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AIRCRAFT WING FLUTTER ASSESSMENT CONSIDERING DAMAGE TOLERANCE - BASED FAILURE STATES

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Abstract: *This paper deals with aircraft wing flutter analysis considering the failure states, originated by the application of the damage - tolerance design philosophy on the wing structure. Such damages may influence the integral stiffness of a wing structure and, as a consequence, to influence its flutter characteristics. Therefore, airworthiness regulation standards require flutter analysis of these failure states. The paper presents the simple method of the wing stiffness transformation. The source model is the detailed static FE model, applicable to include the mentioned damages. Target model is the aeroelastic stick FE model, applicable for aeroelastic analyses. The method of assessment of the influence of damage on the wing flutter is shown. The methodology is demonstrated on the example of a commuter aircraft wing bending - torsional flutter. The method is applicable for compliance with FAR / CS 23.629(g)(h) requirements.*

Keywords: Aeroelasticity, Flutter, Damage Tolerance, Reglamentary Damage.

1. Introduction

Aeroelastic flutter certification analyses of an aircraft structure must include the assessment of many parameters, which may influence flutter behaviour of a structure. Provided that the damage tolerance design philosophy is applied on a structure, the influence of specific failure states must be also analysed (FAR / CS 23.629(g)(h)). The reason is that damage tolerance assumes damages even on a new structure. Damages that are growing during an aircraft lifetime may then influence the integral stiffness of a structure and influence its flutter behaviour.

The proposed method of compliance is based on the usage of standard aeroelastic stick model with the modified stiffness characteristics. These modified stiffnesses are determined for the specific (so called reglementary) damages, representing the damages, which are large enough and cannot occur during an aircraft lifetime. Thus, the proposed approach is conservative. The modified characteristics are obtained from the detailed FE model used for static analyses. The method is good compromise taking into account the accuracy, necessary effort and available means, models and data.

2. Transformation of stiffness characteristics

Aeroelastic stick model, which is ordinarily used for flutter analyses include beam-like elements to model stiffness (vertical bending, in-plane bending and torsional) of structural parts (e.g., wing). Beam-like description, which is based on the slender beam theory, is applicable for the undamaged structure with the gentle changes in the spanwise stiffness. However, considering the failure states with the sharp changes in the stiffness between the undamaged section, damaged section and back, the slender beam theory is not applicable. Due to the damage, strain and stress distribution round about the damaged section are completely different, compare to the slender beam theory.

Therefore, the detailed model (Fig. 1) used usually for static analyses was used for determination of the damaged structure stiffness. Damages were modelled on the detailed shell element model (see example in Fig. 2). Then the static analyses under the unity load (vertical bending, in-plane bending and torsional) were performed.

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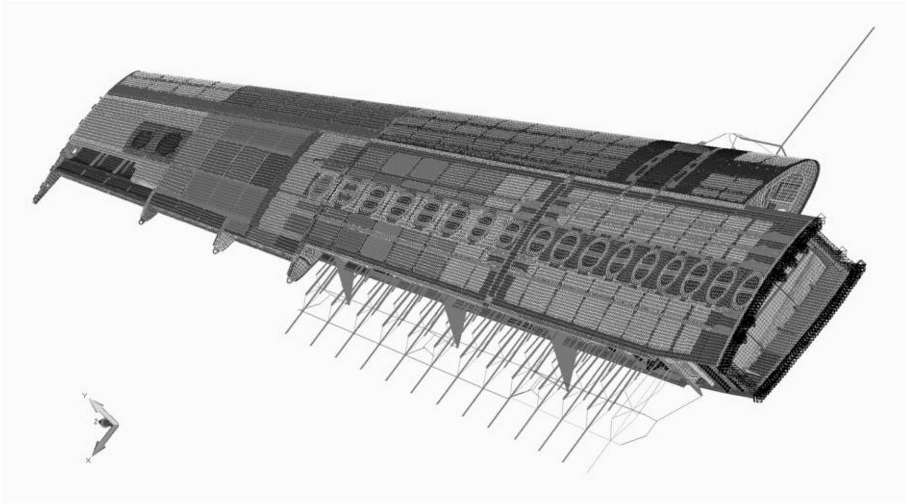

Fig. 1: Detailed static shell element FE model of a wing structure.

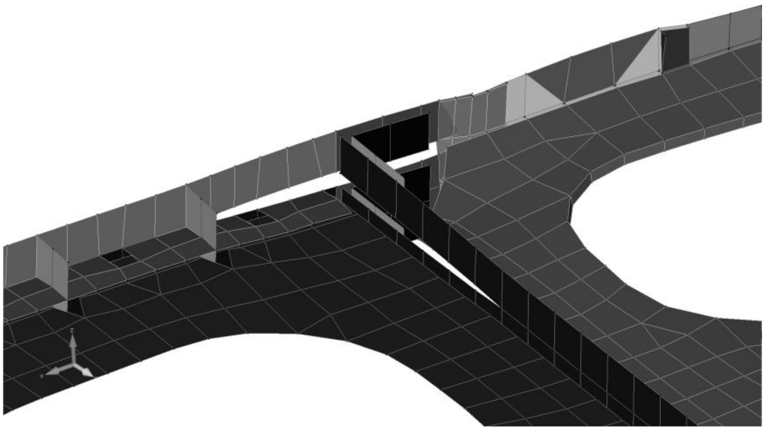

Fig. 2: Example of analysed damage - front spar damage (complete detachment of bottom flange, crack of web up to 1/3 of height), crack of skin under spar up to the closest stringer.

For the purpose of transformation to the stick model, displacements of the shear centre line are required. Therefore, the points of the appropriate sections were selected and the displacements (translational and rotational) were transformed using method of regression (root mean square method - RMS). This approach is applicable considering the slender beam theory deformation model, i.e., assuming the rigid section with no in-plane deformation and with no deplanation. Provided that the reference point is placed on the shear axis, only the deformation terms $\boldsymbol{u_{x0}/F_x}$, $\boldsymbol{u_{y0}/F_y}$, $\boldsymbol{\alpha_y/F_x}$, $\boldsymbol{\alpha_x/F_y}$ and $\boldsymbol{\alpha_z/M_z}$, should be non-zero. Obviously, in the real case, other terms are non-zero as well. The reasons are following: 1) the elastic axis is not coincident with the shear axis, 2) real wing does not fulfil the slender beam theory (especially at the damaged section) and, 3) discretization and numerical character of the solution. Nevertheless, assessing the RMS deviation of deformation values, the proposed approximation can be considered as acceptable in terms of accuracy.

For the beam bending moment (***M***) and displacement angle ($\boldsymbol{\alpha}$) we can write:

$$\frac{d\alpha_{bend}}{dz} = \frac{\pm M_{bend}}{EJ_{bend}} \tag{1}$$

Equation (1) can be discretized between sections ***i*** and ***i+1*** as:

$$\frac{\alpha_{(i+1)bend} - \alpha_{(i)bend}}{z_{(i+1)} - z_{(i)}} = \frac{\pm M_{bend}}{EJ_{(i;i+1)bend}} \tag{2}$$

where cross-sectional inertia ***J*** between sections ***i*** and ***i + 1*** is considered as constant. Analysis was performed on the damaged structure (***p***-index) as well as on the undamaged structure (no index). Both analyses were performed using the same geometry (***z***-coordinates) and the same load ($\boldsymbol{M_{bend}}$). Eliminating these terms we obtain the final equation:

$$\frac{\alpha_{(i+1)bend} - \alpha_{(i)bend}}{{}^{p}\alpha_{(i+1)bend} - {}^{p}\alpha_{(i)bend}} = \frac{{}^{p}EJ_{(i;i+1)bend}}{EJ_{(i;i+1)bend}} \tag{3}$$

Equation (3) characterises the decrease in the bending stiffness due to the damage between sections ***i*** and ***i + 1***. By analogy, for the torsion we can write:

$$\frac{d\alpha_{tor}}{dz} = \frac{M_{tor}}{GJ_{tor}} \tag{4}$$

$$\frac{\alpha_{(i+1)tor} - \alpha_{(i)tor}}{z_{(i+1)} - z_{(i)}} = \frac{M_{tor}}{GJ_{(i;i+1)tor}} \tag{5}$$

$$\frac{\alpha_{(i+1)tor} - \alpha_{(i)tor}}{{}^{p}\alpha_{(i+1)tor} - {}^{p}\alpha_{(i)tor}} = \frac{{}^{p}GJ_{(i;i+1)tor}}{GJ_{(i;i+1)tor}} \tag{6}$$

Despite the inaccuracies, which have been described, the proposed method was found as acceptable. Although the target beam model does not have the correct strain and stress distribution in the damaged section, it has very accurate spanwise translational and rotational displacement in the reference points. Therefore, the model can be considered as enough accurate for the follow-on flutter analysis.

3. Flutter analysis

Aeroelastic stick model is characterised by the stiffness characteristics of the structural parts modelled using massless beam elements placed at the elastic axes of the particular structural part. Inertia characteristics are modelled using concentrated masses with appropriate mass moments of inertia. Engine attachment stiffness as well as connections of structural parts is modelled using spring elements. Various conditions, multi-point constrains, e.g., for the attachment of control surfaces, visualization, connections, etc. are also used.

For the purpose of the described analyses, the stiffness model was modified using the tapered-beam elements allowing specifying the cross-sectional inertia characteristics in the several spanwise sections. This allowed keeping the initial grid positions regardless the spanwise stations of the available stiffness data of the damaged structure. Stiffness model was prepared for both the failure states including damages and the undamaged state (see example in Fig. 3).

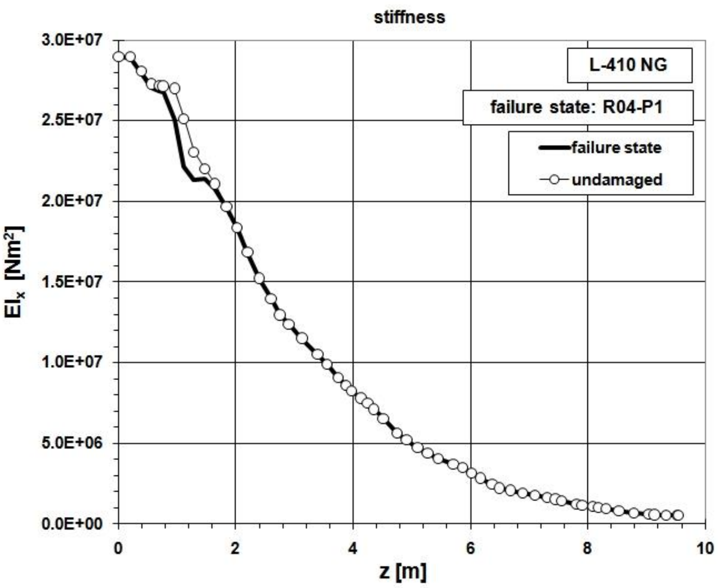

Fig. 3: Stick model bending stiffness example (failure state and undamaged state).

The higher influence of the damages was found on the bending stiffness characteristics while the influence on the torsional stiffness was very low.

Flutter analyses were performed as usual using pk-based method. Aerodynamic matrix is included into the stiffness matrix (real part) and into the damping matrix (imaginary part). The method generates directly total damping of the vibrating system for the selected velocities (true air speed). Flutter analysis is performed as non-matched analyses, i.e., aerodynamic matrices are generated only for the reference Mach number (***M_{REF}***) and for the selected values of reduced frequency (***k***). The velocity and Mach number values do not match, and therefore, the results have reference character. Such an approach is usually employed in the subsonic aeroelastic analysis to evaluate the rate of reserve in terms of the stability with respect to the specific (certification) velocity. Structural damping was set using viscous model. The common value of ***g = 0.02*** was used. Analyses included mode shapes up to the frequency of ***f = 100 Hz***.

Analysed mass configuration include that one on which the bending torsional flutter (Fig. 4) with the critical mode combination of wing 2nd symmetric bending and wing 1st symmetric torsion mode was found. The reason is that this type of flutter instability is sensitive to the characteristics of the wing bending and torsional modes, which may be influenced by the change in the stiffness.

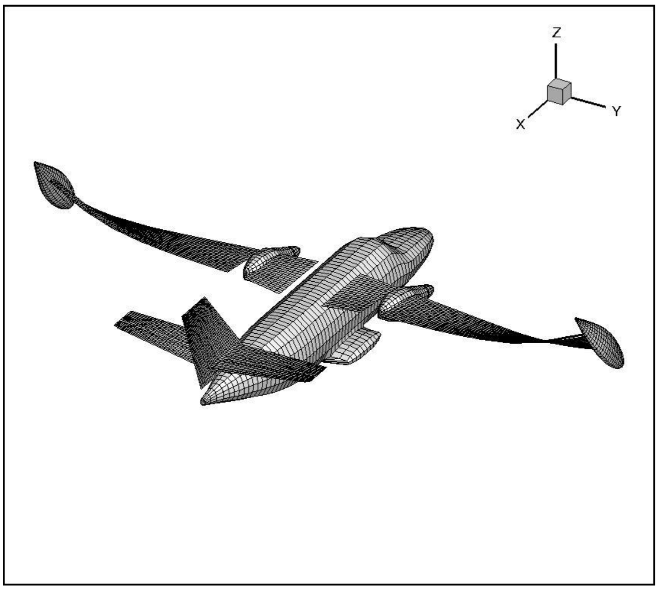

Fig. 4: Aircraft wing bending - torsional flutter shape.

Compare to the undamaged state, the critical flutter speed of the failure states slightly increased while the flutter frequency slightly decreased. The reason is an increase in the difference between the frequencies of the critical modes (2nd symmetric bending and wing 1st symmetric torsion).

4. Conclusion

The paper presents the methodology of the aircraft wing flutter analysis considering the failure states, originated by the application of the damage - tolerance design philosophy on the wing structure. The main problem of the solution is obtaining of the stiffness characteristics of the damaged structure and its transformation from the detailed static model to the target aeroelastic stick model. The proposed method is simple and enough accurate. The application example includes the analysis of bending torsional flutter considering a single specific damage (reglementary damage).

The method is applicable for compliance with FAR / CS 23.629(g)(h) regulation requirements. We can formulate the following statements:

1) Failure state analyses must be performed using the model that includes the stiffness characteristics updated with respect to the results of the ground vibration test.
2) Failure state analyses according FAR / CS 23.629(g) may be performed with regard to those flutter cases with the low reserve towards the certification margin. Application of reglementary damages represent conservative approach with respect to the requirements of FAR / CS 23.629(g).
3) Analysis of the state required by FAR / CS 23.629(h), i.e., the state, for which the residual strength is demonstrated, may be performed analogously. In this case, multiple damages representing the mentioned state of a structure must be taken into account.

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