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Modal stability procedure applied to variability in vibration from electromagnetic origin for an electric motor

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A B S T R A C T

This paper focuses on the variability in vibration from electromagnetic origin for an electric motor. The multiphysics modeling is introduced by the magnetic force density computation and by the coupling of the 2D electromagnetic and 3D structural dynamic finite element models. The modal stability procedure (MSP) and the Monte Carlo Simulation (MCS) are associated for the variability calculation of natural frequencies and frequency response functions (FRFs) of finite element systems with material random parameters. The MSP formulations are developed for 8-node solid hexahedron element modeling the electric stator. The MCS–MSP approach only requires a single finite element analysis, leading to a fast Monte Carlo simulation using MSP formulation. The validation of MCS-MSP is investigated, the uncertainty propagation is discussed and the computational costs of MCS-MSP are presented. This non-intrusive method provides an evaluation of frequencies and FRFs variability for industrial-size models with a large number of degrees of freedom, a large number of random variables and a low or moderate variability level.

1. Introduction

In automotive applications, the noise of electric motors is an important and complex problem. For this kind of application, where both vibratory and acoustic levels are a comfort standard, the machine and its vibration harmonics potentially sweep a range of critical natural frequencies during the working conditions because of the large range of speed and torque. As compared to internal combustion engines, electric machines generate less acoustic noise magnitude but with relatively high frequencies that could be particularly unpleasant for users. Vibrations generated by an electric motor are classed by Gieras et al. [1] considering three main contributions related to three distinct sources: mechanical, aerodynamic and electromagnetic. Progress in mechanical and aerodynamic noise reduction makes the full understanding of magnetic noise generation very important [2]. The acoustic noise from magnetic origin is mainly caused by the direct radiation of the stator under the air gap magnetic forces excitation. Analytical models have been developed to foresee and investigate the magnetic noise [3]. These quick models also suit well with optimization methods to define an initial design of the motor but are limited in terms of accuracy. That is why numerical models development has been undertaken and it appears as an efficient way to reach a good acoustic performance. The coupling of 2D electromagnetic and 3D structural dynamic finite element models seems, for the moment, to be the best compromise to forecast magnetic noise with good precision and acceptable computing time [4]. However, as the computing time cost remains high, the presented coupling method allows reducing calculation time by using an extruded 3D structural mesh. Other approaches have also been proposed to reduce the global coupling calculation time during electromagnetic forces computation [5] or vibrations calculation [6,7]. Furthermore recent works show the ability of numerical models to take into account current harmonics [8] and the great influence of these harmonics coming from the interaction of the machine design and control.

The multiphysics modeling applied to design of electric motors [9] has increased in the last few years and a robust design searches minimal variability in the response when subjected to uncertainties of the input parameters. Uncertainty deriving from measurements, modeling, imperfections, or simply lack of knowledge have effects on the analysis and design of engineering structures. Deterministic methods does not quantify the variability of the responses. One objective of variability studies is to understand different performances measured for theoretically identical systems. Boubaker et al. [10] report the measured booming noise for 15 nominally identical vehicles, leading to a high variability level (10–20 dB). The prediction of finite element model can be improved by using a stochastic method in order to evaluate the

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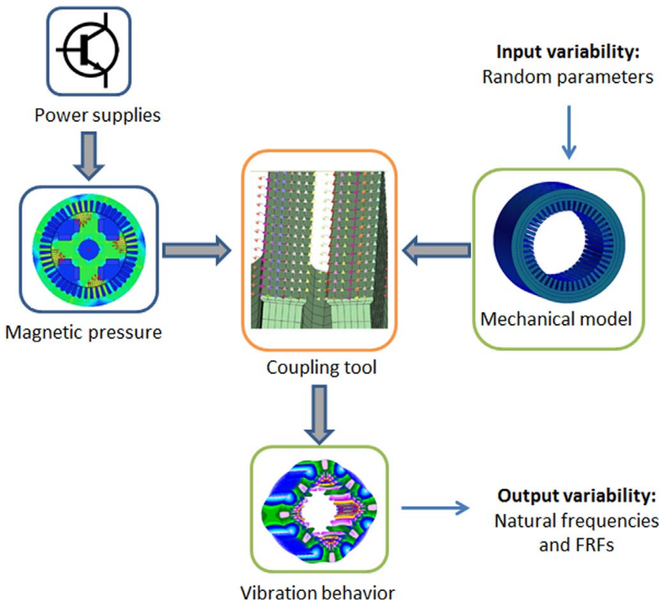

Fig. 1. Mechanical model used to take into account the variability in the multiphysics model.

effect of material properties variability on vibrations of a structure. In this paper, the mechanical model used takes into account the variability in the multiphysics model (Fig. 1). Firstly, a short overview on non-deterministic methods is presented. After description of the electric motor and the corresponding multiphysics modeling, a stochastic method based on modal stability procedure associated to Monte Carlo Simulation and called MCS-MSP is proposed. The MSP formulations for natural frequency and frequency response function (FRF) are developed and applied to an industrial electric stator. The validation of MCS-MSP is investigated. Then, the uncertainty propagation is studied. Finally, the computational costs of MCS-MSP are discussed.

2. Short overview on non-deterministic methods

2.1. Discussion of non-deterministic methods

In analysis and design of engineering structures, current methods for taking into account uncertainties are mostly deterministic with using fixed safety factors. Probabilistic approaches enable uncertainty to be quantified, mainly by using distributions. Many research papers have investigated stochastic methods in structural dynamics since several years.

In automotive vehicles domain, Wood and Joachim [11] studied variability of interior noise levels in collaboration with General Motors, they observed a variation of 10 dB for 12 theoretically identical vehicles. Kompella and Bernhard [12] investigated too variability of frequency response of automotive cars, they observed differences varying from 5 to 10 dB in the low frequency range. Cornish et al. [13] showed measurements on trucks with identical manufacturing and brought out differences up to 35 dB. Blain et al. [14] studied variability of welded plates by considering random parameters as Young's modulus and thickness. Lionnet and Lardeur [15] proposed a hierarchical approach to study vibroacoustic variability of interior noise levels measured in passenger cars. Scigliano et al. [16] investigated experimental and numerical evaluation of intra-variability for the vibroacoustic behavior of a car windscreen. Always in the automotive context, MCS-MSP method was proposed by Martini [17]; formulations for bar, beam and shell elements [10,18,19] were applied to industrial applications. In this paper, this method is here implemented for 8-node solid hexahedron element to evaluate dynamic response variability of an electric stator.

In the electric machine domain, papers are less common than in the mechanical context. Menezes et al. [22] modeled manufacturing uncertainties for electromagnetic simulations by using Monte Carlo simulation. Stocki et al. [23] proposed scatter assessment of rotor-shaft vibration responses with uncertainty on bearing. Mac et al. [24] modeled an electrical machine by using the finite element method and an approximation based on a polynomial chaos expansion in order to quantify the uncertainties.

Methods for solving stochastic problems can be classified in several ways. Benaroya and Rehak [25] or Schuëller [26] proposed classifications. Parametric or non parametric approaches can be considered. Intrusive or non intrusive methods can be distinguished.

The choice of random parameters for a model, and corresponding probability laws, is important for the variability study of a response. In the domain of random vibrations and complex mechanical systems, Durand et al. [27] applied a non parametric approach on structural-acoustic modeling of automotive vehicles to consider both model and parameter uncertainties. For structural dynamics, uncertainties were introduced directly in the global matrices of the system by using maximum entropy principle.

Stochastic perturbation method [28] is widely employed and is interesting for weakly nonlinear problems with a low variability level. Cambou [29] introduced the first order perturbation in finite element models by considering variability of mechanical parameters. Kamiński studied the second order perturbation to improve accuracy [30], proposed a generalized nth order version [31] and applied it to thermo-electro-magneto-mechanical coupling [32]. Falsone and Ferro [33] proposed a method in dynamics by solving eigenvalue problems using nominal and perturbed matrices.

The spectral stochastic method (SSFEM) combined the finite element method and a probabilistic framework. This method was proposed by Ghanem and Spanos [34] for taking into account uncertainties in mechanical models by using random field discretized by Karhunen-Loève expansion [35]. Several complete overviews were devoted to SSFEM by Matthies et al. [36], Schuëller [26], Sudret and Der Kiureghian [37] and recent advances by Stefanou [38]. The discretization of random dimension was made with a family of polynomials, in particular the polynomial chaos expansion. Initially, this class of method was intrusive. Ghanem [39] summarized implementations of SSFEM and proposed a methodology. Papers dealing with stochastic methods rarely proposed errors on mean value or standard deviation. Even so, Ahmad [40] compared SSFEM and MCS methods for an oil rig model composed of bar elements to evaluate natural frequency variability; errors obtained on standard deviation varied with chaos order and so computational cost. These methods are intrusive and are not easy to be used in industrial context with a standard finite element software. More recently, non intrusive approach was proposed to calculate chaos coefficients. The alternative spectral method was combined with regression by Berveiller et al. [41]. A spectral projection was used too by Beddek et al. [42] to study uncertainty propagation in electromagnetic models.

Sampling method as Monte Carlo type was well known and was presented in detail in many papers, especially by Fishman [43]. Monte Carlo method was often considered as a reference method due to its robustness and its reliability. It is a common practice to run Monte Carlo simulation (MCS) to provide the statistic quantities (distribution, mean, standard deviation, coefficient of variation). But the main drawback is the large number of trials needed to obtain convergence, that induces a high computational cost. In order to be used in industrial context, improvement of