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VALIDATION OF THE VIBRATIONAL BEHAVIOUR OF ELECTRICAL MACHINES UNDER ELECTROMAGNETIC EXCITATION USING MANATEE® SOFTWARE AND ALTAIR OPTISTRUCT®

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The present work compares the vibrational behaviour of an electrical machine stator under electromagnetic forces using Finite Element Modelling (FEM) or analytical modelling within MANATEE® electromagnetic and vibroacoustic simulation environment. The Finite Element software coupled to MANATEE® is Altair Optistruct®. Two types of results are computed and compared: a modal analysis is run to obtain eigenmodes of a stator lamination of an electrical machine; Frequency Response Functions (FRF) are computed for the structure lamination under rotating wave excitation of different wavenumbers r. This work is part of a global strategy to speed up the vibroacoustic design process of electric motors under Maxwell electromagnetic forces. A previous work presented an automated coupling tool of electromagnetic and structural mechanics simulation models. This tool is used here to parametrize the same study case for results computation using FEM and analytical model. The two modelling strategies give close results in terms of eigenfrequencies of pure circumferential mode of lamination and dynamic responses.
Keywords: finite element analysis, electromagnetic forces, vibrations

1. Introduction

This article deals with the modelling and the simulation of the mechanical behavior of electrical machines. In fact, electromagnetic noise and vibration is increasingly taken into account by electric machine manufacturers in sectors such as automotive (e.g. alternators, compressors, pumps), railway (e.g. traction machines, power transformers) and naval indutries (e.g. propulsion machinery). Acoustic noise of magnetic origin may be generated by two different kinds of magnetic forces: magnetostriction and Maxwell forces. Both these forces produce circumferential vibrations that may excite the structural modes of the stator yoke. In radial flux electrical machines, the noise is usually produced by the circumferential modes of the yoke excited by Maxwell forces.

A previous work described in [1] validated the electromagnetic to mechanical coupling from MANATEE® software to Altair Optistruct® software in a fully automated way, for three methods: direct method based on Fourier series expansion of nodal magnetic forces, unit rotating wave and tooth excitation methods, the two latters using Electromagnetic Vibration Synthesis (EVS) method.
The present article compares the evaluation of vibrations of electrical machine for two modelling ways:

- Analytical model in MANATEE® software,
- Finite Element Analysis in Optistruct® software using a rotating wave excitation (no use of EVS method here).

1.1 MANATEE®

MANATEE® software [2] initially stands for Magnetic Acoustic Analysis Tool for Electrical Engineering. It is a commercial simulation software dedicated to the fast electromagnetic design of electrical machines, including the evaluation of 3D electromagnetic forces, vibrations and acoustic noise due to Maxwell forces at variable speed.
It is an integrated multiphysics tool and the simulation process is summarized in figure (1). Assuming a weak coupling between structural mechanics and electromagnetics, the electrical currents are first calculated using equivalent electrical circuits. Based on rotor and stator current waveforms, the electromagnetic module computes the airgap flux distribution using subdomain models, which are as accurate as finite element method and as fast as analytical models. The structural module consists in projecting the resulting Maxwell stress on the stator or rotor structure, and evaluating deflections. The acoustic module finally calculate the radiated sound power and pressure levels.

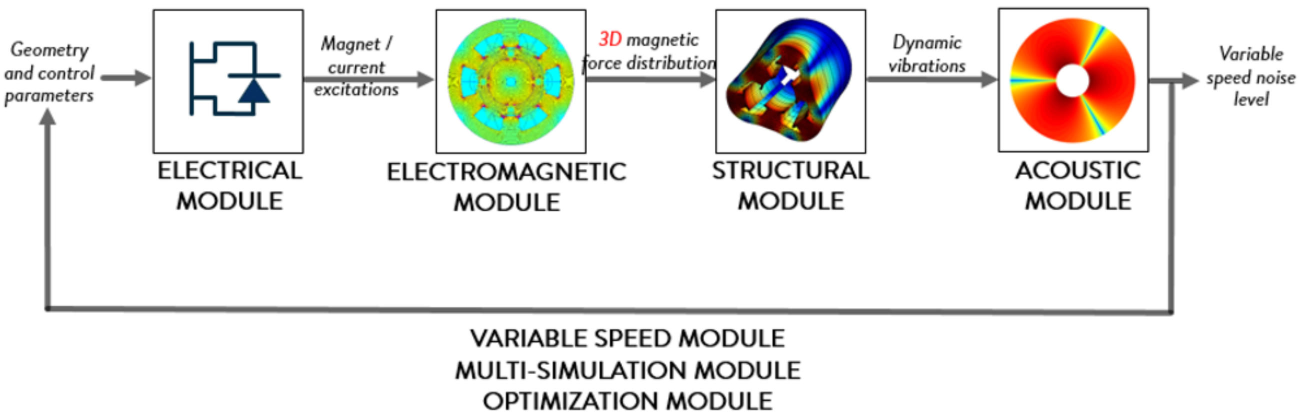


Figure 1: MANATEE® software simulation workflow.

The analytical structural mechanics module of MANATEE® includes
- The calculation of the stator structure natural frequencies [4], including both extensional modes (purely circumferential) and modes involving longitudinal deflections. The lamination is modelled as an equivalent cylinder where the mass of teeth is taken into account. The stiffening effect of teeth is also considered.
- The calculation of radial dynamic deflections of the structure under radial electromagnetic forces based on analytical model (second order transfer function).
- The calculation of radial (and tangential) dynamic deflection(s) of the structure under tangential electromagnetic forces based on analytical model.

The analytical modeling basis of natural frequencies of the breathing and circumferential modes of the 2D stator with teeth as defined in MANATEE® is given in [4] for free-free conditions. MANATEE analytical model includes the effect of free, simply supported or clamped conditions at both ends of the lamination stack using the boundary coefficients of [7]. Besides that, the radial average quadratic vibration velocity over the 3D surface of the stator is also corrected to account for the boundary conditions using the modulating "beam functions" of [8].

1.2 Altair Optistruct®

Altair Optistruct® [3] is a structural analysis solver for linear and nonlinear simulation under static or dynamic loadings. It is a scientific software based on finite-element and multi-body dynamics technology, and through advanced analysis and optimization algorithms. In mechanical engineering, and more specifically in Noise, Vibration and Harshness (NVH) domain, Optistruct® gives a fully featured NVH solver containing computation of normal modes, complex eigenvalues, frequency response analysis, random response, transient and acoustic analysis.
The geometry and mesh description is managed by HyperMesh. In the present work, the geometry and mesh generation is automated through a TCL script (read [1]). The computation is realized by the corresponding solver (Optistruct® for mechanical analysis). Post-processing can be realized with HyperView.

In the present work, the Frequency Response Functions (FRFs) of the structure under unit rotational pressure waves of different wavenumbers computed with Optistruct®, are calculated and post-processed in MANATEE®.

1.3 Goals

The aim of the present work is to validate the structural mechanics module of MANATEE® comparing results to finite element structural analysis for two computations: modal analysis and Frequency Response Function (FRF) computation.
The modelling is first described and results are presented, in terms of computed eigenmodes and FRF, but also computation times.

2. Modelling description

The structure considered is the stator lamination of a Squirrel Cage Induction Machine (SCIM) (see figure (2)). The main geometric parameters are summarized in table (1). The stator lamination is made of iron (cf. mechnical properties in table (2)). In this first work, it is assumed to be isotropic to be able to make a direct comparison with the analytical model of [4] although the stator lamination package is known to be orthotropic.
The stator is excited by radial forces applied on each tooth, defined as rotating waves of wavenumber r. Two examples of such waves are represented on the figure (2), with $r = 0$ and $r = 2$.

Stator core	
Number of teeth Z_s	36
Outer diameter $D_{sy}(m)$	0.4
Inner diameter $D_{sbo}(m)$	0.27
Lamination length $L_{st}(m)$	0.35
Yoke height $H_{sy}(m)$	0.035
Stator slot	
Slot height $H_0(m)$	0.03
Slot width $W_0(m)$	0.012

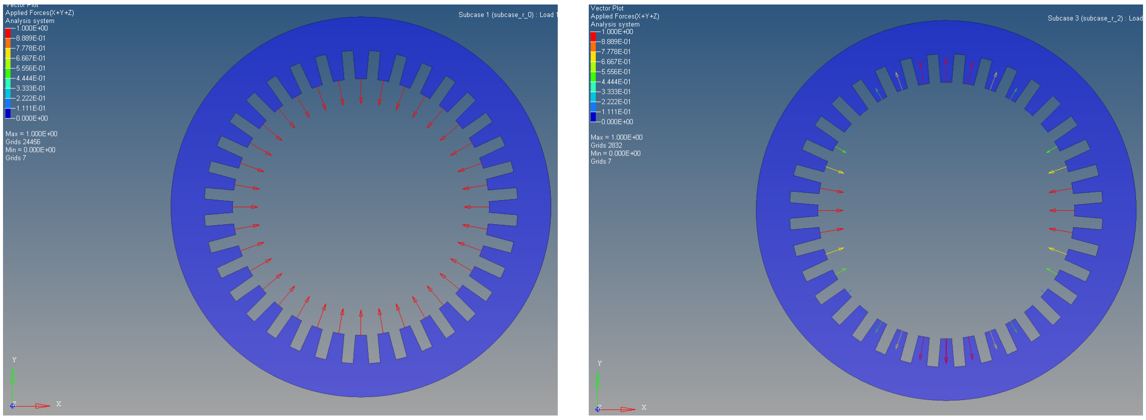
Table 1: SCIM machine's geometry.

The 3D meshing (see figure (3b)) in Altair HyperMesh is built by an extrusion of the 2D mesh (see figure (3a)) of a tooth using a *Solid Map Mesh* tool. Meshing is done with hexahedral elements which are solid elements extracted from 2D quad elements [1]. Meshing informations are summarized in tables (3) and (4).

For both methods, computations are done from 0 to 5000 Hz with 20 Hz step and with following wavenumbers: $r = 0, 1, 2, 3, 4, 5$ for FRF determination. Particularly, for FRF computation us-

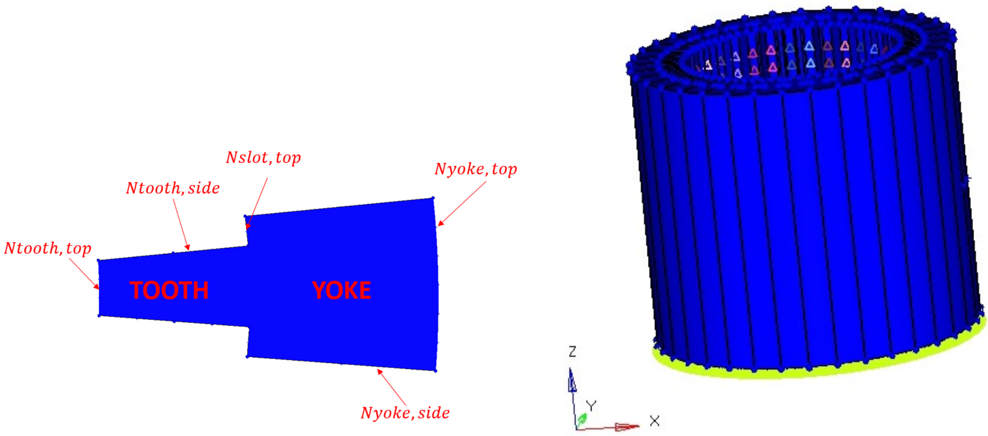
Young Modulus $E(GPa)$	210
Poisson's coefficient $\nu(-)$	0.3
Density $\rho(kg.m^{-3})$	7900
Calculated mass $m(kg)$	159.1
Structural damping $(\%)$	2

Table 2: SCIM machine's mechanical properties.



$r = 0$ $r = 2$

Figure 2: Unit rotating forces of wavenumbers r.



(a) (b)

Figure 3: (a) Parametrization of meshing 2D tooth. (b) Mesh of the stator.

QUANTITY	VALUE
$N_{tooth,top}$	4
$N_{tooth,side}$	16
$N_{slot,top}$	4
$N_{yoke,top}$	15
$N_{yoke,side}$	16
N_{layers}	16

Table 3: 2D meshing information (see figure (3)).

ing Altair Optistruct®, the structure excitation is defined in the TCL script automatically built by MANATEE®. The FRF are then computed over the nodes on the stator yoke. The radial deflection is of interest, obtained by the quadratic average of displacements (see figure (3b)). The results are

Finite Element Model data information	
Total of elements	105120
Total of Degrees-of-Freedom	336960
Element type information	
CHEXA Elements	102528
CPENTA Elements	2592

Table 4: Meshing informations.

represented thereafter in terms of maximum FRF magnitude over yoke nodes.

3. Results and comparisons

3.1 Natural frequencies

The figure (4) represents the eigenfrequencies computed analytically with MANATEE® and numerically with Altair Optistruct®. Table (5) lists the results obtained by the analytical computation of structure's eigenmodes in MANATEE® and Finite Element Analysis realized with Altair Optistruct®. The comparison between the two methods is realized calculating the relative error between both eigenfrequency values for a given mode, FEM results being the reference.

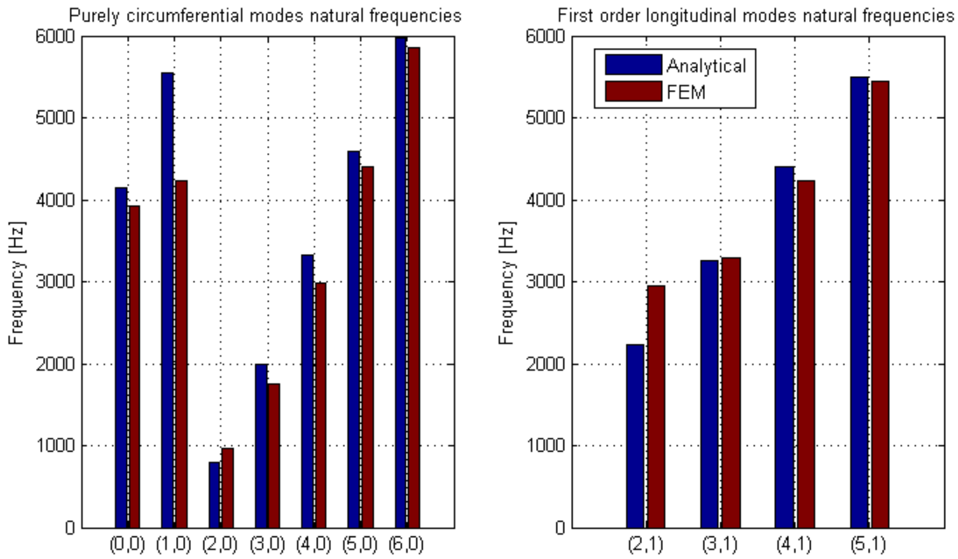


Figure 4: Natural frequencies of stator lamination computed analytically and numerically: on left, purely circumferential modes and on right, first order longitudinal modes.

The eigenfrequencies of circumferential modes of the stator are close and the maximum error between analytical and numerical computations observed in table (5) equals 31.3 %. The closest results are obtained for modes $(3,1)$, $(5,1)$, $(4,1)$, $(0,0)$ and $(5,0)$.

Further modes are computed with FEM: bending, torsion and piston modes of cylinder. Eigenfrequencies are given in the table (6). These modes are not included yet in MANATEE® analytic model.

The eigenfrequencies computed in Altair Optistruct® are enforced in MANATEE® to focuse on the comparison of FRF.

Mode	Eigenfrequencies (Hz)		
	Analytical Results	FEM Results	Relative error (%)
$(0,0)$	4137	3928	5.3
$(1,0)$	5544	4223	31.3
$(2,0)$	799	968	17.5
$(3,0)$	2000	1756	13.9
$(4,0)$	3327	2984	11.5
$(5,0)$	4597	4395	4.6
$(6,0)$	5976	5848	2.2
$(2,1)$	2235	2945	24.1
$(3,1)$	3263	3288	0.8
$(4,1)$	4394	4231	3.9
$(5,1)$	5499	5452	0.9

Table 5: Eigenmodes of the structure computed with both methods.

Mode	Eigenfrequencies (Hz)
1^{st} order bending	1274
2^{nd} order bending	3491
1^{st} order torsion	2071
2^{nd} order torsion	5879
Piston	3586

Table 6: Other eigenmodes results in Altair Optistruct®.

3.2 Frequency Response Functions

The maximum FRF observed on the yoke circumference, obtained in Altair Optistruct® and MANATEE® are visible on the figure (5).

As the analytical model does not compute the bending modes of the cylinder, the FRF plot for $r = 1$ from MANATEE® is not represented on the graph. For each rotating exciting wave of wavenumber r, the FRF obtained with analytical model contains a single peak corresponding to the purely circumferential mode. For instance, for $r = 2$, it is possible to note the resonance due to the mode $(2,0)$ for analytical model results.

Observing the FRF results from numerical model, the rotating wave of wavenumber $r = 1$ excites the two firsts bending modes of the structure in the frequency band $0-5000$ Hz (1274 and 3491 Hz in table (6)). As expected, the rotating waves of higher wavenumbers $r = 2,3,4,5$ excite the respective modes $(2,0)$ and $(2,1)$, $(3,0)$ and $(3,1)$, $(4,0)$ and $(4,1)$, and $(5,0)$ in the frequency band considered.

At the resonance, the FRFs obtained numerically are higher than the FRFs obtained analytically, except for $r = 2$. The maximum magnitude difference between resonance peaks of numerical and analytical FRFs is more than 3.3 dB (ref. 10^{-6} $m/(N/m^2)$) for $r = 0$ and less than 7 dB (ref. 10^{-6} $m/(N/m^2)$) for $r = 5$.
The FRF shapes are similar over and below the resonance.

Note that these results are obtained without tuning factors on the FRF magnitude, but the aim of this work is to generalize this comparison between analytic and finite element methods on various sizes of electric machines in order to define some robust tuning factors in MANATEE.

3.3 Computation time

The computation times are identified for both computation methods in table (7). The analytical model run in MANATEE® allows to obtain natural frequencies and FRF at the same time whereas in

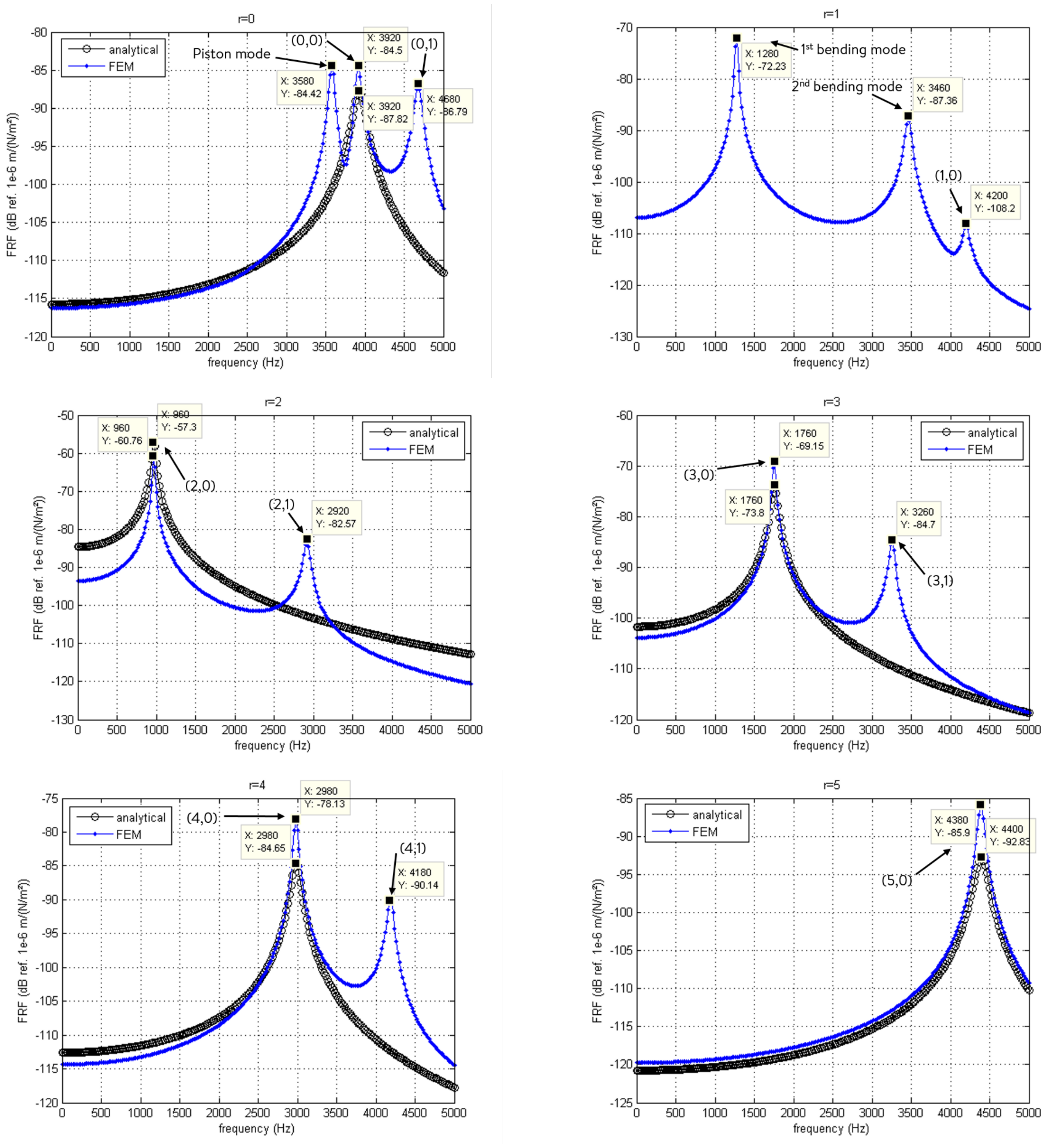


Figure 5: FRF under different rotating waves of wavenumbers r obtained analytically using mechanics module of MANATEE® and numerically using Altair Optistruct®.

Altair Optistruct®, two simulations have to be run. Pre and post processings for FEM computation refers to the automated process developped and described in [1]. The computation of FRFs with FEM software is the most long but gives more informations on structure vibration.

4. Conclusions

This article show that the analytical models of natural frequencies and stator deflections based on an equivalent cylinder, including the effect of boundary conditions, show good agreement with finite element method (coupling of MANATEE® and Altair Optistruct®) in terms of

- eigenfrequencies of circumferential modes and

Computation method	Computation	Pre-processing	Solving	Post-processing	Total
Analytical (MANATEE®)	Modal analysis				
	FRF computation		1.5667 s		1.5667 s
Numerical (Altair Optistruct®)	Modal analysis	0.5 s	567 s	–	567.5 s
	FRF computation	1.5 s	749 s	300 s	1050.5 s

Table 7: Computation times.

- FRF magnitudes at the resonance corresponding to pure circumferential modes.

The analytic structural model of MANATEE® can therefore be used in the early electromagnetic design phase of electric motors to avoid the main resonances between circumferential modes and radial electromagnetic forces.

5. Future work

In the future, the validation of the analytical mechanical model of MANATEE® will be extended to tangential excitations.

Future work also aims at providing some experimental measurements to validate MANATEE® results based on its coupling with Optistruct® or its built-in analytic model. The computations realized in this paper generalized to outer rotor permanent magnet machines will be also studied. Finally, the validation will be extended to orthotropic materials, including the effect of winding and impregnating resin [6].

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