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Whirl flutter-related certification of turboprop aircraft

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Whirl flutter is aeroelastic flutter instability that may appear on turboprop aircraft. It is driven by motion-induced unsteady aerodynamic propeller forces and moments acting on the propeller plane and it may cause unstable vibration of a propeller mounting, leading to the failure of an engine installation or an entire wing. Therefore, airworthiness regulation standards include also requirements related to the whirl flutter; however, these requirements are specified just generally without any detailed description of the acceptable means and methodologies of compliance. This paper describes the methodology of compliance with the requirements of FAR / CS 23 and 25 regulation standards applicable for utility, commuter and for larger transport aircraft.

The principle of the whirl flutter phenomenon is outlined on a simple mechanical system with two degrees of freedom. A flexible engine mounting is represented by two rotational springs of stiffnesses K_Ψ and K_Θ, as illustrated in Fig. 1.

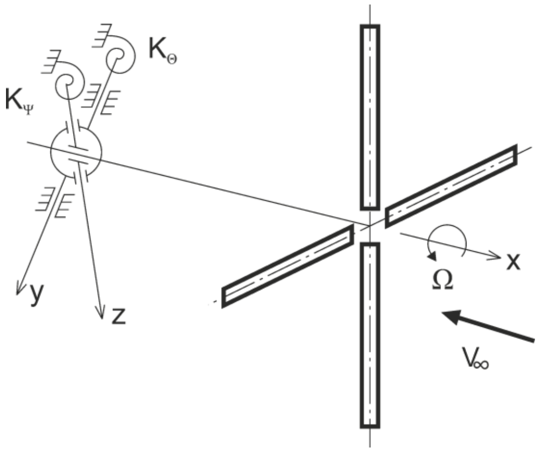


Fig. 1. Gyroscopic system with propeller

Such a system has two independent mode shapes (yaw and pitch) with angular frequencies ω_Ψ and ω_Θ. For a propeller rotation with angular velocity Ω, the gyroscopic effect causes both independent mode shapes to merge into a whirl motion. The axis of rotation of the propeller exhibits 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 changes in the propeller blades' angles of attack, consequently leading to unsteady aerodynamic forces. These forces may induce whirl flutter instability. The flutter state is defined as the neutrally stable state with no damping of the system, and the corresponding airflow ($V_\infty = V_{FL}$) is called the critical flutter speed. If the air velocity is lower than flutter speed ($V_\infty < V_{FL}$), the system is stable and the gyroscopic motion is damped

(Fig. 2a). If the airspeed exceeds the flutter speed ($V_{\infty} > V_{FL}$), the system becomes unstable, and the gyroscopic motion is divergent (Fig. 2b).

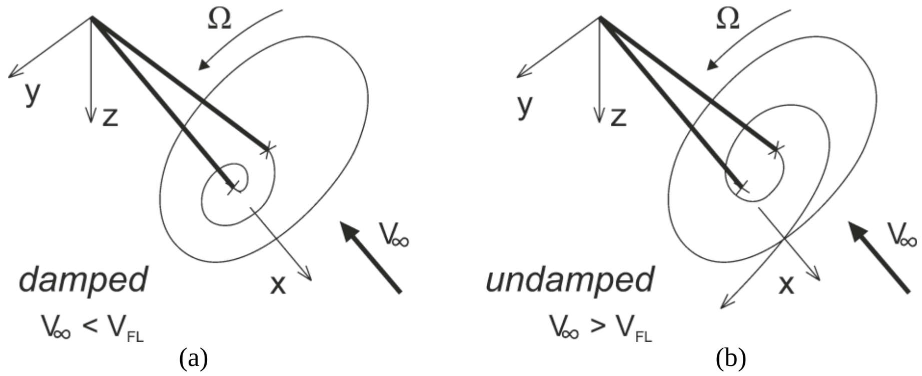
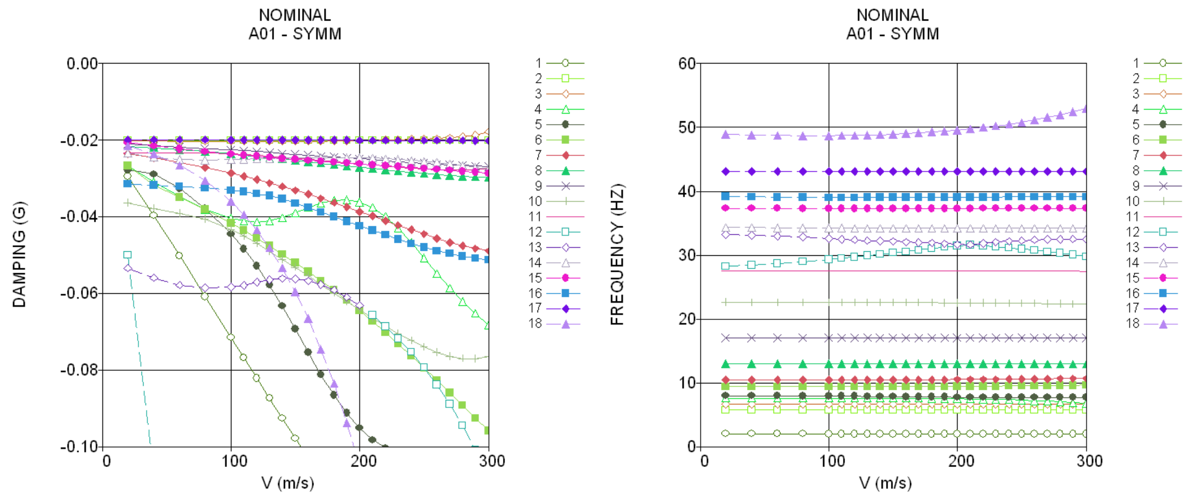


Fig. 2. Stable (a) and unstable (b) states of gyroscopic vibrations for the backward flutter mode

For whirl flutter analysis, two approaches may be employed: 1) Standard approach in which the input data are parameters of a structure and the outputs of the analysis are whirl flutter characteristics, i.e., V-g-f diagrams, and flutter speed and flutter frequency. The solution is performed for multiple velocities and the state with the zero damping represents the critical flutter state. 2) Optimisation-based approach employing gradient-based algorithms. In this case, the flutter speed is set as an input parameter (certification speed), and the results are critical values of structural parameters. This solution, which is performed only for a single velocity, enables to obtain the stability margin for the specified certification speed. The analysed states are then compared with respect to the stability margin only. Such an approach can save large amount of time because the number of analyses required by the regulations is dramatically reduced.

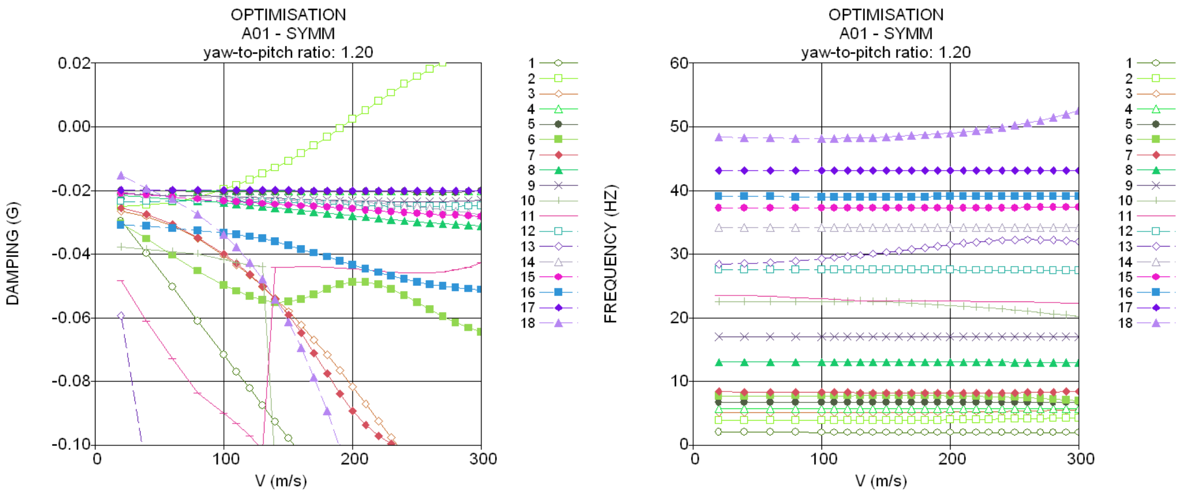
FAR / CS 23 represent the simpler category of standards, applicable to the smaller turboprop aircraft. The whirl flutter-related requirement included in §629(e) is applicable for all configurations of aircraft regardless the number and placement of engine(s). §629(e)(1) includes the main requirement to evidence the stability within the required V-H envelope, while §629(e)(2) requires the variation of structural parameters such as the stiffness and damping of the power plant attachment. The latter represents the influence of the variance of the power plant mount structural parameters when simulating the possible changes due to structural damage (e.g., deterioration of engine mount-isolators). Analysis must include all wing mass configurations, especially fuel load variation. Contrary to that the payload does not have a significant influence. Analyses are performed just for the certification altitude, which is the most critical with respect to both whirl flutter and the value of certification speed ($1.2{*}V_{DTAS}$). Inertia characteristics of rotating parts must be considered with respect to the directions of rotation of a particular part (generator, turbine, propeller), revolutions are usually normalised to a propeller revolutions. For the purpose of certification analysis, the most critical mode of the propeller and engine revolutions are considered, i.e. the mode that produce the maximal normalised moment of inertia of the rotating parts. To comply with the main requirement (§629(e)(1)), the nominal state analyses are performed. For this purpose, the standard approach is employed. Fig. 3 shows an example of a V-g-f diagram of such a calculation for a single mass configuration. No flutter instability is indicated up to the certification velocity (191.4 m/s), and therefore, the regulation requirement is fulfilled.

To comply with the parameter variation requirement (§629(e)(2)), parametric studies that may include huge numbers of analyses would be necessary and such an approach would become ineffective. Therefore, the analysis of stability margins using optimisation-based approach is good for this purpose. In this approach, the flutter speed is set equal to the certification speed, and the results are margin values of structural parameters. Fig. 4 shows an example of a V-g-f diagram of optimisation-based calculation in which flutter speed is equal to the certification velocity (191.4 m/s). Flutter mode (#2) is the engine pitch vibration mode.



(a) (b)

Fig. 3. Whirl flutter calculation (V-g-f) diagram, (a) damping, (b) frequency, nominal state



(a) (b)

Fig. 4. Whirl flutter calculation (V-g-f) diagram, (a) damping, (b) frequency, optimisation-based calculation

Calculations are performed for several values of the yaw-to-pitch frequency ratio to construct a stability margin curve with respect to the engine yaw and pitch vibration frequency. Stability margins are then constructed for all applicable mass configurations. The frequency-based margin may be then compared with the engine vibration frequencies, obtained by the GVT or analytically, to evaluate the rate of reserve as shown in Fig. 5. The dashed line represents the (+/-) 30% variance margin in engine attachment stiffness. Another parameter to be evaluated is the damping. This is provided using the calculation with very low structural damping, represented by the damping of g = 0.005, while the standard structural damping included in the analyses is g = 0.02. As obvious from Fig. 5, there is sufficient reserve in stability of the nominal state (including parameter variations) with respect to the stability margin, and therefore, the regulation requirements are fulfilled.

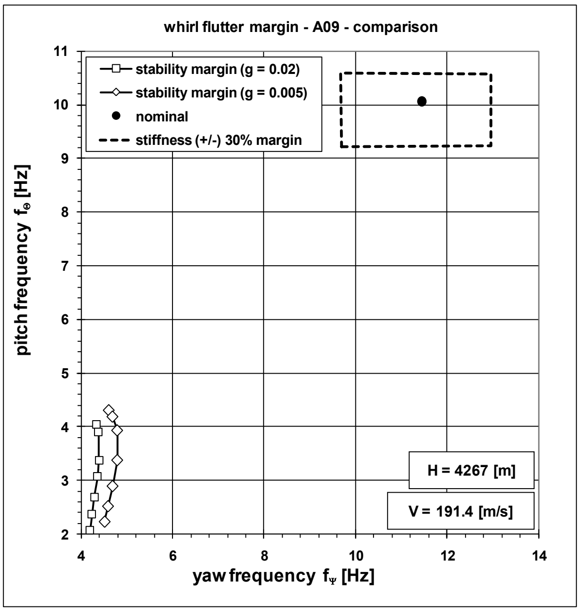


Fig. 5. Whirl flutter stability margin evaluation

FAR / CS 25 is the standard applicable to larger turboprops. In addition to the requirements similar to those of the previous case, some specific states of failure, malfunctions and adverse conditions are required to be analysed as well. These states are: 1) Critical fuel load conditions. This requirement includes the analysis of unsymmetrical conditions of the fuel loading that may come from the mismanagement of the fuel. In this case, fuel model is modified while the power plants model shows the nominal conditions. 2) Failure of any single element supporting any engine. This requirement includes in particular the failure of any single engine bed truss. The failure conditions are introduced into a single power plant mount system while other power plant mount systems use a nominal condition. All engines show the nominal condition. 3) Failure of any single element of the engine. This requirement includes, in particular, the failure of any single engine mount-isolator. The failure conditions are introduced into a single power plant mount system while other ones show nominal conditions. All engine mounts were used under nominal conditions. 4) Absence of aerodynamic and gyroscopic forces due to feathered propellers. The failure states defined in this section represent the states of a nonrotating engine and a nonrotating feathered propeller. The power plant system under such conditions generates no aerodynamic or gyroscopic forces. In addition, the single feathered propeller or rotating device failure must be coupled with the failures of the engine mount and the engine. 5) Any single propeller overspeed. The power plant system under such conditions generates maximal aerodynamic and gyroscopic forces. The condition of overspeed must include the highest likely overspeed of both engine and propeller. The state of overspeed is applied to any single propeller while the other ones are under the nominal conditions. 6) Other failure states coming from the damage-tolerance analysis, from bird strike damages and from damages of the control systems, the stability augmentation systems and other equipment systems and installations.

References

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