IDENTIFICATION OF EQUIVALENT ANISOTROPIC MATERIAL PROPERTIES OF 3D-HETEROGENEOUS STRUCTURES

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ABSTRACT

Finite-element models of heterogeneous structures often need to be simplified by the means of representative equivalent homogeneous materials in order to simulate their mechanical behaviours with a reasonably low number of degrees of freedom. In this paper, a novel method of 3D-equivalent material identification is proposed for finite element anisotropic structures and for models subjected to preloads and friction. Taking into account friction properties as well as compression preloads resulting from the manufacturing process, an equivalent finite-element model for the magnetic core of an electric machine stator is created. The simulated modal basis is then compared to experimental ovalisation modes measured on a real stator, and shows good accuracy. These results offer interesting perspectives for dynamic simulations of heterogeneous structures such as industrial electric machines, for which predicting the acoustic behaviours is a key issue for the automotive industry.

1 INTRODUCTION

Relatively common in finite-element simulations involving composite structures, so-called "homogenisation" methods are developed in order to model heterogeneous structures such as laminates or honeycomb plates. For dynamic simulations on industrial electric machine stators, 3D-homogenisation methods for laminated structures may be required as they are built on multi-layered cores. Some vibration and finite-element modelling analyses have been detailed in the literature (such as the works [1, 2]). The current simulation procedures on electric motor stators have the drawback of relying on delicate measurements on costly prototypes.

This is why a new method is proposed, in order to create homogeneous materials whose elasticity matrices approximate the phenomena existing in the initial heterogeneous structures, and take into account boundary conditions and external preturbations as well. A numerical-experimental application on the finite-element model of the magnetic core of an electric machine stator is proposed, accounting for heterogeneities induced by weld beads as well as the influence of inter-lamina friction and prestress on the elastic behaviour. In the following sections, the development of the algorithm for the identification of elastic properties in the case of triclinic materials will be presented, and followed by applications.

2 IDENTIFICATION METHOD FOR ANISOTROPIC MATERIALS

The identification process must be made on a sample representing the periodicity of the structure to be homogenised. Taking the influence of perturbations on the elastic properties is a necessary prerequisite that the finite-element solver used for the identification on the sample must manage. In order to model friction properties, the elements have to be separated: the interface nodes are doubled and coincident (as illustrated in the ellipses on Figure 1), and each of them only belongs to one of the two elements. Then, creating a superelement (with translational degrees of freedom) at the outer nodes is an efficient way to output a stiffness matrix and merge the nodes at the interface.

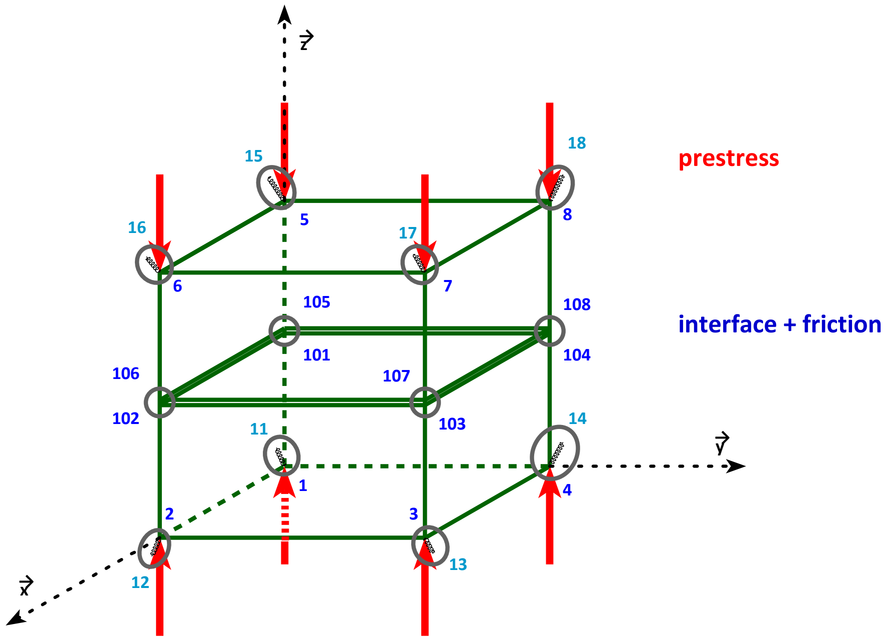

Figure 1: Example of finite element sample

The 21 independent coefficients of a triclinic elasticity matrix C or the associated compliance matrix $S = C^{-1}$ have to be identified independently. The idea of the method is to recompose Hooke's law $\varepsilon = S\sigma$ with 21 independent static simulations on the sample, which are computed in only a few seconds with any commercial finite-element solver.

3 EQUIVALENT FINITE-ELEMENT MODEL OF AN ELECTRIC MOTOR STATOR WITH FRICTIONAL AND PRESTRESS EFFECTS

The finite-element model of an industrial "12-8" switched-reluctance motor is used for this application. An illustration of the model is given on Figure 2. The stator consists in a stack of several hundreds of steel sheets separated from each other by varnish. During its manufacturing process, weld beads are applied on the lateral side of the stack, while the magnetic core is placed under a press. When the pressure is released, the stack is held in one piece by the weld beads, while in the rest of the structure, the only bond between the sheets are bound together is the varnish. This is a source of heterogeneities in the behaviour of the entire structure. Therefore, each colour zone of the model on Figure 2 corresponds to a specific material identification, and therefore to distinct equivalent material properties. The finite-element model as well as the material properties are expressed in the cylindrical coordinate system $\{r, \theta, z\}$.

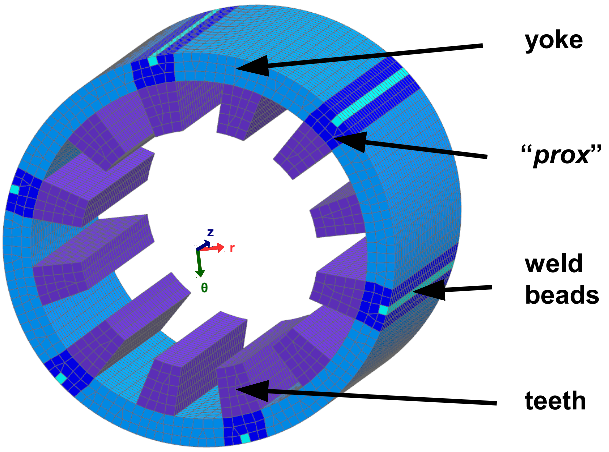

Figure 2: Magnetic core's finite-element model (axis along z)

The compression prestress are computed from the value of 2,500 kg applied on the structure during its manufacturing process, accounting for the distance of the considered zone to the weld beads. At the interface, the contact properties are described by a Coulomb dry friction is of coefficient $\mu = 0.9$. Applying the identification method on each zone then yields the elasticity matrices

$$\tilde{\mathbf{C}}^{\text{yoke}} = \begin{bmatrix} 227 & 65 & 29 & 6\cdot10^{-4} & -1\cdot10^{-5} & 2\cdot10^{-8} \\ & 227 & 29 & 6\cdot10^{-4} & -1\cdot10^{-5} & 5\cdot10^{-8} \\ & & 90 & 2\cdot10^{-3} & -4\cdot10^{-5} & 1\cdot10^{-8} \\ & & & 45 & 3\cdot10^{-3} & 4\cdot10^{-1} \\ & \text{sym.} & & & 45 & 4\cdot10^{-1} \\ & & & & & 78.1 \end{bmatrix} \cdot 10^{9} \tag{1}$$

and

$$\tilde{\mathbf{C}}^{\text{teeth}} = \begin{bmatrix} 233 & 69 & 43 & 2\cdot 10^{-7} & -2\cdot 10^{-7} & 3\cdot 10^{-8} \\ & 233 & 44 & 2\cdot 10^{-7} & -2\cdot 10^{-7} & 1\cdot 10^{-8} \\ & & 14 & 2\cdot 10^{-7} & -2\cdot 10^{-7} & 2\cdot 10^{-8} \\ & & & 3.3 & 2\cdot 10^{-4} & 1\cdot 10^{-1} \\ & \text{sym.} & & & 3.3 & 1\cdot 10^{-1} \\ & & & & & 55 \end{bmatrix} \cdot 10^{9} \tag{2}$$

and the orthotropic material properties for the zone “prox”: $\tilde{E}_r = \tilde{E}_\theta = 205\,\text{GPa}$, $\tilde{E}_z = 157\,\text{GPa}$, $\tilde{G}_{z\theta} = \tilde{G}_{zr} = 51.2\,\text{GPa}$, $\tilde{G}_{r\theta} = 82.1\,\text{GPa}$, and $\tilde{\nu}_{\theta z} = \tilde{\nu}_{rz} = \tilde{\nu}_{r\theta} = 0.25$. The weld beads are modelled with isotropic steel, such as $E = 207\,\text{GPa}$ and $\nu = 0.29$. The same density $7,750\,\text{kg}\cdot\text{m}^{-3}$ is applied to the entire structure.

A modal basis is simulated in real domain between 0 and 10,000 Hz from the entire magnetic core's finite-element model. This simulated modal basis is compared with a set of purely radial modes (of spatial orders 2, 3, 4, 5 and 0), extracted from frequency response functions measured with an impact hammer on the corresponding real stator's magnetic core. These modes are sometimes referred to as “cylinder” or “ovalisation” modes, and are critical for the acoustic behaviour of the entire stator [2]; being able to predict them accurately is thus of particular interest. Finally, the average of absolute frequency discrepancies between simulated and measured modes is 2.83%, while the average MAC-value (expressing the similarities between paired mode shapes) is at 71.9%. Therefore, these results show that the equivalent finite-element model is able to predict the measured ovalisation modes with good accuracy, and without need of expensive updating procedures.

4 CONCLUSION

In this paper, a novel method for identifying equivalent materials to anisotropic structures was proposed. It has been shown that the method is also able to identify equivalent elasticity matrices for an electric machine stator subjected to friction and prestress, and its effectiveness has been validated with experimental data. Additionally, this identification method can be applied to superelements, unlike existing homogenization techniques, and can therefore convert stiffness matrices into equivalent elasticity matrices.

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