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# Conceptual Design of Aeroelastic Demonstrator for Whirl Flutter Simulation

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***Abstract*—This paper deals with the conceptual design of the new aeroelastic demonstrator for the whirl flutter simulation. The paper gives a theoretical background of the whirl flutter phenomenon and describes the events of the whirl flutter occurrence in the aerospace practice. The second part is focused on the experimental research of the whirl flutter on aeroelastic similar models. Finally the concept of the new aeroelastic demonstrator is described. The demonstrator represents the wing and engine of the twin turboprop commuter aircraft including a driven propeller. It allows the changes of the main structural parameters influencing the whirl flutter stability characteristics. It is intended for the experimental investigation of the whirl flutter in the wind tunnel. The results will be utilized for validation of analytical methods and software tools.

***Keywords*—aeroelasticity, flutter, whirl flutter, W-WING demonstrator

## I. Introduction

Aircraft structures are required to have a reliability certificate including the flutter stability. Flutter is a dynamic aeroelastic phenomenon occurring due to interaction of unsteady aerodynamic, inertial and elastic forces emerging during relative movement of the air and a flexible aircraft. The turboprop aircraft are required to be certified also considering the whirl flutter. The whirl flutter (also called gyroscopic flutter) is the specific case of flutter which includes additional dynamic and aerodynamic influences of the engine rotating parts. Rotating parts like a propeller or a turbine increase the number of degrees of freedom and cause additional forces and moments. Moreover rotating propeller causes a complicated flow field and interference effects between wing, nacelle and propeller. The essential fact is an unsymmetric distribution of forces on a transversely vibrating propeller. Whirl flutter may cause a propeller mounting unstable vibrations, even a failure of an engine, nacelle or whole wing. It has been the cause of a number of accidents.

## II. Theoretical Background

Engine flexible mounting is represented by two rotational springs (stiffness $\boldsymbol{K_\Psi}$, $\boldsymbol{K_\Theta}$) as illustrated in the fig.1. Propeller is considered as rigid, rotating with angular velocity $\boldsymbol{\Omega}$. System is exposed to the airflow of velocity $\boldsymbol{V_\infty}$.

Neglecting propeller rotation and the aerodynamic forces, the two independent mode shapes will emerge with angular frequencies $\boldsymbol{\omega_\Psi}$ and $\boldsymbol{\omega_\Theta}$.

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Considering the propeller rotation, the primary system motion changes to the characteristic gyroscopic motion. The gyroscopic effect makes two independent mode shapes merge to whirl motion. The propeller axis shows an elliptical movement. The orientation of the propeller axis movement is backward relative to the propeller rotation for the mode with lower frequency (backward whirl mode) and forward relatively to the propeller rotation for the mode with higher frequency (forward whirl mode). The mode shapes of gyroscopic modes are complex, since independent yaw and pitch modes have a phase shift 90°.

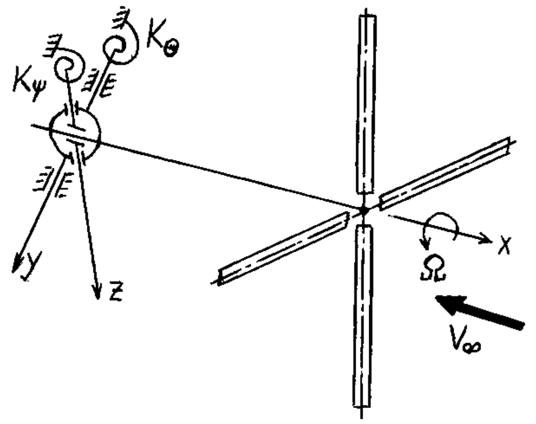
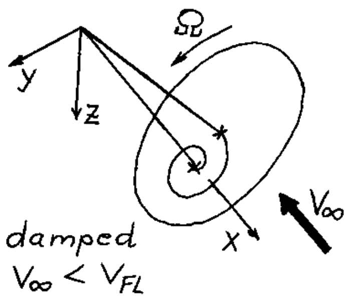


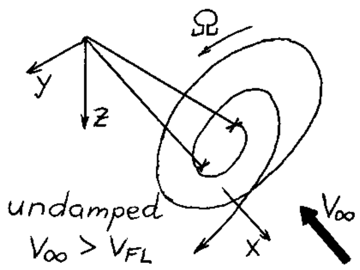

Fig. 1 Gyroscopic system with propeller

The described gyroscopic mode shapes cause harmonic changes of propeller blades angles of attack. They give rise to unsteady aerodynamic forces, which may under the specific conditions induce a whirl flutter. Possible states of the gyroscopic system from the flutter stability point of view for backward mode are explained in the fig.2. Provided that the air velocity is lower than critical value ($V_\infty < V_{FL}$), the system is stable and the motion is damped. If the airspeed exceeds the critical value ($V_\infty > V_{FL}$), the system becomes unstable and motion is diverging. The limit state ($V_\infty = V_{FL}$) with no total damping is called critical flutter state and $V_{FL}$ is called critical flutter speed.

The basic problem of the analytical solution consists in the determination of the aerodynamic forces caused by the gyroscopic motion for the specific propeller blades. The equations of motion were set up for system described in the fig.1. The kinematical scheme including gyroscopic effects is shown in the fig.3. The independent generalized coordinates are three angles ($\boldsymbol{\varphi}$, $\boldsymbol{\Theta}$, $\boldsymbol{\Psi}$). We assume the propeller angular velocity constant ($\boldsymbol{\varphi} = \boldsymbol{\Omega t}$), mass distribution symmetric around X-axis and mass moments of inertia $\boldsymbol{J_Z} \neq \boldsymbol{J_Y}$.




(a)




(b)

Fig. 2 Stable (a) and unstable (b) state of gyroscopic vibrations for backward flutter mode

Considering the small angles simplification, the equations of motion become:

$$J_Y \ddot{\Theta} + \frac{K_\Theta \gamma_\Theta}{\omega} \dot{\Theta} + J_X \Omega \dot{\Psi} + K_\Theta \Theta = M_{Y,P} - a.P_Z$$
$$J_Z \ddot{\Psi} + \frac{K_\Psi \gamma_\Psi}{\omega} \dot{\Psi} - J_X \Omega \dot{\Theta} + K_\Psi \Psi = M_{Z,P} + a.P_y \qquad (1)$$

We formulate the propeller aerodynamic forces by means of the aerodynamic derivatives [1], [2] and make the simplification for the harmonic motion, then the final whirl flutter matrix equation will become:

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

The limit state emerges for the specific combination of parameters $\boldsymbol{V_\infty}$ and $\boldsymbol{\Omega}$, when the angular velocity ω is real. Increasing the propeller advance ratio $\boldsymbol{(V_\infty / (\Omega R))}$ requires an increase of the necessary stiffnesses $\boldsymbol{K_\Theta}$, $\boldsymbol{K_\Psi}$. Also influences of the structural damping and the distance propeller – mode shape node are significant.

The whirl flutter appears at the gyroscopic rotational vibrations, the flutter frequency is the same as the frequency of the backward gyroscopic mode. The critical state may be reached either due to increasing the air velocity or the propeller revolutions. Structural damping is a significant stabilization factor. On the contrary, the propeller thrust influence is barely noticeable. The most critical state is $\boldsymbol{K_\Theta = K_\Psi}$, it means $\boldsymbol{\omega_\Theta = \omega_\Psi}$ when the interaction of both independent motions is maximal. A special case of the eq.(2) for $\boldsymbol{\omega = 0}$ is the gyroscopic static divergence.

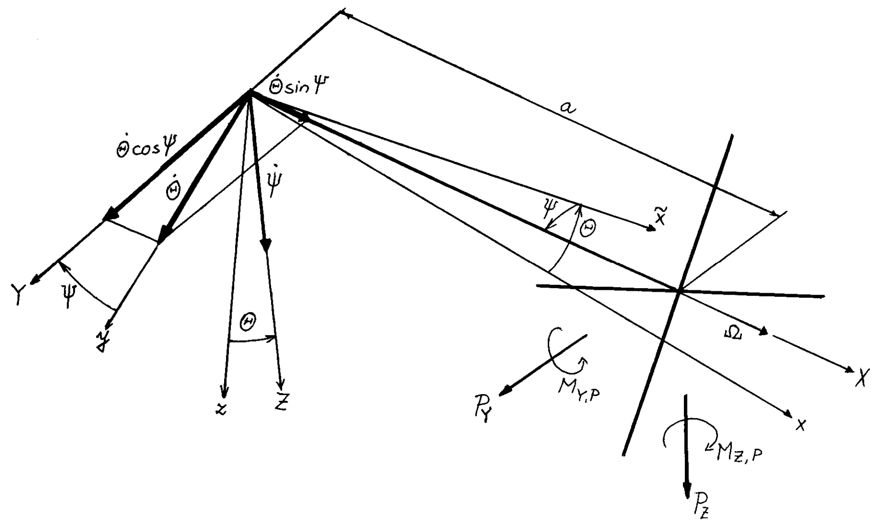



Fig. 3 Kinematical scheme of the gyroscopic system

## III. Whirl Flutter Occurrence in Aerospace Practice

The whirl flutter phenomenon is really serious and it was a cause of several aircraft accidents. The most famous are two crashes of 4-engine turboprop airliner *Lockheed L-188 C Electra II*. First one arose in September 1959 in Texas and the identical event emerged in Indiana only several months later in March 1960. There were killed all the people on board in both cases. The cause of both accidents was destruction of the wing due to forces of the undamped whirl mode of the outer engine. The direct reason was coupling of the propeller and rotor whirl mode with the wing mode. Due to the damage of the outer engine mounting, the whirl mode frequency become closely to the wing mode frequency and excited the wing mode with the destructive outcome. Follow on analyses and experiments with decreased engine mounting stiffness proven it. This phenomenon became famous as prop-whirl-flutter.

Well known is also event of twin turboprop commuter *Beech 190C* which crashed into ocean near the Block Island coastline in 1993 during training mission. The final cause which disproved the original one was investigated by Airline Pilots Association. The direct cause was destruction of the starboard wing caused by the whirl mode. The main contributing factor was decreasing of the engine mounting stiffness due to fatigue damage of the engine bed.

As was demonstrated, the whirl flutter should not be a problem for the undamaged structure. However the decreasing of the engine mounting stiffness due to any kind of defect might lead into the problem of flutter stability. The regulation requirements reflect this, e.g. *FAR 23 § 629 (e) (2)* demanding to include also the changes of the stiffness and damping parameters of the engine attachment into the certification analyses.

## IV. Experimental Research of Whirl Flutter

From the beginning of the whirl flutter research, it was necessary to validate the analytical results by means of the experiments. The main reasons were the complicated physical principle of the whirl flutter, high sensitivity of the whirl flutter stability to the structural damping and unreliability of analytically determined forces on the propeller.

First investigations were accomplished by Bland and Bennett [5]. They measured the propeller forces and stability of the propeller - nacelle component model. Flexibility of the propeller axis was variable in both pitching and yawing. Propeller rotated in the windmilling mode. Comparison of results with theory shown that usage of theoretical aerodynamic derivatives underestimates the flutter, the experimental derivatives gave much better agreement with the experimental flutter states. The used viscous model of structural damping was found as appropriate. The research of the tilt-rotor concept was performed by Reed and Bennett [6] who investigated the aerodynamic derivatives for the configuration with large inclination.

Also interesting are experiments on a simple model of a propeller in windmilling mode installed on a moving car. The stiffness of the propeller attachment was variable, also position of the vibration node point was adjustable.

Previously described applications used only simple models of the propeller and nacelle. More complex model of the aircraft half-wing with engine was tested in NASA Langley [9]. The model was designed as a typical aeroelastic model with duralumin spar and balsa segment structure. Model used four types of the engine suspension with different realization of the engine inertia and engine suspension stiffness.

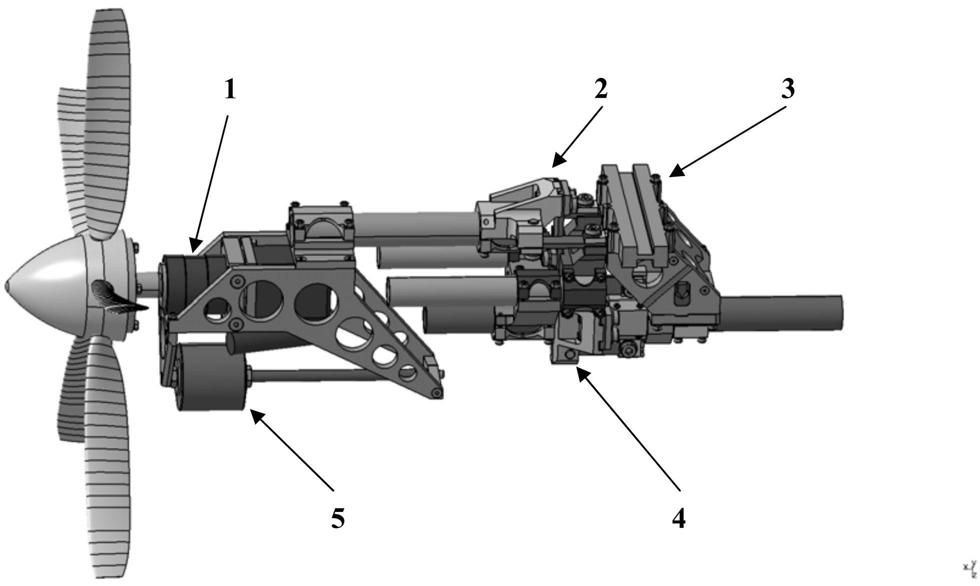



Fig. 4 W-WING nacelle design drawing (1 - motor and gearbox; 2 - pitching attachment; 3 - wing spar; 4 - yawing attachment; 5 - massbalancing weight)

The model did not represent any aircraft type, however the parameters were realistic. The model was used for investigation of the influence of the wing to the characteristics of the whirl flutter.

Further model, even more complicated one was tested in NASA Langley [8]. It represented 4-engine aircraft configuration, similar to the *L-188C Electra II* aircraft. Model was measured on a special suspension with 5 degrees of freedom. There was investigated, that the outer engines are less sensitive with respect to the whirl flutter then inner ones. In this case, the wing made a stabilization effect.

Summarizing the experiences from the experiments we can formulate following statements. Whirl flutter may appear only in the backward mode (see fig.2). Flutter frequency is closely to the frequency of the backward whirl mode without aerodynamic forces. Flutter state might be reached either by increasing the flow velocity or the propeller angular velocity. Structural damping is important influencing factor. On the contrary, the propeller thrust has only minor influence [7], thus the most of experiments used propeller in the windmilling mode. For the simple system of the propeller and nacelle is the most critical case when $K_\Psi = K_\Theta$, it means $\omega_\Psi = \omega_\Theta$ (see fig.1). The gyroscopic coupling is maximal, propeller axis moving trajectory is circular and coupled aerodynamic forces are maximal. This statement is changing when consider the influence of the wing, which causes additional unsteady aerodynamic forces. Increasing the distance of the propeller plane and the engine vibration node point has stabilizing effect. Increasing the air density is destabilizing due to increasing of the aerodynamic forces.

## V. Whirl Flutter Aeroelastic Demonstrator W-WING

VZLU was focused on the development and testing of the aircraft aeroelastic models in the past. Several aeroelastic models of the Czech aircraft were developed, manufactured and tested.

Nowadays, these models are frequently rebuilt and utilized as research demonstrators for the validation of new analytical methods, research of novel concepts or investigation of nontypical aeroelastic phenomena. The whirl flutter aeroelastic demonstrator was adapted from the former aeroelastic model of the L-610 Czech twin turboprop commuter for 40 passengers.

The aeroelastic model has a length scale of **1/5** and a velocity scale of **1/6**. The complete aircraft model was tested in TsAGI Zhukovskij in a **7 m** diameter wind tunnel. Wing / engine and tailplane / fin component models were tested in VZLU **3 m** diameter wind tunnel. The starboard wing / engine component model with a span of **2.56 m** was utilized for the research demonstrator. The wing stiffness was modeled via duralumin spar with the H-cross-section. The aileron stiffness was modeled by the duralumin spar with the rectangular cross-section. The wing was divided into **14** sections spanwise with the lead weights modeling the wing inertia; the aileron was divided into **6** sections spanwise. The aerodynamic shape of the wing was realized by means of a balsa and paper structure. Aileron and spoilers were controlled by means of hydraulic mini-cylinders. Aileron actuation stiffness was made variable by the use of replaceable spiral steel springs. The engine and nacelle part is replaceable. There are three options of the engine and nacelle: 1) nacelle with standard linear engine attachment (L-WING); 2) nacelle with non-linear engine component attachment (N-WING) and finally 3) special nacelle for the whirl flutter (W-WING), which is the subject of the presented paper.

W-WING demonstrator nacelle can be used either separately or can be attached to the mentioned wing. The model is suitable for measurements at the VZLU **3 m** diameter subsonic wind tunnel. The demonstrator do not represent any specific aircraft type, however the structural parameters are realistic with respect to the turboprop commuter aircraft structure.

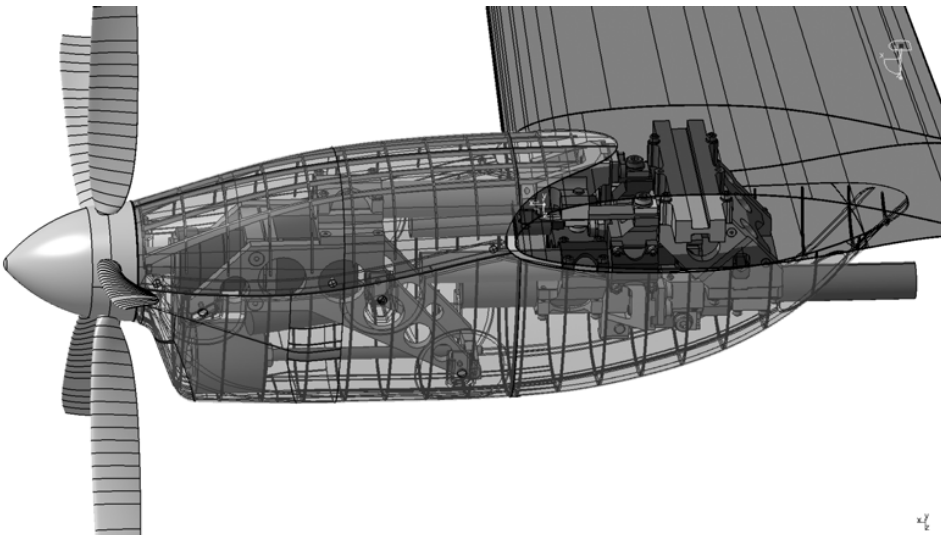


Fig. 5 W-WING nacelle integrated to wing

The demonstrator is capable to simulate changes of all important parameters influencing the whirl flutter. The stiffness parameters in both pitch and yaw are modeled by means of cross spring pivots. The spring leaves are changeable and both stiffness constants are adjustable independently by replacing of these spring leaves. Both pivots are movable independently in the propeller axis direction in order to adjust the node points of both vibration modes. The inertia of the engine is modeled by means of the weight, which is also movable to adjust the centre of gravity of the engine. Provided the nacelle is attached to the wing, it is also possible to adjust the wing dynamic characteristic using weights simulating the wing fuel.

The propeller driven by electro-motor is integrated into nacelle. The propeller represents the real 5-blade propeller *Avia V-512*. Propeller blades are adjustable at a standstill by means of the special tool. Several adjustment positions are available for specific flow velocity ranges. This ability decreases the required motor power and avoids stall states on propeller blades. The required motor power of **500 W** was calculated considering the flow velocity range up to **70 m.s$^{-1}$** and propeller nominal revolutions of **1100 min$^{-1}$**. With regard to the power, mass and dimensions, the servomotor *TGN3-0205-50-320/T1Y* and gearbox *SG 070-3 (T3,H3)* were chosen. Motor is equipped by the servo-amplifier *AKD-P00606-NAEC-E000* which allows to manage the propeller revolutions within the range of ± **25%** around nominal and provides the immediate power and propeller revolutions signal acquisition. From this, we can evaluate the torque moment which is the criterion for estimation of necessity to re-adjust the propeller blades.

The gyroscopic effect of the rotating mass of the engine and propeller is simulated by the mass of propeller blades. There are two sets of blades made of duralumin and steel at disposal. The nacelle coat was manufactured by means of the 3D printing technology. The design drawings of the W-WING nacelle and nacelle integrated into the wing are presented in fig.4 and 5.

## VI. Conclusion and Outlook

This paper deals with the conceptual design of the new aeroelastic demonstrator for the whirl flutter simulation (W-WING). The demonstrator represents wing and engine component of a turboprop commuter aircraft. The demonstrator is complex and unique. It is possible to adjust all main parameters influencing the whirl flutter. Experiments will be aimed to reach the critical states and to evaluate the influences of specific parameters. The purpose is experimental validation of the analytical methods and tools, which are used for the aircraft certification according regulation standards FAR / CS 23 and 25.

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