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Structural dynamics of electric machine stators: Modelling guidelines and identification of three-dimensional equivalent material properties for multi-layered orthotropic laminates

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ABSTRACT

Simulating the dynamic behaviour of heterogeneous finite-element structures such as electric motors often requires to homogenise the models in the first place. Current homogenisation methods do not always imply computing an equivalent homogeneous material's elasticity matrix and are often restrained to specific uses. In this document, a novel approach of equivalent material identification is developed for multi-layered orthotropic structures. A finite-element model of a 3D stratified structure is created, as well as its equivalent homogeneous medium. The dynamic behaviour of the homogeneous structure with the equivalent material identified by the new method is compared at low frequencies to the reference stack and to equivalent materials created using other existing homogenisation techniques. It is shown that this approach is more accurate than existing reference homogenisation methods. Applied to the magnetic core's finite-element model of a real laminated electric machine stator, the method enables simulating the experimental behaviour with good accuracy, without need of time-consuming model updating procedures.

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1. Introduction

In order to analyse a complex structure's dynamic behaviour, modelling its components may become difficult if they are numerous, small, or if some of the assembly properties are not known. This is one of the reasons why the so-called "homogenisation" methods have been developed. They aim at recreating a given heterogeneous structure's behaviour by reducing the multiplicity of its components' properties, and also enable to mesh the structure independently from the sizes of the heterogeneities, that could have imposed numerous degrees of freedom in the models. Such methods are much desired for modelling composite materials, and especially for laminated structures. Kalamkarov et al. [1] have thoroughly listed and compared over 200 studies about homogenisation and have assessed the pros and cons of various analytical methods and specific applications.

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Table 1
Nomenclature.

Symbols	Definitions
$F_{d,i}$	Reaction force on node i , direction d
T_x, T_y, T_z	Translational DOFs
$\Delta l_{d,i}$	Displacement of node i , direction d
$\bar{\psi}$	Global/equivalent property ψ
Subscript n	Referring to layer n
Subscripts x, y, z	Referring to directions x, y, z
DOF	Degree of freedom
FE	finite-element
2D, 3D	Two-dimension, three-dimension
B_{uN}	Number of nodes on face $u=N$
$\mathcal{U}_{hN}$	Set of nodes on face $h=N$

For industrial projects in structural dynamics as well as academic research involving finite-element simulations on heterogeneous structures, the need of efficient techniques able to model homogeneous equivalent structures both accurately and cost-effectively is great [2]. Therefore, there is a significant interest for simple tools yielding results directly usable for common finite-element software. Motivated by the current coming-up of hybrid or 100 percent-electric vehicles, the development of silent devices (as well as other noise, vibration and harshness (NVH) specifications) in the automotive industry involves finite-element modelling of heterogeneous structures such as electric motor stators [3]. In this perspective, the main objective of this paper is to establish a method to determine representative equivalent material properties (elasticity matrices) for laminated structures, especially for the applicability to any kind of finite-element simulation (including dynamic responses, model updating, etc.) without being limited to specific cases.

Concerning stratified materials, many applications are made under the assumption of plane stresses and strains (for instance with laminated beams or shells), for which theory predicts static and dynamic behaviours with good accuracy (e.g. [4]). In addition, there also exist exact theories and solutions describing the vibration of stratified beams and plates, such as the works [5,6], as well as ready-to-use 2D laminated finite elements present in several software programmes (see e.g. [7]). A finite-element-based homogenisation technique taking into account viscoelastic properties in 2D-laminates has been proposed by Koishi et al. [8]. However, some other analyses cannot be simplified by such assumptions – take the case of no dimension being negligible in the model – and have to be meshed in 3D.

A short review of some existing “3D-homogenisation” methods is made, as well as the fields of their applications. Such techniques are particularly relevant when e.g. parts of 3D finite-element models are multi-layered and need to be homogenised. First of all, the relations that may be the simplest for determining a homogeneous material equivalent to a heterogeneous structure, and that are used in many studies (including reference works in the field of composite materials, such as [4,6]), are weighted averages of the different components' elastic constants, sometimes referred to as the “rule of mixtures”. As shown in [6], the expressions are built from the decompositions of the structure's global stresses and strains according to each of the components.

Let us consider a laminated structure composed of N isotropic layers, stacked along the z -axis. For each layer n , the material's corresponding density ρ_n , Young's modulus E_n and Poisson's ratio ν_n are initially known, as well as its volume fraction

$$\chi_n = \frac{V_n}{V^{\text{stack}}}, \quad (1)$$

where V_n and V^{stack} respectively stand for the layer's and the entire structure's volumes, respectively. The definitions of all the symbols are detailed in Table 1. Then, equivalent density $\bar{\rho}$, Young's moduli $\bar{E}_i$, shear moduli $\bar{G}_{ij}$ and Poisson's ratios $\bar{\nu}_{ij}$ may thus be computed with the following relations:

$$\bar{\rho} = \sum_{n=1}^N \rho_n \chi_n, \quad (2)$$

$$\bar{E}_x = \bar{E}_y = \sum_{n=1}^N E_n \chi_n, \quad (3)$$

$$\bar{E}_z = \left(\sum_{n=1}^N \frac{\chi_n}{E_n} \right)^{-1}, \quad (4)$$

$$\bar{\nu}_{xy} = \sum_{n=1}^N \nu_n \chi_n, \quad (5)$$

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