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STABILITY MARGINS EXPERIMENTAL SEARCH OF AN AEROELASTIC SYSTEM

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Abstract: *Aircraft developers and builders commonly design and produce potentially unstable aeroelastic systems. Detailed and reliable knowledge of real dynamic properties of the system has a crucial importance to safety requirements compliance. Dynamic stability margins of an aeroelastic system are identified analytically in the first step and finally verified experimentally. Dynamic response analysis of a real aeroelastic system under operational conditions represents key approach to the experimental study of the systems stability margins in a complex experimental verification process. Operational modal parameters in the form of modal frequencies, modal damping and mode shapes are identified on each stage of operational parameters combination series. Modal damping parameter evolution is of special interest during the testing. The paper presents a technique of combined approaches to the dynamic response analysis during wind tunnel dynamic stability margins testing of an aeroelastic demonstrator.*

Keywords: Aeroelastic system, Modal parameters, Dynamic response, Damping identification.

1. Introduction

Measured vibration response of an aeroelastic system contains valuable information on the dynamic stability of the system at actual operational conditions. Starting by linearity assumption of the mechanical system, it is reasonable to treat with a series of modal models of the system, related to a series of operational conditions states. Basic modal model describes specific aircraft type structure dynamic properties at laboratory conditions. Classical experimental technique Ground vibration test is a standard milestone of a prototype testing and provides the basic modal model suitable to enter in to the fine tuning process of a numerical model. Tuned numerical model then serves as a base for flutter clearance and other simulation of aircraft structural dynamics related phenomena: gust response, excitation due to failure of a rotating part. Operational modal analysis and other experimental dynamics techniques are at disposal to extract modal parameters of aeroelastic system under operational conditions. Parameters of operation are gradually varied according to a carefully designed experimental procedure. Vibration amplitude limit criterion is closely checked in real time to prevent catastrophic destruction of a tested system. Vibration responses are measured and recorded at defined operational parameters levels. Modal parameters, specially, modal damping of potentially unstable modes are then evaluated, to locate operational state of the system between stable – unstable. The paper presents a technique of combined approaches to dynamic response analysis, during wind tunnel stability margins testing of a whirl flutter aeroelastic demonstrator. Theoretical background sketch describes concepts of modal model, dynamic response and stability criteria. Concepts of interpretation set Σ and parameter space Π are explained. Potentially unstable mode detection and tracking in the process of variation of operational parameters are demonstrated on real vibration data measured during whirl flutter aeroelastic demonstrator wind tunnel testing campaign.

2. Mathematical model

We begin a brief theoretical review with standard mathematical model of linear structure in physical space or in the state space (Bold symbols denote matrices or vectors):

$$\boldsymbol{M}\ddot{\boldsymbol{q}}(t) + \boldsymbol{B}\dot{\boldsymbol{q}}(t) + \boldsymbol{K}\boldsymbol{q}(t) = \boldsymbol{F}(t),\ \begin{bmatrix} \mathbf{0} & \mathbf{M} \\ \mathbf{M} & \mathbf{B} \end{bmatrix}\begin{bmatrix} \ddot{\mathbf{q}} \\ \dot{\mathbf{q}} \end{bmatrix} + \begin{bmatrix} -\mathbf{M} & \mathbf{0} \\ \mathbf{0} & \mathbf{K} \end{bmatrix}\begin{bmatrix} \dot{\mathbf{q}} \\ \mathbf{q} \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \mathbf{F} \end{bmatrix} \qquad (1)$$

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Corresponding modal model consists of right side and left side modal matrices $\mathbf{U}_{(mxn)}$ and $\mathbf{W}_{(mxn)}$ and of spectral matrix $\boldsymbol{\Lambda}_{nxn}$, usually n≠m in the case of an experimentally identified model.

$$\mathbf{U} = \begin{bmatrix} \mathbf{u}\boldsymbol{\lambda} & \mathbf{u}^*\boldsymbol{\lambda}^* \\ \mathbf{u} & \mathbf{u}^* \end{bmatrix}, \quad \mathbf{W} = \begin{bmatrix} \mathbf{w}\boldsymbol{\lambda} & \mathbf{w}^*\boldsymbol{\lambda}^* \\ \mathbf{w} & \mathbf{w}^* \end{bmatrix}, \quad \boldsymbol{\Lambda} = \mathrm{diag}\begin{bmatrix} \boldsymbol{\lambda} \\ \boldsymbol{\lambda}^* \end{bmatrix}, \quad \mathbf{f} = \begin{bmatrix} \mathbf{0} \\ \boldsymbol{F} \end{bmatrix} \tag{2}$$

This description of linear structure can handle non conservative and gyroscopic systems, (Byrtus et al., 2010). Using modal decoupling we obtain response function in the frequency domain

$$\mathbf{u}(\omega) = \mathbf{U}(\mathrm{i}\omega\mathbf{I} - \boldsymbol{\Lambda})^{-1}\mathbf{W}^{\mathrm{T}}\mathbf{f}(\omega) \tag{3}$$

Application of Laplace transforms on the decoupled system of differential equations finally provides time domain general solution of original state space model. For t=0, $\mathbf{u_0}=\mathbf{0}^{\mathrm{T}}$.

$$\mathbf{u}(\mathrm{t}) = \mathbf{U}\int_0^{\mathrm{t}} \mathbf{W}^{\mathrm{T}}\mathbf{f}(\tau)\mathrm{e}^{\boldsymbol{\Lambda}(\mathrm{t}-\tau)}\mathrm{d}\tau\,, \tag{4}$$

where $\mathbf{u}(\mathrm{t}) = [\dot{\mathbf{q}}(\mathrm{t})^{\mathrm{T}}, \mathbf{q}(\mathrm{t})^{\mathrm{T}}]^{\mathrm{T}}$is the vector of state space coordinates.

For eigenvalues holds: $\lambda_{\mathrm{i}} = \delta_{\mathrm{i}} \pm \mathrm{j}\omega_{\mathrm{di}}$, where $\delta_{\mathrm{i}} = -\zeta_i\omega_{0\mathrm{i}}$, and $\omega_{0\mathrm{i}} = \sqrt{\omega_{\mathrm{di}}{}^2 + \delta_{\mathrm{i}}{}^2}$, whereas $\omega_{\mathrm{di}} = 2\pi\mathrm{f_i}$. Relation (4) formulates general solution of (1) in time domain in the case of arbitrary waveform of input excitation forces. The structure of (4) gives insight into any response of linearized aeroelastic system. Forced response reflects frequency content of all acting excitation sources. Periodic or quasi-periodic, random and transient forces are acting on the aircraft structure in flight and by acceleration, braking and taxi movements on the ground. These forces are summed in to resultant generalized force vector **F**. Real amplitudes of exciting forces are limited. Thus the exponential term with spectral matrix $\boldsymbol{\Lambda}$ has fundamental role in vibration response amplitude evolution. Resonance and instability phenomena can arise depending on the properties of system related eigenvalues λ_{i}. Resonance problem occurrence becomes in the case of coincidence of excitation force frequency components with imaginary parts of eigenvalues. Instability problem is associated with real parts of eigenvalues. It is necessary take in to account both phenomena during aeroelastic system testing, to carefully distinguish instability and other frequency components of the vibration response.

Simplified dynamic stability criteria for the system with no repetitive roots are: The equilibrium of the system is stable, if all $\delta_{\mathrm{i}} < 0$. If at least one $\delta_{\mathrm{i}} > 0$, the systems equilibrium is unstable, (Muller, 1977). Experimental operational modal analysis is working commonly with damping factor, ζ_i. Thus we consider in the stable operational region, $\zeta_i > 0$ for all modes, on the instability margin $\zeta_i = 0$ for at least one mode and in the unstable operational region, $\zeta_i < 0$ for at least one mode.

3. Vibration response analysis

It seems reasonable to introduce interpretation set Σ, in which all relevant data on the tested system are collected, as basic modal model parameters, results of numerical simulations, geometric position and directions of all transducers definition, configuration of the tested system, number of engines, propeller blades and characteristics of all other sources of internal and external excitation. The set Σ serves as correct interpretation base by frequency analysis of system vibration response.

Moreover a set of parameters P is defined, for a potentially unstable system. The set P contains all parameters relevant to influence the systems stability characteristics. Generally operational modal parameters are functions of P, we can write Λ = Λ(P), U = U(P), W = W(P). An aircraft aeroelastic system contains as parameters in the P wind speed v, air density ρ, fuel distribution and mass m and occasionally propeller rotational speed n, which is relevant to the special whirl flutter phenomenon. Parameters of P define r-dimensional space Π. Stability characteristics of a tested system are systematically evaluated and stable subspace Π+, stability margin O and unstable subspace Π- are identified inside Π, in the course of experimental campaign, (Malinek, 2016).

Vibration responses of the aeroelastic demonstrator presented in the article were measured at six points and recorded on the PC disc during experimental wind tunnel runs. In the same time the vibration responses were analyzed on-line to detect vibration amplitude immediately and compare them with a predefined limit to prevent demonstrator catastrophic failure in the case of a fast unstable vibrations ramp-up due to instability. Moreover two parameters of P were continually measured and recorded: wind speed v and propeller rotational speed n. Series of operational conditions points in the $v - n$ space was sequentially set up with increasing *v* and *n* during wind tunnel testing for a given demonstrator variant. Vibration response of the demonstrator at the wind speed level was recorded and vibration amplitude evaluated. If the vibration amplitude was lower than a preset limit, wind speed *v* was increased by a small step and propeller speed accommodated to wind speed, as the propeller was working in wind-milling mode. Vibration response was then measured and evaluated for a new wind speed point. The sequence continued until maximal wind speed 45 m/s was reached, or vibration limit was exceeded. The process is demonstrated on the next example of aeroelastic demonstrator V2L+2.5 and V2T0 variants results.

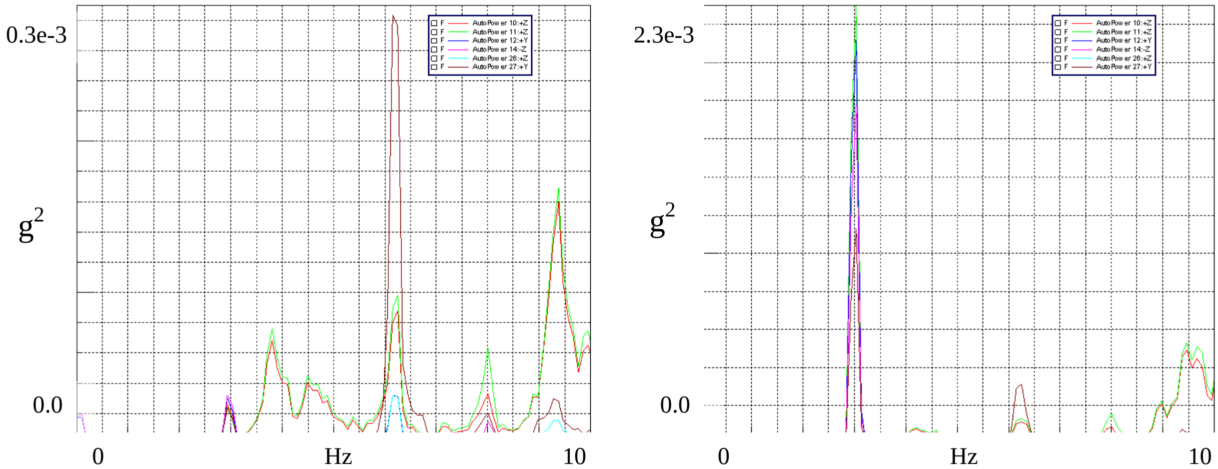

Fig. 1: Variant V2L+2.5, Frequency spectra of vibration response: v = 20 ms, n = 1511 RPM Left, no instability; v = 30 m/s, n = 2391 RPM Right, unstable vibrations starts on frequency 2.8 Hz.

Frequency spectra interpretation is based on the Σ set of information relevant to the aeroelastic demonstrator. Laboratory modal test results: Frequency of engine vibration modes 2. 8 Hz, 1st vertical wing bending mode 3.5 Hz, 2nd vertical wing bending mode 9.9 Hz and 1st horizontal wing bending mode 9.4 Hz. The frequency 6.2 Hz is 1st bending of test stand. Point 12-Y and 14-Z are on the engine nacelle front, point 26-Z and 27-Y are on the nacelle aft, points 10-Z and 11-Z are on the wing tip, Z –vertical, Y – perpendicular to the wind flow horizontal. The demonstrator models one half of wing with one engine.

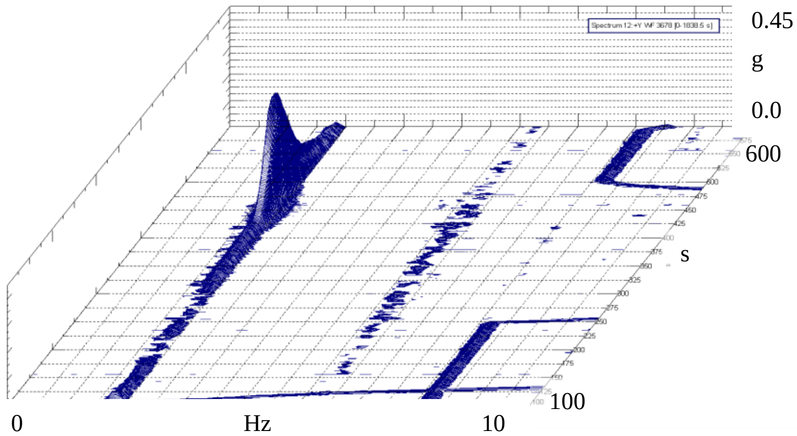

Fig. 2: Variant V2L+2.5, Frequency spectra time evolution. Unstable vibrations ramp-up of the 2.8 Hz mode. Wind speed was quickly returned to stable region after vibration amplitude limit overrun.

Stability margin was reached during the run according to amplitude criterion. Vibration data were analyzed on the constant levels of parameters v and n off-line. Modal parameters of potentially unstable modes were extracted from vibration responses. Operational modal analysis (OMA) software package from LMS TestLab system was applied. Nevertheless OMA fails by identification of negative damping factor in the unstable region. Logarithmic decrement concept was then used instead of OMA to determine negative damping factor by procedure modified to frequency-time-amplitude domain.

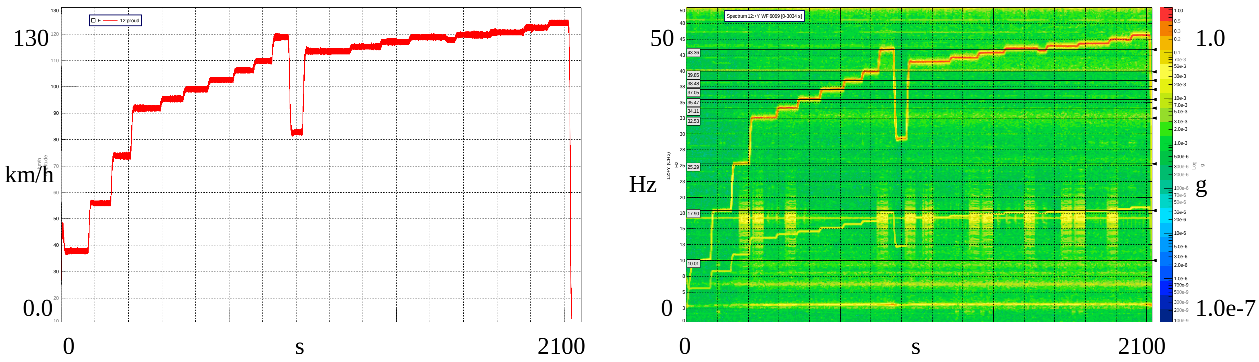

Fig. 3: Variant V2L+2.5, Wind speed v was carefully varied, until stability margin was (two times) reached. Propeller speed was derived from unbalance vibration response.

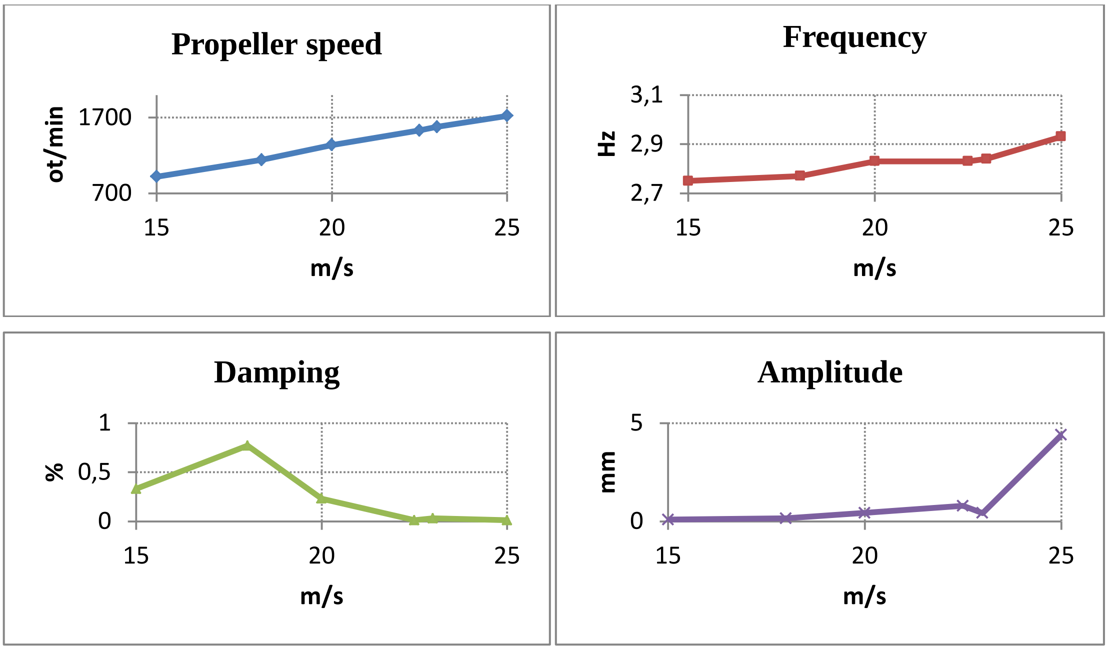

Fig. 4: Variant V2T0, Modal parameters and amplitude of whirl flutter mode as a function of wind speed.

As an example of experimental procedure output the composed results of operational modal parameters of the demonstrator variant V2T0 are presented in the Fig. 4.

4. Conclusions

The article presents briefly a procedure of experimental investigation of operational modal parameters of an aeroelastic demonstrator during wind tunnel testing. The method is suitable for stability margins research of real aeroelastic systems as well as other potentially unstable mechanical systems.

Acknowledgement

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