CUSTOMER STORY // ELECTRICAL ENGINEERING

SIMULATION OF COPPER WIRE WINDINGS IN ELECTRIC MOTORS

The application of optiSLang enables the verification and optimization of material models for an improved simulation of the material behavior of copper wire windings in electric motors.

Introduction

The simulation of heterogeneous materials makes high demands on the calculation regarding computing time. Approaches of idealization are often used to minimize computational time, but should also be capable of describing the behavior of the components precisely. The result of such idealizations is a synthetic material model. The general intention is to verify and optimize the model with the help of appropriate tests.

This article describes such a procedure using the example of windings for electric motors. These windings are made of copper wires embedded in a matrix material consisting of impregnating resin. The impregnating resin serves as a mechanical stabilizer, electrical insulation and heat dissipation. The copper wires conduct electricity and thereby generate the magnetic field for the motor. Modelling individual wires in the simulation would lead to an extremely large amount of computing time and model size. Thus, an idealization of the windings in the simulation model is normally unavoidable.

In literature, two different approaches can be found for idealization. One uses the approach of Chamis, which specifically applies for the simulation of plastics. Another option is the approach of continuum mechanics, which is mainly used for inhomogeneous materials such as concrete or short-fiber-reinforced plastics.

For the verification of the obtained material, a simple bar shaped specimen is extracted from the windings of the electric motor. The so-called slot bar is taken from the area between the teeth and the slots of the lamination stack.

Methodology

Idealization and FE simulation

For the idealization of the component behavior, the continuum mechanics approach of micro and macro structures is used. In this case, the macro level describes the global behavior of the body. For the micro level, a point of the macro level is defined which represents all points of the macro level, the so-called Representative Volume Element (RVE). The approximation of homogeneous material properties in the macro-level and a sufficiently small microstructure

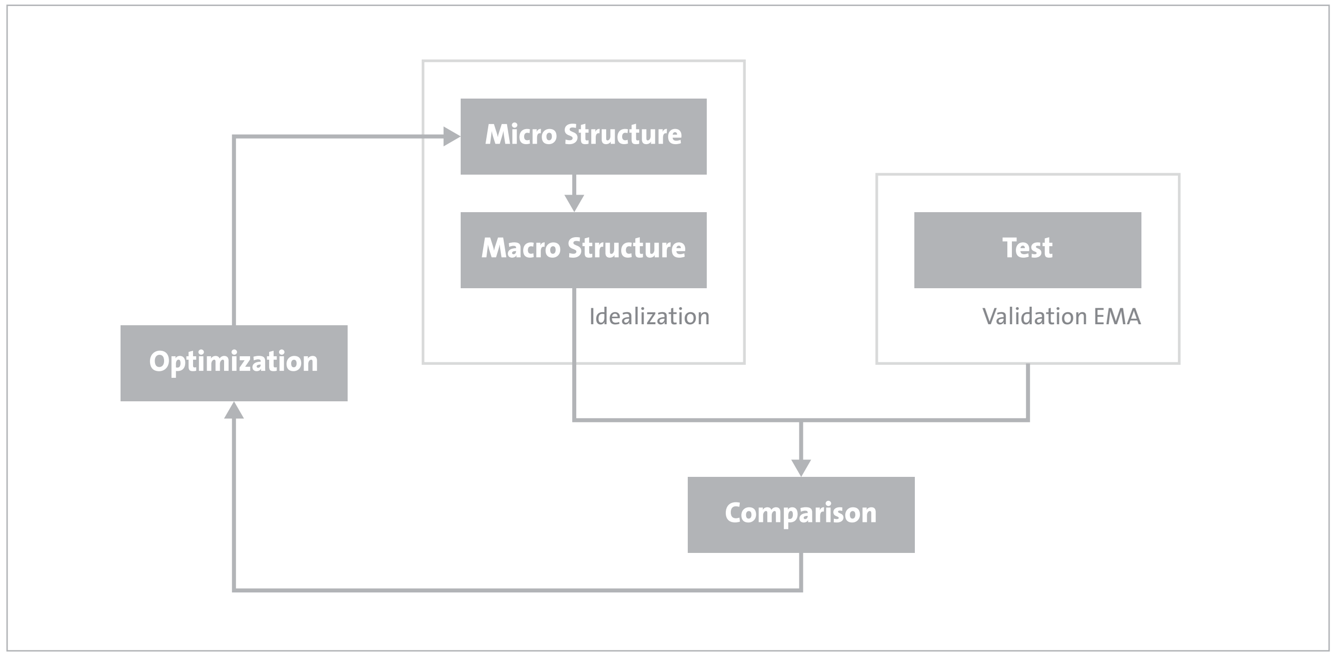

Fig. 1: Flow chart

enables the derivation of the RVE constraints. If the RVE is now exposed to deformation loads, its stiffness matrix can be determined. The so considered anisotropic material can be used for calculating the macroscopic structure.

Using this structure, an idealized material is defined having the same characteristics as the real component. Afterwards, for the slot bar, a computational modal analysis is carried out with this idealized material. The experimental modal analysis serves as a reference test.

The calculation and measurement are compared by using the MAC criterion and the material parameters are optimized regarding the test results. The flow chart of this process is shown in Fig.1.

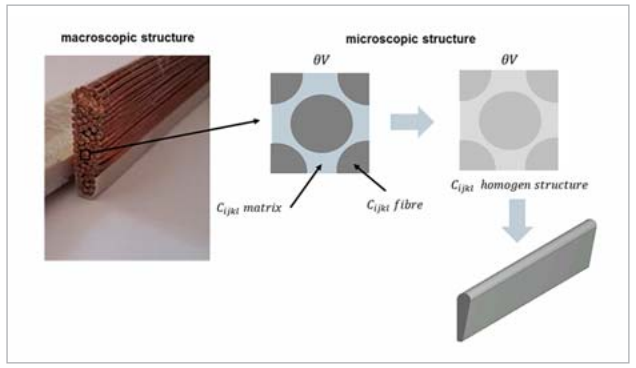

Fig. 2: Homogenization

The values of Young's modulus and Poisson's ratio are taken from literature and serve as initial values for the copper wire. Impregnating resins are specifically developed for the usage in electrical machinery, usually as epoxy resins. The material is properly adapted referring to the later application of the engine and its manufacturing. Epoxy resins have time and temperature independent properties and are viscoelastic. The determination of the initial values is performed by measurements on the resin samples also taking into account the independency regarding temperature and time.

With the help of these output values, the homogenization of the slot bar is conducted. The obtained anisotropic material model is used in the computational modal analysis of the slot bar.

Reference test

For the calibration of the calculated modes, the experimental modal analysis is used. The slot bar is set to oscillate freely by mechanical excitation. The amount of excitation and the resonant response are measured at various points on the bar. The transfer functions for the determination of modal sizes, natural frequency and eigenmode can be derived from the difference between the input and output signals. The measured eigenvalue is then compared to the calculated ones from the simulation.

In this case, the measured mode shapes intended to be used for verification are the first three bending vibration modes and the two torsion mode shapes shown in Figure 3 (see next page).

Calibration of eigenvalues

The Modal Assurance Criterion (MAC) is used for the comparison of the mode shapes with

$$MAC = \frac{[\emptyset_i \cdot \emptyset_j]^2}{[\emptyset_i \cdot \emptyset_i] \cdot [\emptyset_j \cdot \emptyset_j]}$$

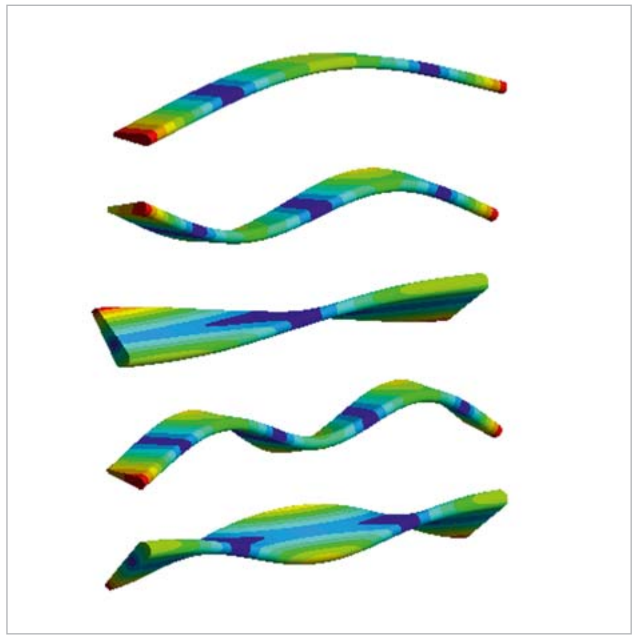

Fig. 3: Mode shapes of the slot bar | top down - 1st bending, 2nd bending, 1st torsion, 3rd bending, 2nd torsion

The comparison of the Experimental Modal Analysis (EMA) with the simulation of the bar resulted in the following correlation:

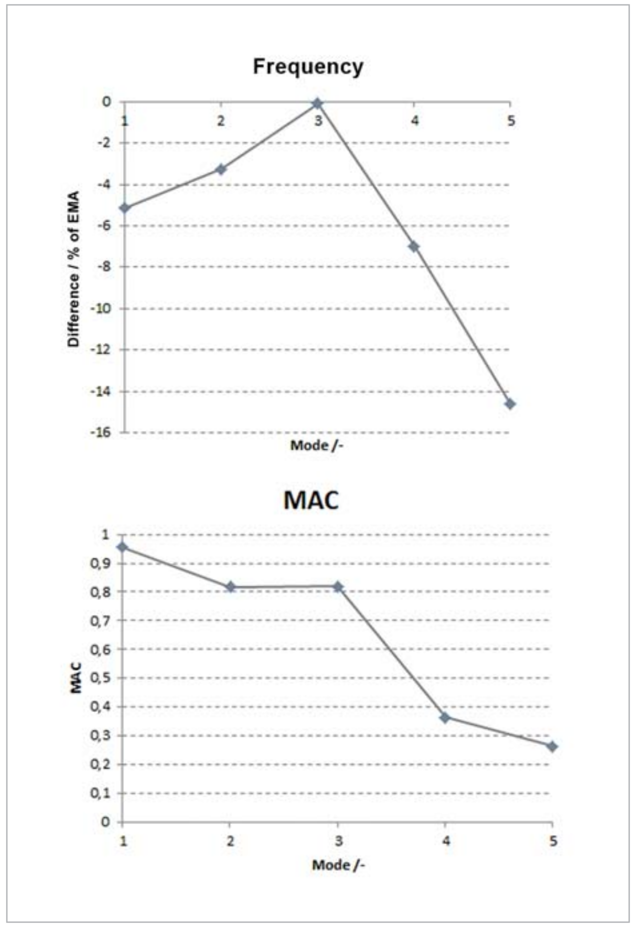

Fig. 4: Comparison of the Experimental Modal Analysis (EMA) with the simulation of the bar

Differences between the initial simulation and measurement can especially be observed in the higher modes. The frequency difference could particularly be improved by optimizing the material parameters of the microstructure.

Sensitivity analysis and optimization
First, the influence of various parameters on the natural frequencies and mode shapes is studied using a sensitivity analysis. The parameters for copper such as Young's modulus, Poisson's ratio, storage modulus, as well as the Poisson's ratio of the resin or geometry values like the wire diameter, are taken from literature.

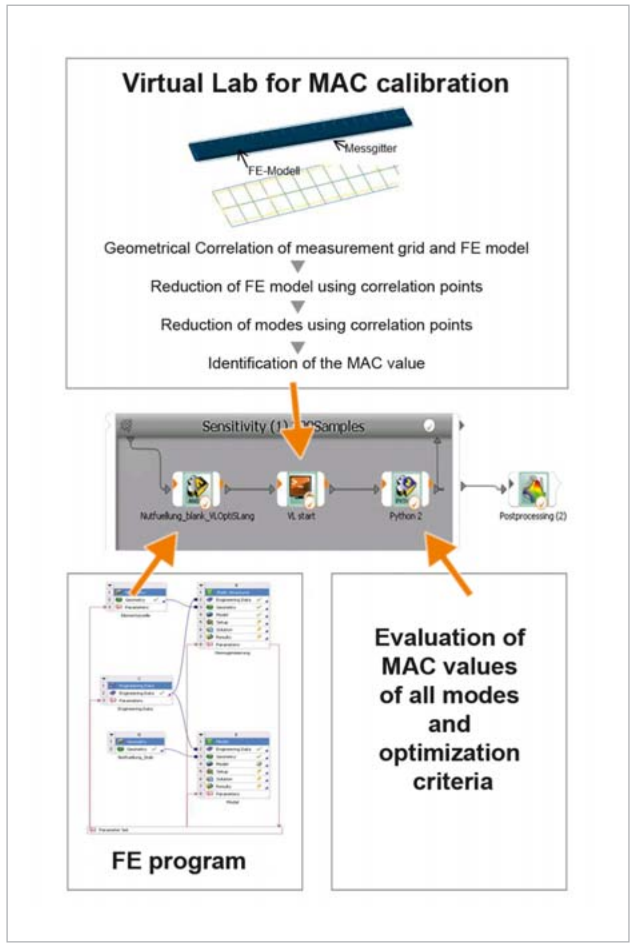

Fig. 5: Workflow overview in optiSLang

For the first five modes, the sensitivity analysis reveals the elastic modulus of resin and copper, as well as the wire diameter to be the main parameters. Here, the elastic modulus of copper and the wire diameters mainly determine the bending modes while the torsional modes are primarily determined by the storage modulus of the resin as well as the wire diameter. Following the sensitivity analysis, an optimization of the main parameters is performed using an Adaptive Response Surface Method (ARSM).

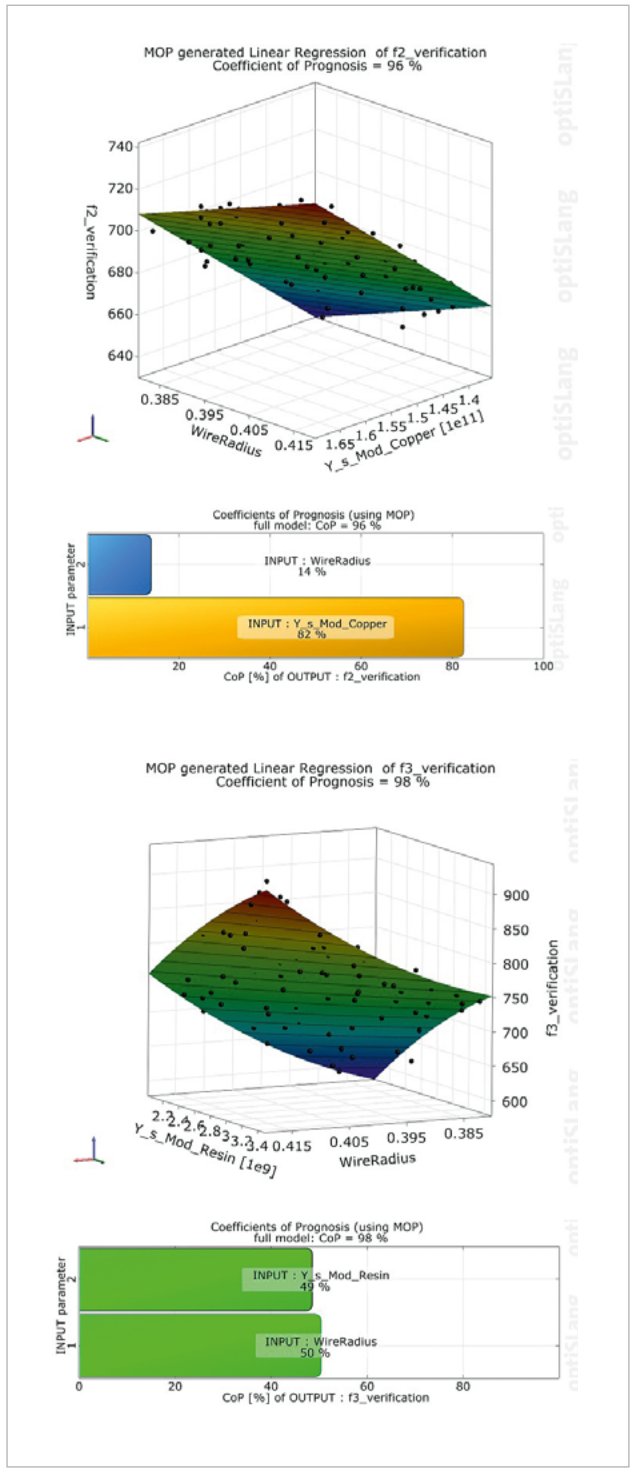

Fig. 6: Metamodel of Optimal Prognosis (MOP) and Coefficient of Prognosis (CoP)

Summary and Results

The results after an optimization of the material parameters show a significant improvement of the frequency and MAC calibration. This method allows an optimal idealization of the windings yielding an improved result quality in the simulation of stator behavior.

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