the former aeroelastic model of a commuter aircraft. The demonstrator is used for the experimental research of whirl flutter aeroelastic phenomenon. Two experimental campaigns were accomplished in the frame of the previous project. Currently, the demonstrator is intended for further experiments in the frame of the OFELIA project. For this purpose, the modification of the demonstrator design and other upgrades were proposed. Submitted paper describes the preparatory activities including the demonstrator design, instrumentation, and aerodynamic and structural analyses. Gained experimental results will be subsequently utilized for verification of the analytical models and computational tools that will be used for development of the new power plant system, characterized as an open-fan concept, utilized for a new generation short-medium range turboprop aircraft.*

Keywords: Flutter, whirl flutter, W-WING, OFELIA project.

1. Introduction

Whirl flutter is a specific type of aeroelastic flutter instability, discovered by Taylor and Browne (1938), which may appear on turboprop aircraft due to the effect of rotating parts, such as a propeller or a gas turbine engine rotor. The complicated physical principle of whirl flutter requires experimental validation of the analytically results obtained, especially due to the unreliable analytical solution of the propeller aerodynamic forces. Further, structural damping is a key parameter, to which whirl flutter is extremely sensitive and which needs to be validated. Therefore, aeroelastic models are used. A comprehensive description of whirl flutter experimental research is provided by Čečrdle (2023). VZLU's previous experimental activities included aeroelastic wind tunnel testing in the frame of the Czech aircraft structures certification. Aeroelastic models, that were formerly used for certification purposes, are currently often rebuilt, and utilized as research demonstrators for research of novel concepts, systems, methods, etc. The developed research demonstrator represents the half-wing and engine with a powered rotating propeller of a typical commuter turboprop aircraft structure.

2. W-WING whirl flutter aeroelastic demonstrator

Whirl flutter aeroelastic demonstrator (W-WING) was adapted from a half-wing with a span of 2.56 m with the engine of a former aeroelastic model of the commuter aircraft for 40 passengers. The total mass of the model is approximately 55 kg. The demonstrator was used for whirl flutter wind tunnel measurements in the frame of the previous project. Currently, the demonstrator is intended for further experiments in the frame of the OFELIA project. Based on the experience from the past activities, design modifications

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and further upgrades of the demonstrator were proposed. The main change is the installation of the new motor with the sufficient power. Also, additional sensors and equipment are installed. In addition, the system of steady and unsteady flow field measurement was proposed for the dynamic response measurements. The baseline (i.e., unmodified) variant of the demonstrator is shown in Fig. 1. The wing and aileron stiffness is modeled by a duralumin spar of variable cross-section. The inertia characteristics are modeled by lead weights. The aileron is actuated by the electromagnetic shaker placed at the wing root via a push-pull rod.

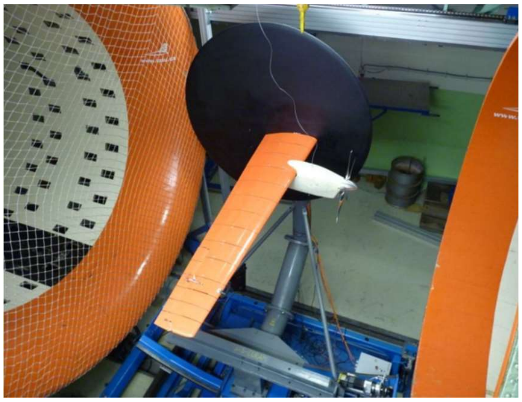

Fig. 1: W-WING baseline (unmodified) state.

The nacelle model has two DOFs (engine pitch and yaw). The stiffness parameters are modeled by means of cross-spring pivots. The leaf springs are changeable, and the stiffness parameters can be adjusted independently by replacing the spring leaves. Both pivots are independently movable in the direction of the propeller axis to adjust the pivot points of both vibration modes. The inertia of the engine is modeled by the replaceable and movable weight. The gyroscopic effect of the rotating mass is simulated by the mass of the propeller blades. Currently, two sets of blades made of duralumin and steel are available.

3. Propeller aerodynamic force analysis and motor selection

The most important modification is the installation of the new motor. The formerly used motor was selected assuming the propeller operation near the zero-thrust condition. Therefore, the required power was relatively low. Obviously, the operational slot for a specific blade angle of attack was limited in terms of the airflow velocity range. However, during the past tests, this range was found as too narrow and such an operation was found as ineffective. To avoid this practice, demonstrator was equipped with the new power plant system with the sufficient power to operate without limitations (as much as possible) in terms of the airflow velocities and propeller revolutions. New power plant enables to provide the test with real thrusted propeller using the fixed rpm thrusted mode of the propeller rotation. Using this approach, the evaluation of the thrust influence on the whirl flutter stability is applicable, contrary to the usage of the windmilling propeller as was typical practice in the past.

In order to predict the necessary power of the motor and operational margins of the propeller in terms of the revolutions and airflow velocities, the analytical study of the propeller aerodynamic forces was performed. The analyses were aimed at determining the areas of the propeller operation modes, i.e., thrust, reversal, zero-thrust and generator. The analyses were based on the CFD solver of the full NS equations for a viscous compressible flow based on the finite volume method. The rotating domain of 1/5 cylinder with the periodic condition was used. Solution included fully parallelized K-ω SST turbulence model with variable CFL. The example of results representing the required power vs. advance ratio is shown in Fig. 2.

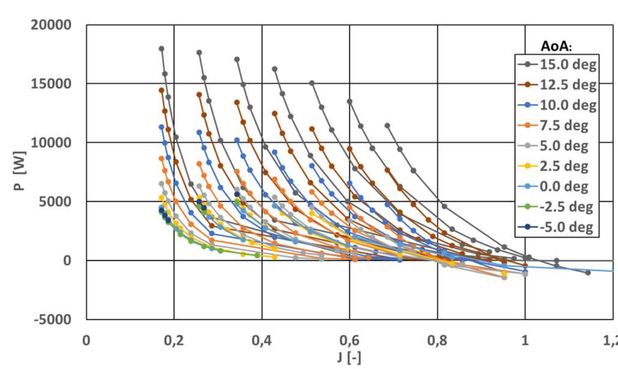

Fig. 2: Propeller power vs. advance ratio state.

Based on the results of analyses, and on further limitations (mass, dimensions, etc.), the selection of the appropriate motor has been done. The expected available operational power is 10–11 kW. This selection was the technical compromise with respect to obtain the maximal power and to keep the acceptable mass and dimensions.

4. New Demonstrator Nacelle Design

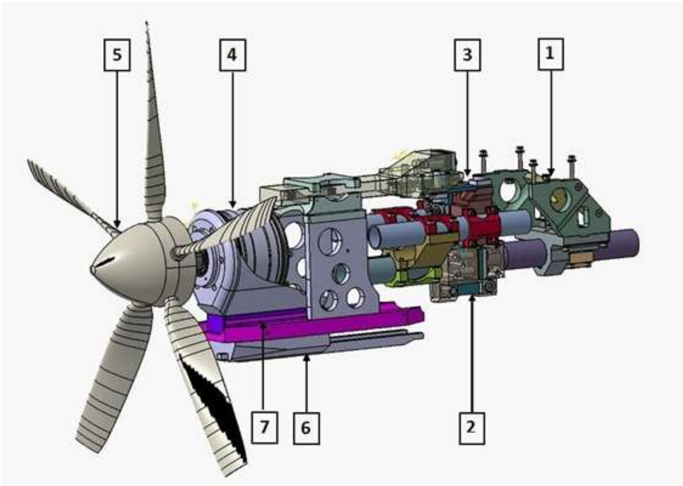

Fig. 3: Uncovered nacelle: (1) Wing mounting, (2) Yaw attachment, (3) Pitch attachment, (4) Motor, (5) Propeller, (6) Movable weight, (7) Thrust measurement cell.

The nacelle underwent an extensive redesign, particularly in the front part, while preserving the external contour of the fairing. The connection between the motor and the propeller was redesigned, and the motor was replaced by the more powerful, water-cooled, and larger one. Space was allocated for a load cell between the new motor console and the rest of the structure. A new thrust metering load cell was designed for this allocated space and the required range. The solution of the sliding weight compensating for the displacements of cross springs was reworked. The root part of the nacelle was reinforced. Fig. 3 shows the design model of the new nacelle with the description of the main parts while Fig. 4 shows the covered nacelle.

5. Strength Checks

The appropriate strength checks of the newly designed structure using FEM were performed. Calculations included:

1) Propeller blade attachment and propeller (shaft) strength check with respect to the propeller aerodynamic forces and centrifugal forces. Calculations included front and rear part of the propeller boss and the propeller blade mounting.
2) Propeller blade modal analysis. The purpose was to evidence the “rigidity” of the blade.
3) Thrust measurement cell analysis. Analyses included several load cases.
4) Stress analyses of cross-spring pivots and other parts of the assembly. Applied load included aerodynamic load generated by the propeller and the weight load. Analyses included all variants of cross-spring pivots (pitch and yaw). Static deformation of the assembly is compensated by means of special wedge-shaped washers placed under the leaves of the pitch spring attachment. Each set of leaves has the specific set of washers. This compensation eliminates static deformation theoretically to zero, in practice, some small deformation remains.

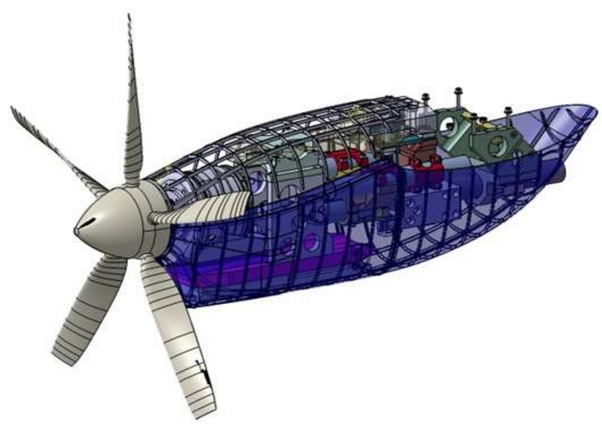

Fig. 4: Covered nacelle.

6. Demonstrator instrumentation

Propeller is powered by the motor with servo amplifier to manage and evaluate propeller revolutions, torque, and immediate power. In addition, independent (optical) rpm sensor is installed. Finally, balance cell for measurement of the propeller thrust is installed.

Demonstrator is equipped with the system of aerodynamic excitation by aileron flapping deflection. Various excitation signals (harmonic, sweep, impulse) are available. Aileron is actuated via push-pull rod using an electromagnetic shaker (and amplifier) placed behind the splitter plate. Push-pull rod is instrumented by the deflection sensor for evaluation of aileron angular deflection and as safety guard to prevent damage of shaker and rod.

Mechanical instrumentation includes strain gauges in the root and half-span sections to measure the vertical bending, in-plane bending, and torsional deformations. Demonstrator is also equipped with 18 uniaxial accelerometers. Wing is instrumented at six spanwise sections and two positions chordwise for the vertical direction and at a single position in the wingtip for the in-plane (longitudinal) direction. Nacelle is instrumented in two sections (front and rear) for both vertical and horizontal directions and at the front section also for the longitudinal direction.

The data acquisition and processing are provided using in-house LabVIEW-based application. The application is also used to control the propeller rotation (constant or controlled rate ramp) and to manage the aerodynamic excitation by the aileron flapping (harmonic constant, harmonic sweep, impulse). The same application is also used for the calibration of sensors. Finally, the application provides a safeguard preventing the destruction of the demonstrator, provided the response at the critical points exceeds the preselected threshold, by turning off the propeller motor, the wind tunnel fan and, provided used, turning off the aerodynamic excitation by the aileron. The data acquired by the program consist of "slow" data (at a sampling frequency of 2 Hz), which include propeller revolutions and airflow velocity, and real-time data from the strain-gauges and selected accelerometers (2 000 Hz sampling frequency) depicted in the time domain as well as pre-processed into the form of the power spectral densities. The program also provides the immediate power and propeller revolutions signal from which the torque of the propeller is evaluated. Apart from the described application, the LMS TestLab system is used. The system acquires the continuous signals from all accelerometers and the airflow velocity signal. The amplitude evolution of the frequency components corresponding to the engine whirl motion are monitored in real-time. The data are then used for the assessment of the demonstrator vibration response using the methods of FFT and OMA.

Independently of the described measurement systems, the aerodynamic flow field measurement is provided. It gives pressure and velocity data on several points of the flow field. Acquisition will be done one location at a time. Sensors include Aeroprobe, L-shaped five-hole fast response 1kHz and Wire probe for CTA Dantec Streamline anemometer. The grid of measurement points for the steady aero measurement includes 15 points while the grid of measurement points for the unsteady aero measurement includes 17 points in total in four quadrants.

7. Conclusion and Outlook

The paper describes the mechanical concept and preparatory activities related to the aeroelastic demonstrator for experimental investigation into whirl flutter phenomenon. The demonstrator's concept allows adjusting of all main parameters influencing whirl flutter. A broad testing campaign in the VZLU 3 m-diameter wind tunnel is planned. The test schedule includes dynamic response and whirl flutter stability mechanical measurements and aerodynamic flow field measurements. The experimental results will be subsequently utilized for verification of the analytical models and computational tools (Dugeai et al., 2011) that will be used for development of the new power plant system, characterized as an open-fan concept, utilized for a new generation short-medium range turboprop aircraft.

Acknowledgement

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