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Multiphysical modeling and optimisation of induction traction motors

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Abstract - A numerical multi-physical model, electromagnetic, mechanical and acoustic, for an induction motor able to predict the electromagnetic noise at variable speed is firstly presented. Experimental measurements but also finite element simulations validate the model for different type of industrial motors. In a second time, this multi-physical model is employed with the design of experiment method to build response surfaces of the electromagnetic noise with respect to the main factors. The aim of the study is to find an optimal design or more simply, to avoid unacceptable designs of the machine, in term of noise for variable speed applications.

I. INTRODUCTION

Electrical machines operating at variable speed generate vibrations and noise that can be harmful for the machine itself and for its environment. Thus, it is necessary for the manufacturer to take into account noise and vibration at the design stage.

There are many tools and methods of analysis, which enable to study coupled phenomena : a classical method is the finite element method (F.E.M) in magneto-dynamics (including coupling circuit). However, in the case of strong coupling, these electromagnetic models, vibroacoustic, or thermics, would take a considerable computing time. This would make structure optimisation practically impossible. In order to solve this problem, a multiphysical model is developed.

The objective of this work is to develop an numerical multiphysical models (electromagnetic, mechanical and acoustic) for induction motors. The complete model is coded using the data-processing tool MATLAB, making possible the determination of fast and simple prediction of the acoustic noise. F.E.M. validation and experimental measurements are presented.

Then, in order to find the optimal design, in term of noise for a variable speed application, this model is coupled to a design optimisation manager SOPHEMIS [1].

The major part of the work is devoted to a study of sensitivity with the aim of deducing the significant factors on the noise. Then, the modeling of the noise is achieved thanks to the particular 'treillis' designs.

Several response surfaces give then the noise according

to significant factors, with respect to different speeds of the machine. The goal is to find the optimal design or more simply, to avoid unacceptable designs of the machine, in term of emitted noise.

II. MULTI-PHYSICAL MODELS

The multi-physical model : electromagnetic, mechanical of vibration and acoustic is recalled. Many results, F.E.M. and experiments comparisons are given in the following Ref. [2].

A. Electromagnetic Model

Using the finite element software OPERA-2D, the air-gap induction created by the induction motor as a function of space and time is firstly calculated. In order to derive a more flexible and general model of induction in the air-gap, air-gap permeance (P_e) and the magnetomotive force (mmf) [3], [4], [5] are computed. The permeance can be determined using simple assumptions :

- the magnetic circuit has a high permeability and a linear characteristic,
- the tangential component of the air-gap flux density is negligible relative to the radial component [2].

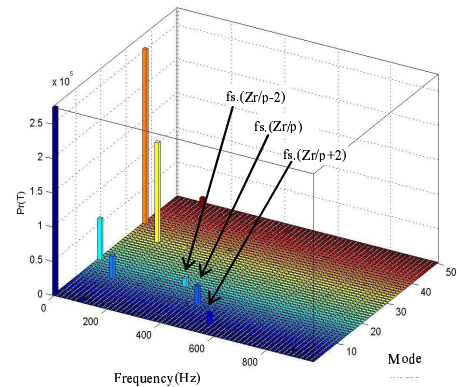


Figure 1: Harmonics of radial force in space and time

The comparison results are very satisfactory, as shown in ref. [2]. Hence, the radial forces and FFT applied to the stator slots are deduced versus time and space (fig 1).

B. Acoustic and Vibratory model

In this study, vibrations are the consequence of excitation of a mechanical system by electromagnetic forces. Once the forces applied to the stator have been determined, we can now study the vibrations which correspond to deformations whose amplitudes will have to be calculated.

Each mode shape is associated with a mechanical frequency of resonance. The rather simple formulas given by [6] easily make it possible to find the frequency of resonance of each mode of a stator (yoke + teeth)[7]. The model was improved by to take winding into account [2].

The analytical vibration model was validated numerically by ANSYS calculation of the vibration modes of the stator structure, including : yoke, yoke+teeth, yoke+teeth+frame and yoke+teeth+frame+winding. A part of the obtained results of simulations are presented in Table 2.

The resonant modes of asynchronous machine were studied experimentally with various configurations : without flask and rotor, without rotor, complete machine. The obtained results are only compared with the analytical model [8].

Table 2 : Comparative table of the resonance frequencies of the stator machine for each mode.

Mode number (m)	Analytical Method (Hz)	F.E.M (Hz)	Analytical Method (Hz)	Experimental Method (Hz) (damp.coeff)
0	3610	3642	3236	3283(1.5)
2	657	699	591	616(2.16) 731(2.22)
3	1858	1831	1673	1406(1.47) 1622(2.1) 1769(1.16)
4	3564	3200	3209	3106(0.96) 3383(0.88)

(yoke+teeth+frame) (yoke+teeth+winding+frame)

The sound power W can be written as a function of frequency, amplitude of vibrations, mode order and stator surface [9] :

$$W = \frac{\sigma 8200 f^2 Y_{md}^2 S_e}{2m + 1} \quad (1)$$

The analytical model makes it possible to calculate the total acoustic noise by making the vectorial sum of all the lines obtained.

The machine was tested at various speeds, that allowed us to highlight a particularly dangerous speed. Moreover, some results are over-estimated but the quality of those is respected (figure 2). In spite of the inaccuracies, major lines appear, which is of primary importance in view of noise reduction. To know which lines to reduce does not require to know its amplitude precisely. Its frequency, on the other hand, must be well given.

Lastly, taking into account the complexity of the studied phenomena and the many steps of calculations making it possible to lead to the results, the latter seem very satisfactory [10].

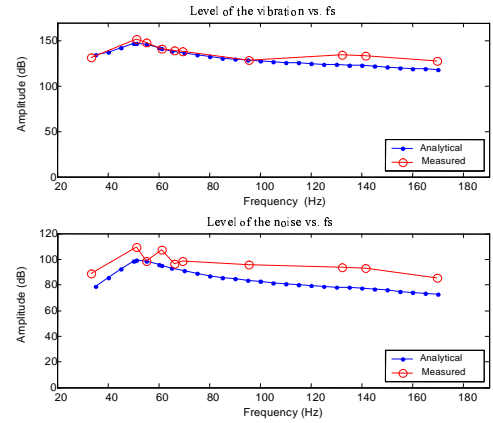


Figure 2: Comparative results of the noise and vibration of the asynchronous machine.

II. RESEARCH OF OPTIMAL CONDITION

Once the different models finalized and assembled into a single multi-physical model”, it becomes possible to study the variations of the main variables representing the vibration sources. This is achieved by the building of response surfaces, and by the launching of optimizations. The privileged tool employed is the Design of Experiments Method [1]. The goal is then is to obtain models giving reliable representations of the variations of the noise, with respect to the significant factors.

First of all, a sensibility analysis using the global coupled model is described. The overall audible noise produced by the asynchronous machine stands as the studied variable (the response). An analytical relation linking the noise amplitude with nine variation sources (the factors) has been established.

A screening design is calculated. It gives the ability to determine the influent factors, with respect to the response, inside the design space. This domain is implicitly defined by the intervals of variation, for the nine factors (Table 3).

Table 3 : Intervals of variation - Screening analysis.

Factors	Lower bound (-1)	Upper bound (+1)
stator number slots (Z_s)	36	54
rotor number slots (Z_r)	40	44
stator slot opening (l_{se})	0.0131	0.0145
rotor slot opening (l_{re})	0.0055	0.0065
height of the yoke (h_{cut})	0.057	0.063
width of the air-gap (e)	0.0019	0.0021
length of the stator (L_1)	0.35	0.39
length of the rotor (L_2)	0.35	0.39
height rotor isthmus (H_{is})	0.003	0.006

For the calculation of the screening, instead of a complete design with 512 experiments (2^9), a fractional design with 64 experiments (2^{9-3}) was defined for each frequency, by respecting the good compromise between the number of experiments and the precision of the results [8].

The frequency, is regarded as a parameter, because it takes 5 values between 50 and 130 Hz.

A. Response analyzing

The histogram presented in the figure 3 allows to quickly consider relative effects of the factors. Thus the extreme importance of the factors is noted: rotor slots number (Z_s) and the height of yoke (h_{cul}), but too the interaction ($Z_s Z_r$) which has an effect higher than that of (Z_r) (fig 4).

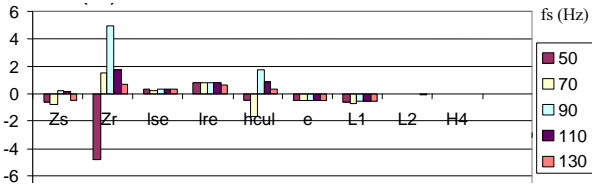


Figure 3: Average effects of the principal factors for various frequencies.

Also, let us note that the frequency (fs) modifies considerably the tendency of the principal effects (h_{cul}) and (Z_r). Thus, the effect of (Z_r) on the noise is -4.80 dB for a frequency of 50 Hz, whereas it is $+4.95$ dB for 90 Hz (fig 3).

We also notice that effects of the factors (Z_r), ($lres$), (e) and (lse) are notable, whereas the effects of the factors (His) and ($L2$) are almost null.

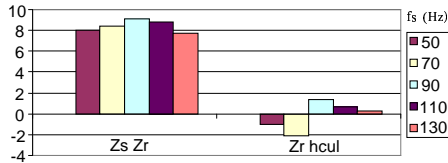


Figure 4: Average effects of the more significant interactions for various frequencies.

B. Response surface

From preceding the lattice design, we chose a RSM design [1] in order to identify the value of the factors selected. The figure 5 represent the surface of response in noise in function frequency (fs) of the machine and number of rotor slots number (Z_r).

Thus the minimum of the noise is obtained for a slots number equal to 44. We can also consider the rotor 26 slots as being nonnoisy. Consequently, the machine that us will realize will have 44 rotor slots.

We had the possibility by the intermediary of ALSTOM TRANSPORT to construct an asynchronous prototype of machine allowing to validate our step. A new engine has then summer defined with an aim of minimizing the acoustic noise.

We were however subjected to constraints which us did not allow to modify the geometrical parameters of stator, of which the number of stator slots was fixed at 36.

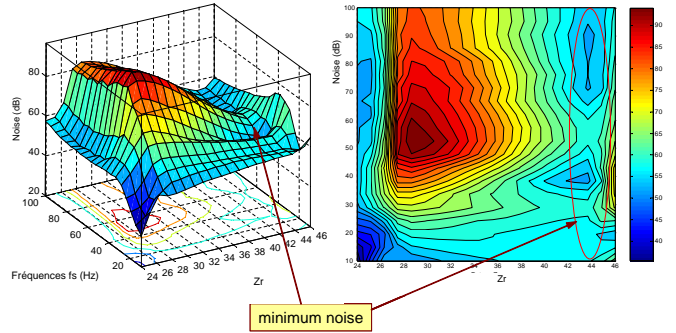


Figure 5: Surface response and determination of the minimum zone in noise.

Below, we point out the factors of the rotor of the asynchronous machine, as retained by the analysis of the screening: - a stator slots number (Z_r); - rotor opening teeth (lre); - width of air-gap (e); - height of rotor isthmus (His).

The figure 6 represent the surface of response in noise in function rotor slots number (Z_r) and height of yoke. We can notice the reversed effect of the variation of Yoke on the response, around resonance [10].

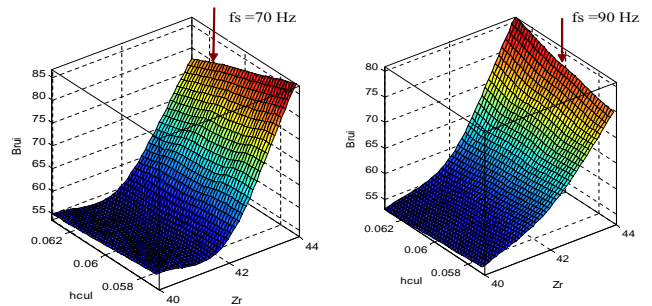


Figure 6: Surface response in noise function rotor slots number and height of yoke.

The frequency (fs) was considered in our model as being a factor, in function of which the level of total noise moves. The height of isthmus (His) in spite of the little of influence which it had on the noise, is closely related to leakages in the rotor. It was thus regarded as an element of constraint on the dimensioning of the rotor slots.

a) Determination of the final shape of the rotor

The value of the air-gap then was slightly increased by 0.1 mm, a more significant value would be likely to affect the electromagnetic operation of the machine. We have increased the value of the isthmus of 1 mm ($His=4$ mm) and decreased there value of the rotor opening teeth

($l_{re}=1.5\text{mm}$). We have moreover acts over the width of small and the great base of the rotor teeth. The leakages were thus brought back to 1.3 mH, end value acceptable.

The prototype was produced and tested with the Ornans factory (France). It has was initially necessary to validate its electric performances and thermics, because they represent the first conditions with to respect to pass at the following stage which is the measurement of vibrations and of the acoustic level.

b) Experimental comparisons between the various rotors tested

Vibratory and acoustic results of measurement of the prototype engine (rotor with 44 slots) are presented on the figures 7 and 8, and compared with the results of the existing engines: engines with 26 and 28 rotor slots.

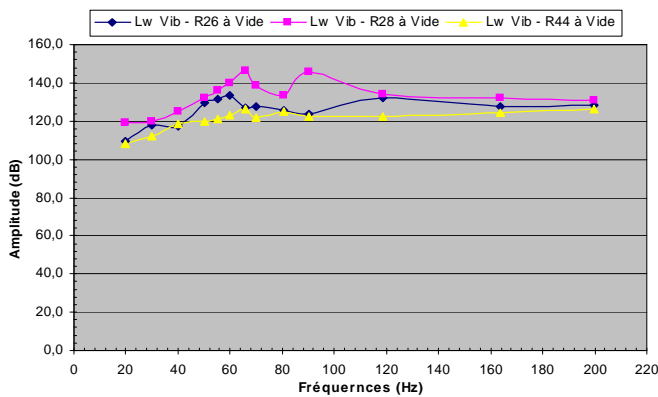


Figure 7: Comparaisons entre les différents moteurs quant au vibrations émises

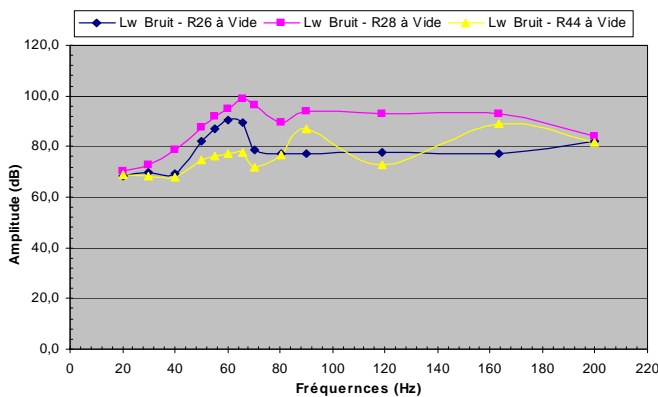


Figure 8: Comparisons between the various machines as for the radiated noise.

At the operation point corresponding to resonance ($f_s=65.8\text{ Hz}$), we notice a fall sensitive of the sound level (11.6 dB on the 26 rotor slots and 21 dB on 28 rotor slots). But we notice for rotor 44 rotor slots that the frequency corresponding to levels of the maximum noises is moved away to 163.5 Hz.

The various experimental results show that our choice is justified. We showed that our tool made it possible to minimize the noise and vibratory of origin electromagnetic for various speed, with performances identical.

III. CONCLUSION

The purpose of this work is to present some results obtained from the exploitation of a complete coupled model of induction motors. Different multi-physical aspects are considered: electromagnetic, mechanic and acoustic phenomena are taken into account in a single model. The Design of Experiment Method is then the privileged tool used to make the complex relationships between the main variables appear avoiding then unacceptable designs of the machine in term of noise.

Lastly, to validate the step, a prototype of asynchronous machine of average power (250 Kw) was realized and a good compromise between the minimization of the acoustic level of machine and its performances are reached.

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