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Updating of jet trainer aircraft FE model according to results of ground vibration test

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Computational (FEM) models of aircraft structures used for aeroelastic analyses must be validated according to experimental results. Flutter analyses have ultimate character and accuracy, and reliability of flutter results are strongly dependent on the accuracy and reliability of the input modal data. Therefore, the model updating according to the ground vibration test (GVT) results is required. Basically, updating is a problem of multidisciplinary optimization (MDO). The Bayesian Least Squares Estimation Method is frequently employed. The objective function (OBJ) is expressed as

$$OBJ = \{\Delta R\}^T [W_R]\{\Delta R\} + \{\Delta P\}^T [W_P]\{\Delta P\}\,. \tag{1}$$

It represents the weighted sum of the error in design responses $\{\Delta R\}$ and the difference in design variables $\{\Delta P\}$. $[W_P]$ and $[W_R]$ are then diagonal scatter matrices for design variables and for design responses, respectively. The solution is iterative, expressed as

$$\{P_u\} = \{P_0\} + [G]\{-\Delta R\}\,, \tag{2}$$

where $\{P_u\}$ is the vector of design variables after updating; $\{P_0\}$ is the vector of design variables before updating; $\{\Delta_R\}$ is the design response change vector and $[G]$ is the gain matrix calculated according to Bayesian Estimation Theory as

$$[G] = ([W_P] + [S]^T[W_R][S])^{-1}[S]^T[W_R] \ \text{ or } [W_P]^{-1}[S]^T([W_R]^{-1} + [S][W_P]^{-1}[S]^T)^{-1}, \tag{3}$$

where $[S]$ is the sensitivity matrix representing rates of design response changes with respect to change in design variables.

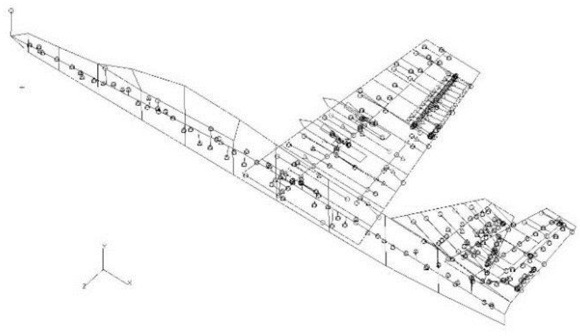


Fig. 1. FEM model (jet trainer aircraft)

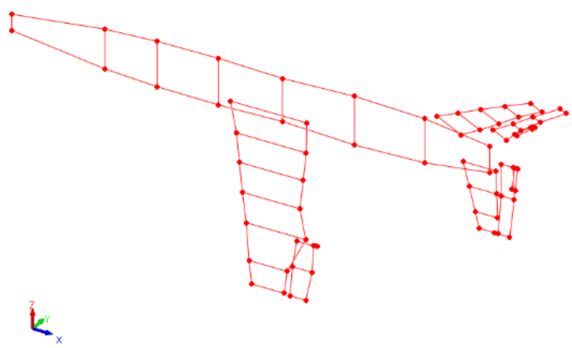


Fig. 2. GVT model (jet trainer aircraft)

Updating is usually performed in several steps in which the strategy is appropriately modified according to the situation. The key issue is the appropriate selection of design variables and design responses and setting of scatter values. FEM model has a character of a dynamic stick model. Stiffness model includes mass-less beam-like elements (structural parts) and scalar springs (specific connections, control surface actuation, etc.). Inertia model includes lumped mass elements with the appropriate moments of inertia. The model usually includes a single side only with either symmetric or antisymmetric boundary condition. The example is shown in Fig. 1. GVT data are reduced and adjusted. Provided that uniaxial sensors are used; the deformations are to be recalculated to the triaxial scheme. The appropriate selection of points is important as it affects the correlation criterion of mode shapes. Fig. 2 shows the example of the grid of experimental points.

Compared to the inertia data, the stiffness data based on the virtual prototype are considered as less accurate and reliable, thus, the stiffness data are used as design variables. The data, which are not considered as design variables must be validated and adjusted prior the updating. Therefore, the preparatory activities include the adjustment of control surfaces and tabs mass data according to the weighing. In addition, the total inertia data are adjusted according to the prototype weighing. Finally, effective stiffness of tabs actuation is updated according to the static stiffness measurements.

Design variables include beam-like elements vertical bending stiffness, in-plane bending stiffness and torsional stiffness and scalar spring stiffness modeling control surface actuations and structural part connections. Design responses (i.e., natural frequencies, MAC-values) include bending and torsional modes of the main structural parts and flapping modes of control surfaces. Modes are split into symmetric and antisymmetric modes and the updating is performed for both groups separately. Therefore, separate models with the diverse final values of design variables for symmetric and antisymmetric case are obtained.

Table 1. Experimental modes (symmetric) selected for updating

#	title	f_0 [Hz]
01	1st symmetric wing bending	14.603
02	Symmetric aileron flapping	14.970
03	1st fuselage vertical bending	18.130
04	Symmetric elevator flapping (fixed stick)	24.101
05	1st symmetric tailplane bending	27.979
06	2nd fuselage vertical bending	35.263
07	1st symmetric wing torsion	38.461
08	2nd symmetric wing bending	51.943
09	1st symmetric wing in-plane bending	60.224
11	2nd symmetric wing torsion	70.131
12	1st symmetric tailplane in-plane bending	76.146
14	1st symmetric tailplane torsion	87.698

Mode pairing (FEM and GVT) is performed manually by a visual comparison of mode shapes using the specific graphic format showing node lines and modal deformation of structural parts. Although MAC-values are used as design responses, automated pairing of modes according to MAC-values is not applicable as it may lead to inappropriate pairing, because the aircraft structure is very complicated dynamical system with the high modal density.

First, updating of the baseline configuration is performed. As the next step, correlation analysis of the updated model for additional mass configurations with the corresponding GVT data is performed and, provided that the results are not satisfactory, further updating using additional design variables is performed. As the result, the diverse models for each mass configuration may be obtained. Note that the possibility to include the GVT data of multi-mass configuration into updating process and take a single model for multiple mass configurations is not recommended. Contrary to that, updating considering only a subset of major modes, contributing to a specific flutter instability, is feasible.

Model updating is demonstrated on the example of the new Czech jet trainer aircraft. GVT included a single (baseline) mass configuration for which a complete set of modes has been measured. Additional configurations included specific pod-based configurations or specific conditions of the control system. For these additional configurations, just appropriate modes were measured, e.g., pod-modes, control system transfer functions, etc.

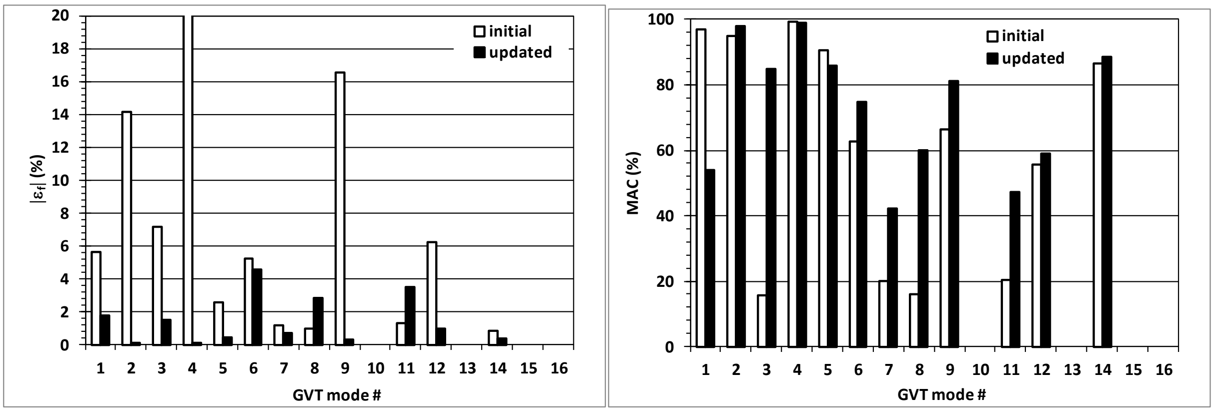


Fig. 3. Comparison of initial and final model, baseline configuration, a) frequency error, b) MAC-values

As the example, updating of the symmetric model is presented here. Experimental results of the baseline configuration included 16 symmetric modes, from which 12 modes were selected for updating. The list of the selected experimental modes is shown in Table 1.

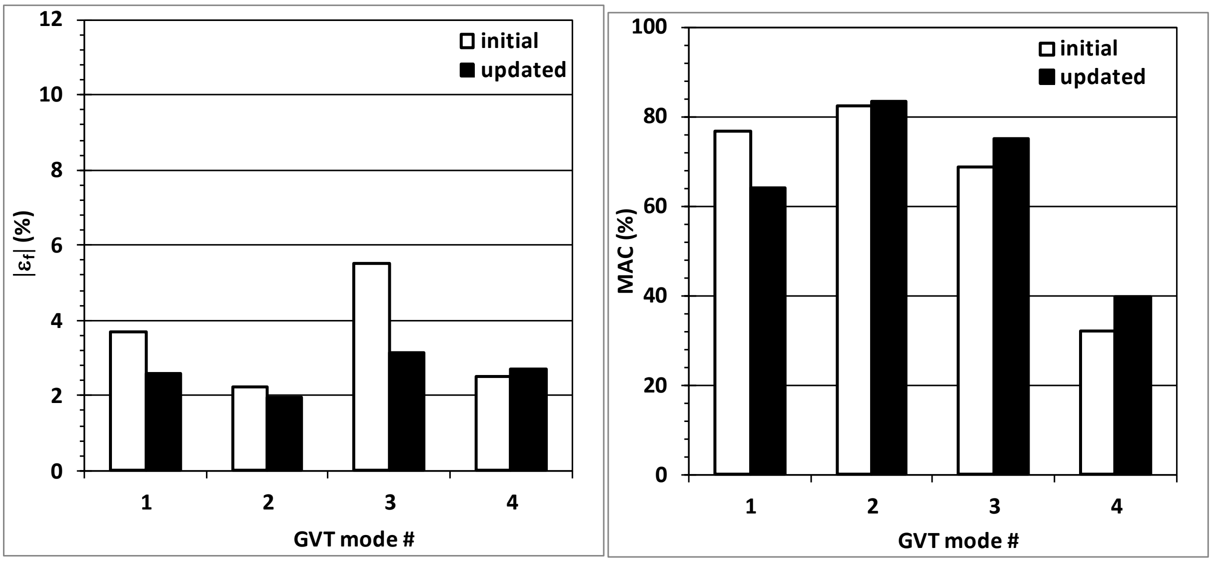


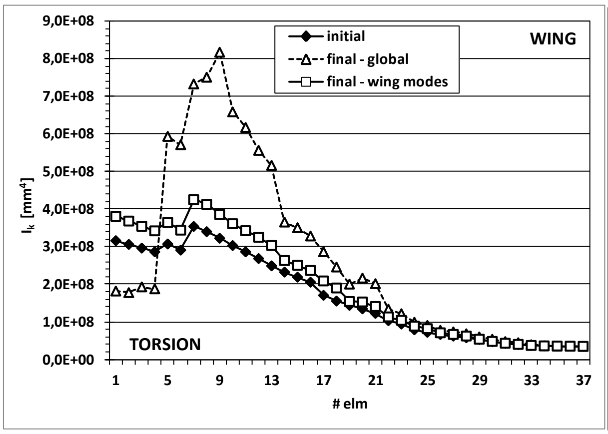
Fig. 4. Comparison of initial and final model, wing modes, a) frequency error, b) MAC values

Comparison of the initial and final pairing of modes is shown in Fig. 3. Pair numbers correspond to the GVT-mode numbers according to Table 1. Fig. 3a demonstrates relative error in natural frequencies. The final errors are less than 4.5 %. This is excellent result. Fig. 3b shows a comparison of the initial and final state in terms of MAC values. The results are also good, all MAC values increased or remained. The only exception is the mode # 01 (1st symmetric wing bending) for which the low MAC value is caused by the aileron points.

Nevertheless, provided that the MAC is considered excluding the aileron points, the value increase to 97.6 %. The reason is the cross-influence of 1st symmetric wing bending and aileron flapping modes, the frequencies of which are very close one another.

In addition, updating to the subset of four wing modes (1st wing bending, 1st fuselage vertical bending, 2nd fuselage vertical bending and 1st wing torsion), which are the main modes contributing to the wing flutter, was also performed. As the initial state, the model updated for the baseline configuration was used, except for the wing stiffness, for which the initial stiffness was used. The results are shown in Fig. 4. The improvement of the model agreement with the GVT results is not as significant as for the previous example. The main advantage here is the much lower change in wing stiffness parameters compared to the global updating of the baseline configuration.

Changes in design variables during updating are presented in Fig. 5 by showing the wing stiffness distribution in the spanwise direction expressed as the cross-sectional inertia. Bending and torsional stiffness for the initial state and for the two presented updated states are shown. As apparent from the figure, the changes in design variables for the global updating is very significant, especially in the root area in which the influence of the local flexibility of the wing and fuselage connection is simulated. Also, stiffness hump roughly at the 1/3 of spanwise station is significant. This hump is caused by 2nd bending and torsional modes, which are included into the design space for the global updating. Contrary to that, the changes of the wing stiffness parameters for updating to the wing modes are low and character of stiffness spanwise distribution was kept. The reason is that just 1st wing bending, and torsional modes were included into this updating.



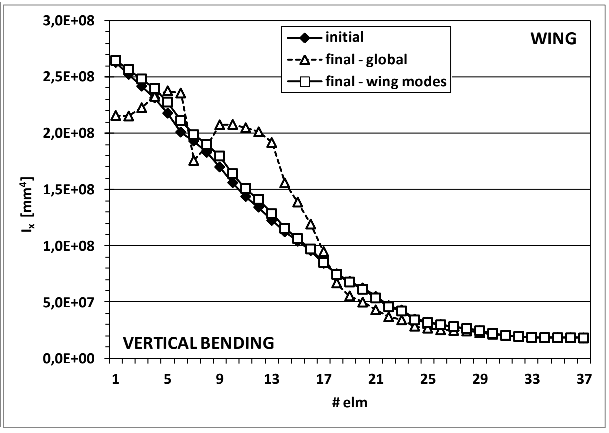


Fig. 5. Design variables change, initial state, final state – global, final state – updating to wing modes, a) wing torsional stiffness, b) wing bending stiffness

To conclude, modal parameters of updated models got much closer to the target GVT data. Updated models are prepared for the final phase of flutter calculations of the subjected aircraft.

Acknowledgements

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[1] Čečrdle, J., Updating of finite element model of aircraft structure according results of ground vibration test, Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 230 (7) (2016) 1348-1356.