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MODAL CHARACTERISTIC OPTIMIZATION OF THE BLADE OF THE TEST RIG

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Abstract: *Article is focused on modal characteristic of the blade which is important component of the experimental test rig for blade flutter measurement. Modal characteristics are obtained using experimental (EMA) and simulation (SMA) modal analyses. The MAC criterion is used for comparison of eigenmodes of the individual material variants. The main aim is to increase the first eigenfrequency (corresponding to the torsional eigenmode) to extend the range of excitation frequencies for blade forced oscillation. Therefore, the current version of the steel blade is replaced by the versions made of laminate which offers more possibilities for increasing the torsional dynamic stiffness, even with possible optimization of its core structure.*

Keywords: Blade, Flutter, Modal Characteristic, Laminate, Torsional Stiffness.

1. Introduction

The analyzed blade is the middle one in a cascade of five blades that are placed within a transonic linear cascade test rig. This device is placed in a wind tunnel to investigate blade flutter, which is simulated by forced torsional oscillating the middle blade at frequencies up to 200 Hz. Pressure sensors on the blades detect how their oscillation affects the air flow field.

For accurate measurement of the flutter, it is necessary that the torsional stiffness of the blade is as high as possible and at the same time that the first eigenfrequency (corresponding to the torsional eigenmode) is sufficiently different from the frequency of the forced oscillation. It is assumed that replacing the steel blade with a laminated one will increase the torsional dynamic stiffness in order to achieve a wider range of blade oscillation frequencies in the measurements.

The modal characteristic of a real blade with free boundary conditions is obtained by experimental modal analysis (EMA), where the response function to impulse excitation by an impact hammer is determined. A 3D accelerometer is used to measure the output signal in the time domain (Ewins, 2009).

Simulation modal analysis (SMA) is used to obtain modal characteristics when real boundary conditions (BC) are considered (blade attachment in the test rig) or when a given blade material variant is not physically available. The SMA is performed using a FEM simulation model.

The MAC (Modal Assurance Criterion) method is used to determine the similarity of two eigenmodes of two different structures. If the eigenmodes are identical, the MAC = 1. If the eigenmodes are very different, the MAC → 0. In this paper, the custom software MACMAT is used, whose output is a matrix consisting of MAC values for each combination of eigenmodes of the two blades being compared. As a result, the FEM simulation model is validated by comparing SMA with the EMA results (without BC) and a comparison of different material variants based on the SMA results (with BC) is performed.

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2. Steel blade

The original, steel version of the blade is analyzed using EMA with free boundary conditions, where both ends of the blade shafts are placed on a flexible pad (Fig. 1). A grid of 40 measurement points is chosen on the blade to correctly represent the expected eigenmodes. The eigenmodes are compared with the SMA results using the MAC method: for the first 4 eigenmodes, MAC $\rightarrow$ 1, the relative difference in eigenfrequencies for identical eigenmodes $\Delta_{\Omega}^{rel} \leq 1\%$. The results show that the FEM simulation model correctly represents the modal behavior of the real steel blade.

The SMA is then performed considering real boundary conditions: as expected, the first eigenfrequency correspond to the torsional eigenmode and its frequency is $\Omega_1^{steel} = 288$ Hz.

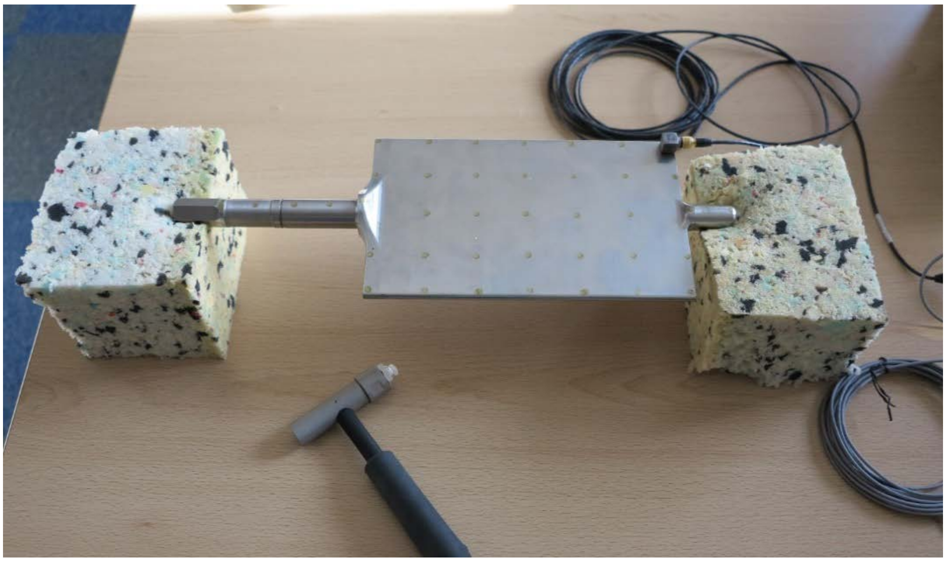

Fig. 1: Experimental modal analysis setup of a steel blade.

3. Fully laminated blade

The surface of the fully laminated blade is made up of 6 layers of carbon fabric, each one with a thickness of t = 0.3 mm. Their orientation is regularly alternated (rotation of ±45° to the blade longitudinal axis). The core inside this volume is filled with the same fabric, orientated at an angle of +45° to the blade longitudinal axis (Fig. 2). As a source of laminate properties (material constants, layers orientations), a paper Vomáčko (2021) is used.

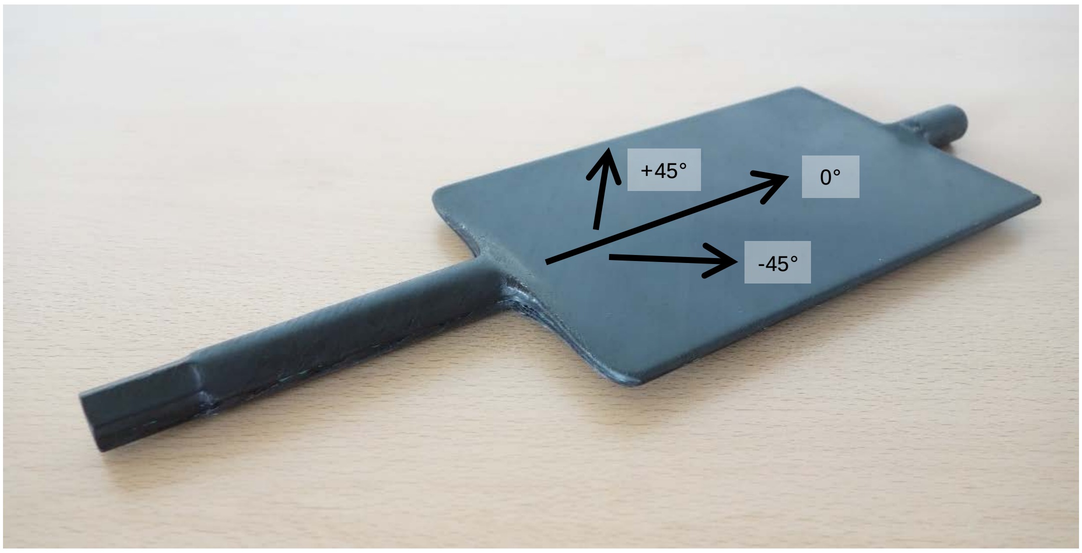

Fig. 2: Representation of the individual layers and core orientation of orthotropic material on real fully laminated blade.

The FEM simulation model of the fully laminated blade respects the material composition of the real blade. The 6 surface layers are defined by 3D penta-type elements created by extruding 2D elements from the blade surface, the core is filled by a free 3D mesh of hexahedral elements (Fig. 3). The orientation of all elements corresponds to the orientation of the fabric of the real blade.

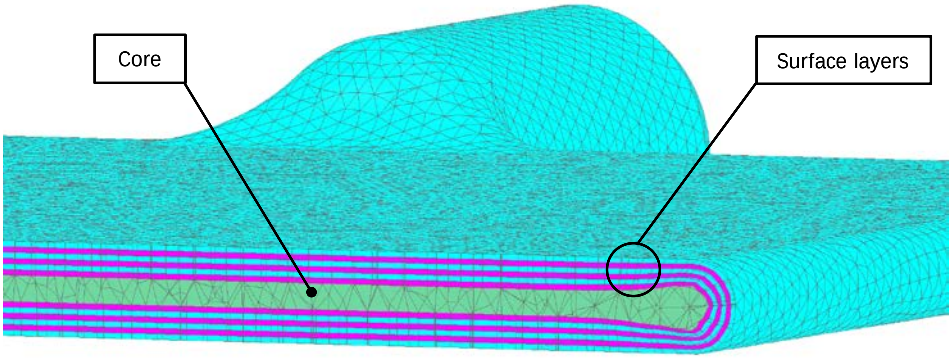

Fig. 3: FEM model – structure of 3D elements of layers and core (cross-sectional view).

This blade version is analyzed using EMA and SMA without BC and compared using MAC method in the same way as the steel version. Although the similarity of SMA eigenmodes #3 and #4 to EMA eigenmode #4 is only partial (MAC ≈ 0.5), the similarity of the other eigenmodes is still very good (MAC > 0.9) and the relative difference of the corresponding eigenfrequencies $\Delta_{\Omega}^{rel} < 10\%$. It is clear that the FEM simulation model accurately represents the modal properties of a real fully laminated blade, especially for the first torsional eigenmode.

The result of the comparison of this blade variant with the steel one considering BC is the MAC matrix (Tab. 1), which shows the following conclusions:

- The eigenmodes (1, 1) and (2, 2) are equivalent (MAC = 1 lies on the matrix diagonal).

- The eigenmodes (3, 4) and (5, 6) are equivalent but swapped (MAC = 1 lies out of the matrix diagonal).

- Increase in first eigenfrequency (torsional mode) by +12%: $\Omega_1^{\text{fully lam}} = 322$ Hz.

Tab. 1: MAC matrix for SMA of the steel blade (row) and SMA of the fully laminated blade.

i		1	2	3	4	5	6
	Ω_i [Hz]	288	541	929	1 343	1 788	1 876
1	322	1	0	0	0	0	0
2	407	0	1	0	0	0	0,1
3	1 092	0	0	0	1	0	0
4	1 163	0	0	1	0	0	0
5	1 589	0	0,1	0	0	0	1
6	2 217	0	0	0	0	1	0

4. Laminated blade with foam core

Since the increase in Ω_1 is not sufficient by using a fully laminated blade, another material option is considered. It is based on the fully laminated variant, but its core is partially replaced by foam material. The point of modifying the core is to reduce the moment of inertia of the blade as much as possible with the least loss of torsional stiffness and strength. The shape of the foam filling the part of the core obtained by topological optimization is shown in Fig. 4. Since this variant exists only as a virtual CAD model, only the SMA (considering BC) is performed using the FEM simulation model.

The result of the comparison of this blade variant with the steel one when considering BC is the MAC matrix (Tab. 2). The comparison of the eigenmodes with the steel variant using the MAC method is identical to that of the fully laminated blade. However, a higher increase in the first eigenfrequency (corresponding to the torsional eigenmode) is essential - increase by +27%: $\Omega_1^{\text{lam + foam}} = 366$ Hz.

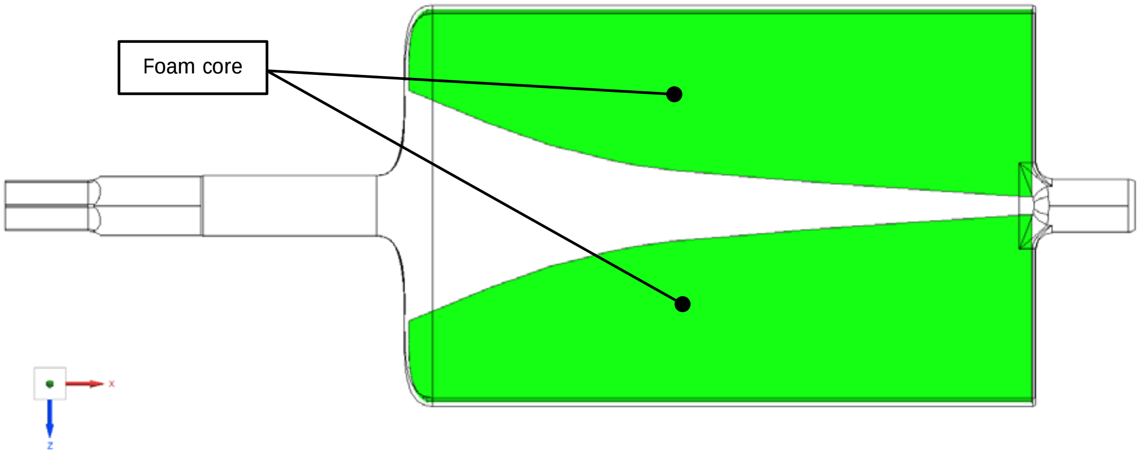

Fig. 4: CAD model of the laminated blade with the foam core.

Tab. 2: MAC matrix for SMA of the steel blade (row) and SMA of the laminated blade with foam core.

i		1	2	3	4	5	6
	Ω_i [Hz]	288	541	929	1 343	1 788	1 876
1	366	1	0	0	0	0	0
2	419	0	1	0	0	0	0,1
3	1 140	0	0	0	1	0	0
4	1 284	0	0	1	0	0	0
5	1 536	0	0,1	0	0	0	1
6	2 200	0	0	0	0	1	0

5. Conclusions

The modal properties of the blade of the experimental device are very important to ensure accurate measurement of the air flow field when researching blade flutter. The main objective is to increase the first torsional eigenfrequency to be sufficiently different from the forced oscillation frequency. This is done by changing the blade material to laminate, including modifying the structure of its core.

Using experimental (EMA) and simulation (SMA) modal analysis, the modal characteristics of 3 material variants of the blade are identified: steel, fully laminated and laminated with foam core. Using the custom MACMAT software, a Modal Assurance Criterion (MAC) eigenmodes comparison is performed to validate the FEM simulation model based on the EMA results (modal analysis without BC consideration) and to compare two different material variants (2 SMAs with BC consideration).

In this way, the key first eigenfrequency (corresponding to the torsional mode) increased from the original value of Ω_1^{steel} = 288 Hz, namely by 12% for the fully laminated blade ($\Omega_1^{fully\ lam}$ = 322 Hz), respectively by + 27% for the laminated blade with foam core ($\Omega_1^{lam\ +\ foam}$ = 366 Hz).

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References

Ewins, D. J. (2009) Modal Testing: Theory, Practice and Application, 2nd Edition. John Wiley & Sons.

Vomáčko, V. and Kolář, J. (2021) Simulation Model of Steel and CFRP Blade for Flutter Measurement, in: Polymer Composites 2021 conference, Tábor, pp. 56–61.