CASE STUDY // ELECTRICAL ENGINEERING

SIMULATION, OPTIMIZATION AND TESTING – SUCCESSFULLY COMBINED

The calculation of the structural and mechanical behavior of electric machines already in the conceptual design phase helps to reduce development cycles and to fulfill the complex demands on the components properties.

In most cases, geometries and components are generated only virtually in the early project phase. This makes the validation of simulations much more complicated. Therefore, robust and physically-based calculation methods are required using the data of standardized material tests. Mechanical material data can generally be obtained from existing data sheets or are generated by analytical calculations and standardized load tests of material samples. This approach reaches its limits if a heterogeneous material structure exists that cannot be resolved practicably with the Finite-Element-Method (FEM).

FEM-compatible material parameters

Here, a process is described which allows a standardized generation of FEM-compatible material parameters of heterogeneous material structures via model updating. The procedure is going to be explained using the example of a resin-impregnated copper windings as part of electrical machines. In this case, model updating means the iterative variation of selected model parameters to obtain an optimal calibration between the results of a simulative and experimental modal analysis.

The copper wires fixed in the stator slots of permanent magnet synchronous machines are embedded in a thermoset matrix for electrical insulation, thermal connectivity as well as mechanical fixation. A detailed resolution of the fine slot structure in structural-mechanical simulations is impractical because of the highly intensive modelling and computation effort. A pragmatic way to overcome that issue is to substitute the heterogeneous material model of the copper windings with a homogeneous one having transversely isotropic properties. The stiffness behavior of the slot structure is described by five independent surrogational parameters.

The quantification of the surrogational parameters is conducted by comparing the ANSYS simulation results of the Eigenfrequencies and deflection shapes of a specimen with the results of an experimental modal analysis. A section of the copper windings of an electric machine stator (Fig. 2) was used as a test specimen.

Optimization of the surrogational parameters

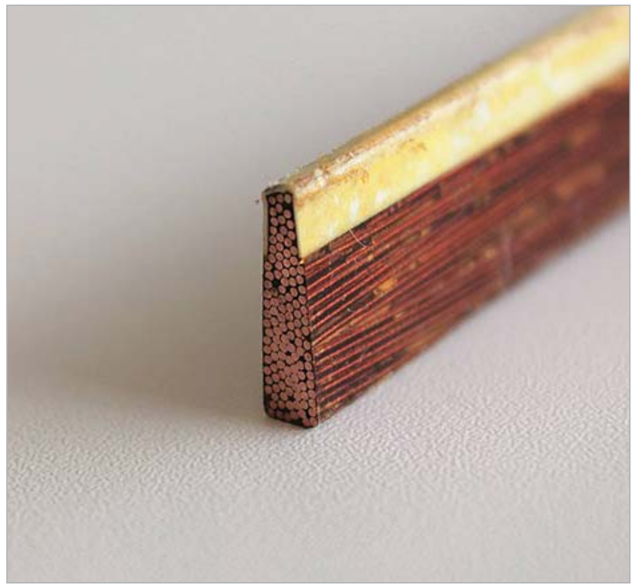

Fig. 2: View of the specimen made of copper windings embedded in a resin matrix

For the experimental modal analysis a laser scanning vibrometer was used to measure the surface velocities in normal direction to the longitudinal area of the test specimen. In order to provide an appropriate design space for the model updating, the classical laminate theory by Chamis was used. Because of the analytical correlations, it is possible to calculate the surrogational parameters for the simulation of a transversely isotropic material by using the properties of the base material - in this case, copper and resin. The design space can be set symmetrically around the analytically calculated base values.

The model updating for the identification of the surrogational material parameters is performed automatically in optiSLang. The objective function of the optimization task consists of terms which compare the modal deflection shapes using the Modal Assurance Criterion (MAC), as well as terms which take into account the variation of the Eigenfrequencies.

In Figure 3 (top), the experimentally identified Eigenfrequencies and deflection shapes of the sample up to 6 kHz are shown. Within the first and fourth bending moment in the longitudinal direction of the structure, the slightly conical cross-section of the sample causes, in some modes, an anti-phase vibration over the width of the sample (see Figure 3, right). The simulation, based on the analytically calculated surrogational parameters, shows nine Eigenfrequencies in the same frequency spectrum. A sensitivity analysis of the five orthotropic surrogational parameter showed a strong correlation between the objective function and the modulus of elasticity in fiber direction as well as a lower correlation between the objective function and the shear modulus in opposite fiber direction. The variation of the other parameters neither affected significantly the Eigenfrequencies nor the mode shapes.

According to the response shape (Fig. 4), both modulus of elasticity in fiber direction and shear modulus in opposite fiber direction can be optimized in regard to the objective function. Due to the low significance, the values for the Poisson's ratios of the system as well as for the modulus of elasticity in opposite fiber direction can be equated with the analytically calculated values.

Fig. 3: Comparison of the experimental (top) and simulated mode shapes

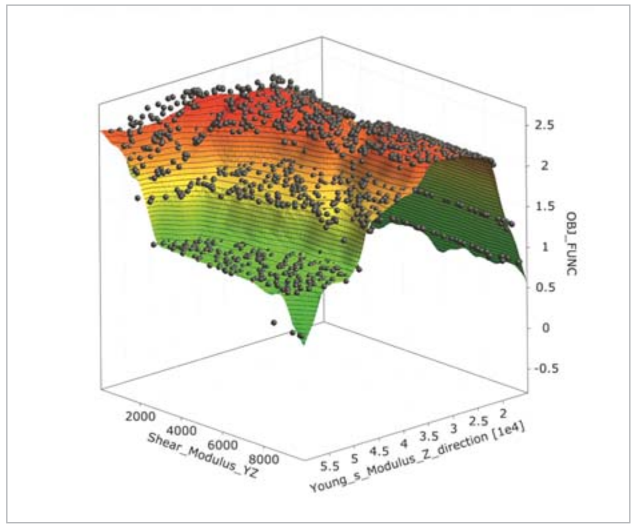

Fig. 4: Response shape for the parameters of the elasticity modulus in fiber direction and shear modulus opposite fiber direction in regard to the optimization criterion

The deviation of Eigenfrequency was reduced

When comparing the MAC-matrix calculated by using the obtained material data to the MAC-matrix derived from the analytically calculated material data, a significant improvement of the MAC-values of all compared modes can be seen. The MAC-value of the 2nd mode shape could be increased by 20%, the one of the 4th mode shape was even doubled by the optimization. At the same time, the Eigenfrequency deviation between experiment and simulation could be reduced for all modes. The non-identified modes of the experimental modal analysis were either not sufficiently stimulated (eg. torsional vibrations) or not directed normally to the longitudinal surface of the specimen (eg. bending mode in transverse direction).

Altogether, the automated model updating quickly generated a set of FEM-compatible surrogational material data representing the structural dynamic behavior of the copper windings for a transversely isotropic modeling approach. With this process, concepts can be evaluated significantly more accurately regarding their mechanical properties in early project phases. There is also the opportunity to further analyze and understand even hardly quantifiable model parameters - such as contact stiffness or temperature induced residual stress. In summary, this can be seen as an important step towards a higher correspondation between simulation and experiment.

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