Fast Prediction of Variable-Speed Acoustic Noise and Vibrations due to Magnetic Forces in Electrical Machines

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***Abstract* -- This paper presents a new multiphysic model and simulation environment for the fast calculation and analysis of acoustic noise and vibration levels due to Maxwell forces in variable-speed rotating electrical machines.**

In the first part, some numerical methods for the prediction of electromagnetic noise are analyzed and compared to analytical or semi analytical techniques.

In the second part, a new coupling of electrical, electromagnetic and vibro-acoustic models based on analytical and semi-analytical modeling techniques is presented. This model is validated by comparing simulation results to experimental results on several electrical machines at variable speed, including surface permanent magnet (SPMSM), interior permanent magnet (IPMSM) and squirrel cage induction machines (SCIM). The main resonances and noise levels are correctly estimated by the models implemented in MANATEE® simulation software, and the calculation time at variable speed varies from one second to a few minutes including harmonics up to 20 kHz.

***Index Terms*—Acoustic noise, Vibration, Electromagnetic forces, Numerical Simulation, Electrical machines**

I. Nomenclature

Symbol	Description
f	frequency of an airgap permeance, mmf, flux or magnetic pressure harmonic wave
f_R	mechanical frequency [Hz]
f_s	fundamental supply frequency [Hz]
mmf	magnetomotive force [A]
p	pole pair number (2p poles)
r	wavenumber of an airgap permeance, mmf, flux or magnetic pressure harmonic wave
Z_r	rotor slot number
Z_s	stator slot number
FEA	Finite Element Analysis
GCD	Greatest Common Divider
IPMSM	Interior Permanent Magnet Synchronous Machine
LCM	Least Common Multiple
SCIM	Squirrel Cage Induction Machine
SPL	Sound Pressure Level
SWL	Sound Power Level
WRSM	Wound Rotor Synchronous Machine

II. Introduction

A. Sources of noise and vibration in electrical machines

THE vibro-acoustic design of electrical machines can be as important as its electromagnetic or thermal design in an increasing number of applications. This is the case of rotating machines working close to human presence in industrial applications (e.g. elevator, conveyor motors), household appliances (e.g. HVAC, electric curtains), transportation (e.g. ships, trains, electric cars, pedal-assist bicycles) and energy (e.g. wind turbine generators). More generally, the vibration and acoustic noise levels of electrical machines have to be controlled and reduced as part of their global environmental impact.

Noise and vibration sources of electrical machines are usually classified in mechanical, aerodynamic and magnetic sources [1]. Mechanical noise and vibrations can come from bearings, gears and brush commutators, whereas aerodynamic noise is due to air pressure periodic variations coming for instance from mounted fans or air-gap vortices due to slotting effects ; in high speed machines, these aerodynamic forces can also excite the structural modes of the machine and give high pitch noise [2].

Magnetic vibration and audible noise are due to the deflections of the magnetic circuits of the electrical machines under magnetic forces; magnetic forces are defined as forces arising from the presence of a magnetic field, which can be due to permanent sources as in permanent magnet synchronous machines, or induced by some current sources as in induction machines. Two types of magnetic forces occur in electrical machines: magnetostrictive and Maxwell force [3]. Qualitatively, magnetrostrictive forces occur in magnetic sheets and tend to shrink the material along the field lines, whereas Maxwell forces are mainly located at the lamination interface with air and globally tends to bring the stator closer to the rotor (law of minimal reluctance); both phenomena are quadratic function of the flux density and can result in radial deflection of the yoke and acoustic noise. Although the scientific debate is still not closed on the respective contribution of these forces in the different electrical machine topologies and power ranges [4][5][6][7], this paper only focuses on Maxwell forces; experimental results presented in this paper and author's experience confirm that there is no need to model magnetostrictive effects to account for main electrical noise issues occurring in both asynchronous and synchronous machines, even when considering power ranges from W to MW.

A. Noise and vibration issues due to magnetic forces in electrical machines

Electromagnetically-induced acoustic noise can be a key contributor to the global sound power level of electrical machines for several reasons. Firstly, due to the strong harmonic nature of magnetic forces in both time and space domains, magnetic noise is characterized by strong tonalities (emergence of a given harmonic above the background noise)

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and usually occur in the most sensitive frequencies of the human ear (1 to 10 kHz). This makes it sound particularly unpleasant, especially as some progress is made on the reduction of the other broad-band noise sources (e.g. use of water cooling technology instead of fans). Secondly, the design optimization of electrical machines with respect to cost, weight and efficiency tend to minimize materials, leading to thinner yoke width and increased vibration levels. The search for low-cost and high power density machines requires to make a trade-off between electromagnetic and NVH performances.

After manufacturing, the redesign of a noisy converter-fed machine due to electromagnetic forces is generally expensive and time-consuming. When electromagnetic noise is not due to converter harmonics and is only related to fundamental current, for squirrel-cage machines, a new rotor with a different slot number is generally manufactured [8][9], or the noisy rotor is skewed of one slot pitch, the stator manufacturing being more expensive; for permanent magnet synchronous machines (PMSM), a new magnet geometry, a new stator slot number with a new winding architecture, or a stepped-skew of the magnets are different techniques that can be applied to reduce the noise and vibration levels. When electromagnetic noise is coming from converter harmonics, these design changes are useless and the main solution relies on a change of the switching frequency or the switching strategy [25]. Last-minute software modifications are not possible for applications requiring high safety levels (e.g. electrical traction); moreover, the change of the supply strategy affect the loss distribution between the converter and the machine, and can have side effects like the increase of torque ripple harmonics and temperature rise.

Due to the lack of calculation models, these post-manufacturing techniques are generally applied empirically, without having enough time to identify the root cause of the noise issue, and do not lead to expected improvements. Besides that, they require to re-run the electromagnetic design process and sometimes lead to a loss of electromagnetic performances: as an example, the skewing technique lowers the fundamental torque and the electromagnetic efficiency.

Some models must therefore be developed to estimate acoustic noise and vibration levels at an early design stage. Once the electrical machine is manufactured, some specialized post-processing techniques must also be developed to help understanding the noise and vibration generation process, identify its sources and reduce them with passive or active methods while keeping initial electromagnetic performances.

These models must be multi-physics: an electrical model is necessary to calculate converter current harmonics responsible for high frequency magnetic forces and noise; an electromagnetic model is necessary to calculate Maxwell stress distribution in the machine; a structural model is necessary to calculate the lamination dynamic deflection under magnetic forces; an acoustic model is necessary to calculate the sound power level and sound pressure level of the machine.

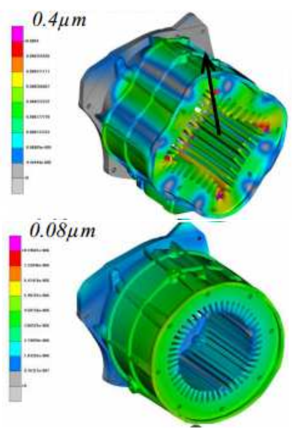
This paper therefore reviews the different methods for calculating noise and vibration due to magnetic forces, especially numerical methods. A semi-analytical method is then presented and validated, showing accuracy comparable to FEA methods while achieving high calculation performance.

II. On the use of FEA method for vibro-acoustics of electrical machines

A. *Analysis of some FEA-based vibroacoustic studies*

A first method to estimate the noise and vibration levels due to magnetic forces is to use a fully numerical model based on Finite Element Analysis (FEA). To answer this need for vibroacoustic virtual design of electric motors, most commercial electromagnetic FEA software (e.g. Flux, Jmag, Maxwell) already propose a coupling with some structural FEA software; alternatively, some integrated multiphysics environment (e.g. Ansys Workbench, Comsol Multiphysics) can be used to carry integrated electromagnetic and vibroacoustic numerical calculations. In this part, some articles using these techniques are reviewed and their conclusion are analyzed.

In [15] a Simulink model is coupled to 2D magnetodynamics with Maxwell, and a 3D structural model is solved under Nastran using a modal decomposition approach. Although Simulink allows to obtain the full frequency spectrum of stator and rotor currents, only 3 harmonics are then effectively included in the FEA electromagnetic simulation. The solving time of the 2D electromagnetic model made of 12,418 first order triangular elements is not given (it is necessarily larger than 45 min given in [14]), but the structural simulation time is 45 min up to 3 kHz on a high performance workstation for a single speed. The acoustic simulation under Actran is not presented in the paper. This means that this type of simulation, presented as a “fast numerical coupling method”, can easily reach two days of calculation at variable speed (56 hrs in [14]), without coupling with acoustics and assuming that the coupling between Maxwell2D and Nastran has been automated. The largest identified harmonics in the magnetic forces and in the stator vibrations are $\{f=2f_s, r=2p=4\}$ (clockwise direction), $\{f=\pm 12f_s, r=0\}$, and $\{f=-22f_s, r=2p=4\}$ (anti-clockwise direction) (see Fig. 6).



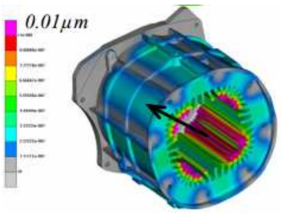


Fig. 1: Stator and housing deflection under magnetic forces at $2f_s$ (r=4), $12f_s$ (r=0) and $22f_s$ (r=4) [15]

The first vibration wave is due to the squared fundamental flux density creating the largest harmonic force – its frequency is too low to excite the 2p lamination mode, but it results in high magnitude forced vibrations. It is not linked to slot / pole interaction. The second vibration wave is due to stator current harmonics, the combination of stator flux waves {f=-5f_s, r=p} and {f=7f_s, r=p} giving rise to a pulsating radial and tangential Maxwell force wave {f=12fs, r=0}, which is not linked to slot / pole interaction. The third vibration is given by r=GCD(Zs,2p)=2p=4 and f=LCM(Zs,2p)f_R-2f_s=22f_s and is linked to stator slot / rotor pole interactions. This expression can be derived analytically as shown in [18][19]. The same type of harmonic force is present at the other frequency LCM(Zs,2p)f_R+2f_s=26f_s which is also mentioned in [12].

[12] presents another FEA-based study on the same machine at variable speed. The 2D electromagnetic FEA based on Maxwell does not include any current harmonics, but includes rotor eccentricity. The strong electrical circuit coupling is ignored, although it may affect magnetic forces as noted in the paper. The electromagnetic simulation time is not given, but it is necessarily higher than the 45 min per speed of [14] due to the eccentric model. The 3D structural simulation time is 45 min per speed as in [14].

A resonance at 4600 Hz is found with the 44th harmonic of the rotation frequency (f=22f_s) due to 4th circumferential mode of the lamination, and a second resonance is found with the 48th harmonic (f=24f_s) due to the 0th mode (breathing mode) of the lamination at 5700 Hz.

Provided that the natural frequencies are calculated using FEA or analytical methods, these two resonances could be predicted analytically. The first force wave is the one previously identified coming from a pole/slot interaction, the second one is the pulsating (r=0) radial and tangential force wave occurring at multiples of LCM(Zs,2p)f_R=24f_s, also due to pole/slot interaction [13].

Due to high computation time in structural FEA, the speed discretization step is only 1000 rpm, but it is not small enough to correctly capture resonance effects. Indeed the minimum speed steps ΔN_s is given by (for a synchronous machine) [8]

$$\Delta N_s = 60\frac{\xi f_{r0}}{p} \qquad (1)$$

where f_{r0} is the lowest natural frequency of the structure with damping ξ. This is illustrated in Figure 2.

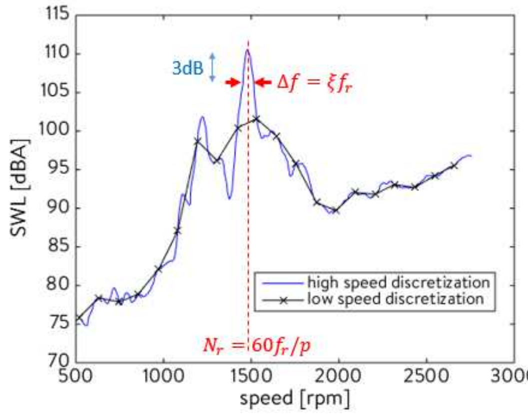


Figure 2 : Illustration of the impact of the speed discretization step on the estimation of the maximum sound or vibration level

In this example where the lowest natural frequency is 400 Hz, assuming a 1% damping the width of the peak at resonance is 4 Hz and the associated speed variation is 120 rpm. To capture the maximum vibration level correctly, the speed step should be chosen much smaller than 120 rpm.

More generally, the total number of simulation steps depends also on the speed range of the machine:

$$\mathrm{N}_{tot} = \frac{N_{max} - N_{min}}{\Delta N_s} = \frac{f_{max} - f_{min}}{\xi f_{r0}}$$

The larger is the electrical machine, the lower is the natural frequency and the higher is the number of simulations to be run. Similarly, the wider is the speed range of operation and the larger is the number of simulations to run. Outer rotor of PMSG have lower damping due to missing winding: to assess their vibroacoustic behavior with 10 rpm variation and 0.15% damping with a first mode at 50 Hz, one obtains Ntot= 200 simulations. For a high speed small BLDC machine going from 0 to 100000 rpm with a lowest mode at 5 kHz and a 2% damping due to stator damping one obtains Ntot=1000 simulations.

[14] is a similar FEA study on the same machine, still using Maxwell2D and Nastran. The aim of the paper is to study the effect of current induced harmonics on noise and vibration.

The 2D electromagnetic model has 3862 second order triangular elements, and the quasi-static electromagnetic solver takes 45 min for each speed. The coupling between electromagnetic mesh and structural mesh takes 5min per speed when optimized, due to large file (30000 nodes) writing and reading processes. The Nastran 3D model, probably similar to the one used in [15][12], has 497455 elements, 2305183 DOF, and 7056 nodes in which magnetic forces are applied. The overall calculation time of a vibration spectrogram with 100 rpm speed discretization, this time meeting the criterion given by (1), is then 56 hours. It is shown that a torsional mode at 800 Hz is excited by harmonics at f=6f_s, 12f_s and 24f_s; the stator mode r=4 is excited by harmonics at f=20f_s and 26f_s. Simulation results show that the effect of stator current harmonics due to slotting and winding effects do not create new resonances and only shift the overall vibration level of 17 dB independently of speed. The authors do not provide any explanation for this large difference.

Flux [9] proposes a coupling with LMS Virtual Lab [11],

Nastran or Ansys. This coupling with Nastran has been developed in the framework of AVELEC project [16][17] on the same machine, a WRSM with p=2 and Zs=48.
[17] investigates the use of Flux to calculate the vibroacoustic behaviour of this same WRSM. It is shown that a tradeoffs must be done between calculation time (linked to rotor angular step) and accuracy. It is advised to use regular mesh of rotor and stator airgap bands, and make them coincident using a rotor angular step proportional to the mesh angular width. However, this means that the maximum frequency of the force spectrum is proportional to the speed, giving only results at 500 Hz at 1000 rpm (see Fig. 3).

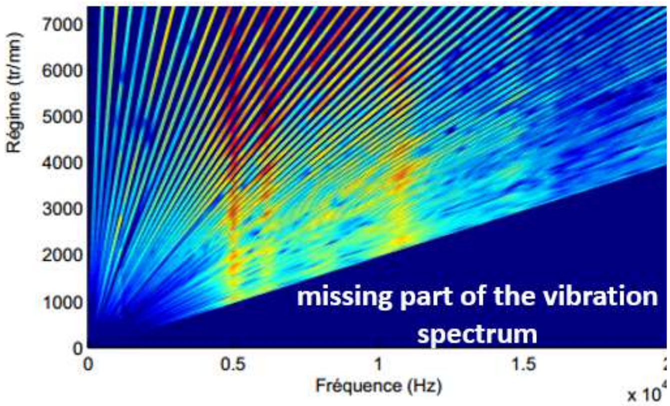


Fig. 3: Calculated spectrogram from [17]

Even with this method, up to 4 dB of variations is obtained below 10 kHz due to numerical errors. The choice of the airgap radius to calculate the Maxwell stress is also discussed and significant variations of airgap flux harmonic magnitude are observed when the integration path is situated below the middle of airgap; the path should be taken at the airgap middle or closer to the stator. An experimental comparison between calculation and tests is done, but no absolute comparison is possible due to missing color legend. The same resonances as previously identified based on analytical considerations are found.

[30][31][32] investigates the use of COMSOL Multiphysics to calculate the variable speed electromagnetic noise of an induction machine. They report having to simplify the problem in order to reduce the high computing time of the electromagnetic fields (several hours for one operating speed). Besides that, although COMSOL is supposed to be an integrated multiphysic environment, a special tool had to be developed by the authors in Matlab to make the harmonic conversion of the Maxwell stress tensor, and be able to run the structural and acoustic models in the frequency domain. Finally, different structural models (with and without housing) had to been defined due to the uncertainty on the coupling between the stator lamination and frame. The conclusion of the work presented in [32] is the ability of the multiphysic numerical tool to account for a resonance at 1500 rpm.
The elliptic mode (m=2) natural frequency of the stator stack can be estimated close to 1100 Hz using semi-analytical models of [29]. The induction machine is a 4-pole (p=2) with Zs=48 stator slots and Zr=38 slots. The largest magnitude slotting harmonic magnetic force has then a wavenumber r=Zr-Zs+4p=-2 due to saturation, which occurs at frequency f=fs(Zr(1-s)/p+4)=1150 Hz at no-load based on analytical considerations presented in [24]. A strong resonance therefore occurs at nominal speed due to the excitation of the stator stack ovalization mode with a saturated magnetic force harmonic.

Jmag software also proposes a coupling with LMS Virtual Lab for the calculation of magnetic vibration and noise.

In [36] Jmag is used in 2D for the magnetic force calculation of a 18/6 SRM. The structural calculation is carried using modal superposition with Nastran NX based on harmonic loads. The acoustic model is solved up to 4000 Hz using AML (Automatically Matched Layer) algorithm. The acoustic impact of airgap length and winding layout is then studied. The analysis is carried at fixed speed; no calculation time nor comparison with experiments is given.
Following the same method, [36] presents a fully numerical vibroacoustic analysis of a PMSM up to 4 kHz at a fixed speed. It is demonstrated that the definition of the boundary layer leads to 5 to 10 dB variation depending on the frequency. No comparison with experiments is given.

Ansys [39] also proposes a methodology to calculate the electromagnetically-induced vibration and noise levels in electrical machines.
[33][34] presents a full electromagnetic and vibro-acoustic calculation using Ansys environment for the calculation of magnetic vibrations and Sysnoise for the calculation of acoustic noise. The time varying magnetic forces are applied to a 3D structural model, and the structural response is calculated using modal superposition method. The acoustic pressure is then calculated in the frequency domain using BEM.
Some comparison are done between calculated and measured vibration and acoustic spectra. The full numerical calculation only contains 7 harmonics up to 6 kHz, whereas measured spectra are very rich. The vibration and sound pressure level magnitude matches with less than 5 dB on the calculated 6 harmonics. The paper concludes that the magnetic noise excitations are proportional to the stator slot passing frequencies, and that the highest peaks corresponds to the excitation of some structural modes. The computing time is not reported, but acoustic calculations are carried at a single speed.
In [35] Ansys is also used to calculate the vibration response of a stator using force wave decomposition. The modal decomposition is stored and the vibration synthesis is performed. The full process at variable speed takes a “couple of hours” on a quad-core PC with 16 Gb RAM, but it depends on the complexity of the magnetic loads and the calculation time does not include magnetic force calculation with Maxwell, nor acoustic calculations. Some comparison are shown with experiments in terms of vibration, showing excellent agreement with measurements, with up to 5 dB difference in magnitude.

B. *Conclusions on FEA advantages and drawbacks*

Previous examples show that FEA calculation results are sensitive to the meshing process of the electromagnetic, structural and acoustic models, contrary to analytical or semi-

analytical techniques such as subdomain models [21]. The high sensitivity of torque calculation [27] naturally applies to radial magnetic forces as shown in [13], and therefore to the resulting noise and vibrations. In acoustic FEA, the first order elements (with linear shape functions) dimensions have to be chosen such that the biggest one is at least six times smaller than acoustic wavelength [38], which strongly limits the maximum frequency that can be captured. At low speed, assessing high frequency electromagnetic behavior requires higher computation time.
Besides that, previous case studies show that the complexity of the vibroacoustic behavior of studied machines is sometimes limited, and that the use of FEA is not necessary to identify the main harmonic forces and resulting resonances with the main lamination modes.

To conclude, the advantages of numerical models are

- *A priori* high accuracy compared to analytically based techniques, although there is still a lack of valuable comparisons between FEA and experiments in terms of noise and vibration levels at variable speed
- modeling of complex structural boundary conditions on the motor frame and the effect of non-linear damping viscoelastic materials
- possibility to directly work on the “real” geometry based on CAD files, and to model any type of topology contrary to analytically-based techniques which necessarily address a limited class of topologies (e.g. circular frames)
- modeling of non-linear electromagnetic effects in electric machines where saturation has a significant vibroacoustic role
- strong circuit coupling, allowing for instance to include the vibroacoustic effect of eccentricity in equalizing currents and induced current harmonics due to slotting.

The limitations of numerical models are

- the prohibitive computation time of electromagnetic FEA solver when either considering PWM effects up to 10 kHz, asymmetrical machines (e.g. eccentricities) or low symmetry machine with a high number of poles and slots, strong circuit coupling, or 3D effects (e.g. skewing)
- the prohibitive computation time and representativity limitation of structural FEA when considering vibrations above 8 kHz and a speed discretization step small enough to capture the maximum noise and vibration levels
- the difficulty to estimate the high frequency vibroacoustic levels at low speed, due to time-frequency limitations (e.g. 500 Hz at 1000 rpm for [17])
- the time consuming set-up of the coupling between the physics (e.g. mesh interfaces, force projection, time to harmonic conversions, load application), and the resulting increase of calculation (5 min per speed to couple Maxwell2D and NASTRAN in [14])
- the time consuming set-up of the structural model (e.g. homogenization techniques for the laminated core, resin and copper mixture, coupling techniques for frame to lamination interface)
- the prohibitive computing time for use in an early design stage as a relative comparison and not an absolute evaluation (for instance, to help choosing the best slot number or to optimize the magnet pole geometry),
- the missing physical and mathematical validation of electromagnetic force to mechanical mesh projection (e.g. with energy conservation).

III. MANATEE MULTIPHYSIC MODELS

A. Introduction

MANATEE [29] initially stands for Magnetic Acoustic Analysis Tool for Electrical Engineering: it is a 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. The topologies handled by MANATEE include induction machine, surface, inset or buried permanent magnet synchronous machines, with outer or inner rotor.
It is an integrated multiphysic tool whose simulation process is summarized in Fig. 4. Assuming a weak coupling between structural mechanics and electromagnetics the electrical currents are first calculated based on equivalent circuits. Based on rotor and stator current waveforms, the electromagnetic module calculates the airgap flux distribution. The structural module consists in projecting the Maxwell stress on the stator or rotor structure, and evaluating the resulting dynamic deflections. The acoustic module finally calculates the radiated sound power and pressure levels.

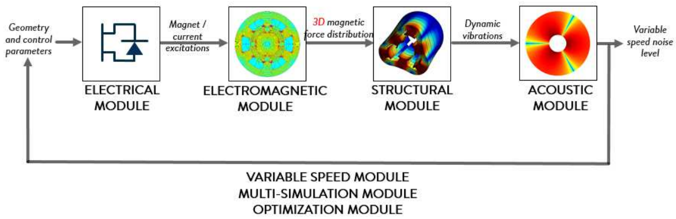


Fig. 4: MANATEE simulation process

B. Electrical model

The equivalent circuits are based on similar analytical models developed in [8][20] for the extension to time and space harmonics. The difference is that the equivalent circuit parameters (e.g. leakage inductance, magnetizing inductance, back emf) can be either calculated using subdomain electromagnetic models or with the freeware FEMM [26]. The fast calculation time of subdomain models allow to strongly couple the electrical circuit with electromagnetics [21].

C. Electromagnetic models

MANATEE offers the possibility to use three different electromagnetic models: permeance / mmf models, subdomain models [21] and finite element models with FEMM [26]. These three models are compared in the following table.

	Permeance MMF	Subdomain	FEMM
Calculation time	++	+	--
Accuracy	-	++	++
Robustness to geometry	+	+	++
Skewing	Yes	Yes	Yes
Eccentricities & uneven airgap	Yes	No	No
Saturation	+	-	++
Faults (short circuits, broken bar)	Yes	No	No

The permeance / mmf model allows to qualitatively account for saturation [23], faults and asymmetries (eccentricities, uneven airgap [22]), but also notches, and can easily include the effect of PWM harmonics [25]. The accuracy of the permeance / mmf model can be improved using an automated coupling with FEMM; the rotor mmf of an interior PMSM can be calculated accurately using FEMM, or the effect of magnetic wedges on the permeance [23].

D. *Structural model*

The structural model includes a projection of magnetic forces on the modal basis of the structure to calculate their effect on the radial deflections of the outer yoke.

Similarly to the electromagnetic model, MANATEE offers the possibility to work either with analytical models, or with FEA. The software is indeed coupled to the open-source software GetDP for structural calculations (modal analysis, frequency response functions), but also to commercial FEA software such as Altair Optistruct.

The analytical model is based on an equivalent cylinder, where the effect of tangential forces on radial deflections of the yoke are included using an equivalent bending moment as in [28]. The natural frequencies are computed analytically using similar models as in [8].

A. *Acoustic model*

The acoustic model uses an analytical model of radiation efficiency as presented in [8]. [28] indeed demonstrates that there is no need of higher accuracy radiation efficiency models.

B. *Numerical performances*

A special care has been taken to optimize the numerical implementation of MANATEE models. All the electromagnetic domain calculations are done in the time and angular domain with matrix computations.

A variable speed calculation can be done smoothly with a very small speed step using synthetized spectrograms. Spectrogram synthetization algorithm consists in evaluating magnetic forces at a single speed, and identifying the rotation direction and the speed of the harmonics and the evolution of their magnitude with speed. This way the full noise and vibration spectrogram can be synthetized using the modal basis calculated at fixed speed. The variable speed noise level of an induction machine up to 20 kHz can be calculated in less than 1 second on a 2GHz single core laptop. The validation of spectrogram synthetization is presented in Fig 5 where it is favorably compared to several single speed simulations.

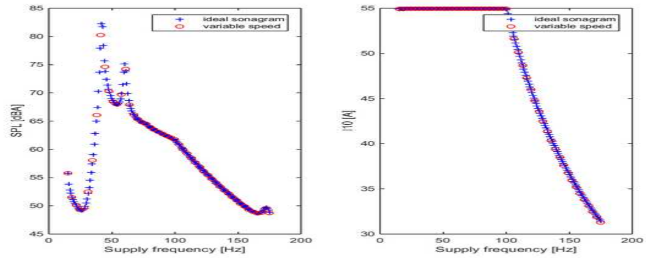


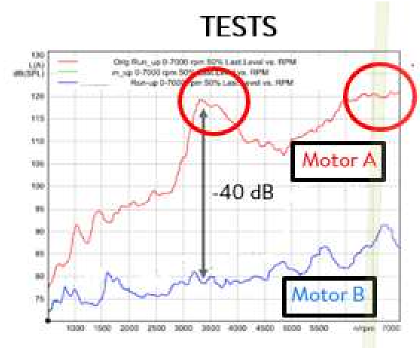
Fig. 5: Validation of the fast synthetization spectrogram algorithm

Besides that, time and space symmetries of the airgap field are automatically identified to reduce matrix sizes. Some field reconstruction techniques are also applied to avoid calculating the full fields.

IV. EXPERIMENTAL VALIDATION

In this part, some experimental validations of MANATEE simulation environment are provided. It should be noted that these experiments are done in “real conditions”: no semi-anechoic chamber (sound pressure level may be affected by reverberation field), background noise (load machine, cooling units), real eccentricities and supply harmonics. However, these conditions are more representative of the industrial practice: very few electrical machine manufacturers have the possibility to test their machines in “ideal conditions” using anechoic chambers. A favorable comparison of simulation results to in-field measurement, far from laboratory conditions, can therefore be seen as a proof of robustness.

The first comparison is given in Fig. 6 on a IPMSM traction machine with concentrated winding run at 50 % partial load up 7000 rpm. Two main resonances are observed in both simulation and tests. MANATEE simulation shows that the first one is only linked to rotor magnetic field (rotor pole mmf / stator slot harmonic interaction), whereas the second one is linked to a stator subharmonic field due to tooth winding. Both resonances occur with the ovalization mode of the lamination stack, leading to 125 dB. This two huge resonances can be avoided based on a few seconds of calculations without any call to finite element methods. The redesign of this machine with MANATEE led to 40 dB reduction in sound pressure level.



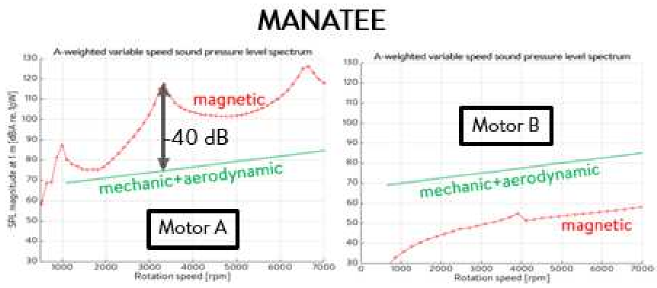


Fig. 6: Comparison between experiments (top) and MANATEE simulation (bottom) on two different IPMSM (motor A and motor B). Experiments include gearbox, cooling and converter noise while simulation only contain magnetic noise under sinusoidal supply

The second comparison focuses on the frequency characteristics of noise in Fig. 7 in a large induction machines for pump application. A strong resonance occurs due to the interaction between a slotting line and the 4th lamination mode of the stator. In this case, a redesign of the rotor slot with MANATEE gave 15 dB reduction in sound pressure level. The calculation time of the full noise spectrum up to 12.4 kHz at variable speed takes a few seconds.

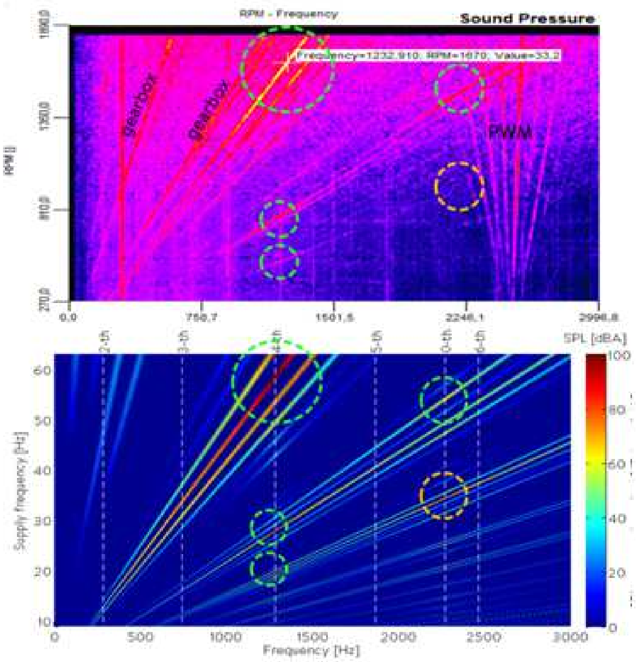


Fig. 7: Comparison between experimental SPL spectrogram (top) and MANATEE simulation (bottom) on a SCIM. Experiments include gearbox, cooling and converter noise while simulation only contain magnetic noise under sinusoidal supply

V. Conclusion

The advantages and drawbacks of numerical techniques for the prediction of variable speed noise and vibration due to magnetic forces in electrical machines are underlined.

It is shown that the vibroacoustic behavior of an electrical machines can be quantified using analytical or semi-analytical methods in a very short computing time with the same order of magnitude of accuracy than fully numerical methods (~5 dB). This allows the machine designer to avoid main resonance issues during the early design phase; one can also easily sweep pole per slot combinations or run magnet shape optimization in order to minimize both torque ripple and acoustic noise. Besides that, the significant sensitivity to meshing process of finite element techniques is avoided using subdomain models for electromagnetics and analytical models for acoustics.

VI. Acknowledgment

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VIII. BIOGRAPHIES

J. Le Besnerais currently works in EOMYS ENGINEERING as an R&D engineer on the analysis and reduction of acoustic noise and vibrations in electrical systems.

Following a M.Sc. specialized in Applied Mathematics (Ecole Centrale Paris, France) in 2005, he made an industrial PhD thesis in Electrical Engineering at the L2EP laboratory of the Ecole Centrale de Lille, North of France, on the reduction of electromagnetic noise and vibrations in traction induction machines with ALSTOM Transport. He worked from 2008 to 2013 as an engineer in the railway and wind industries (Alstom, Siemens Wind Power, Nenuphar Wind) on some multiphysic design and optimization tasks at system level (thermics, acoustic noise and vibrations, electromagnetics, structural mechanics and aerodynamics). In 2013, he founded EOMYS ENGINEERING, a company providing applied research and development services including modeling and simulation, scientific software development and experimental measurements.