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Vibration and acoustic noise of industrial reactors associated to converters in railway domain: design and material impacts

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Abstract

Purpose - The purpose of this paper is to present the original study of an industrial reactors with different air-gap materials in order to reduce vibration and noise of reactors. Acoustic comfort is an increasingly important factor at the design stage of industrial reactors associated to converters. In addition, power converters in railway domain are more and more compact and powerful.

Design/methodology/approach – Experiments, simulations and test devices are used to determine the main physical phenomena that generate the undesirable audible noise. Electric and vibratory measurements (modal and operational analysis) are compared with the numerical calculations. PWM and sinusoidal supply are taken into account and different prototypes with different materials in the air-gap are built.

Findings – This study analyzes and details the origin of the electromagnetic noise due to the vertical mode, in order to reduce vibration and noise of reactors. A detailed analysis by finite element simulation and experimental measurements of free-free mode or forced mode under electrical excitation was conducted to interpret the vibrations of the structure. In addition, in order to observe trends and the impact of magnetostriction effect, we propose a simplified model.

Originality/value – This paper gives a response about the origin of the noise with different experimental measurements. Changing the air-gap material is beneficial for the deflection of the reactor. But it has been presented that, following the shape of the reactor, it is beneficial to reduce or increase the stiffness of the material depending on the column height. For a fixed Young's modulus air-gap, a ratio Column height / air-gap thickness exists which make it possible to cancel the deflection.

Keywords – reactor or inductor design, magnetic forces, Maxwell stress, noise, vibration measurement.

I. INTRODUCTION

The design process of such components becomes more and more multi-physical. Effectively, the “miniaturization” leads to new design constraints, such as taking account of the thermal issues due to many additional current harmonics in the windings, as well as the emission of sound. Acoustic comfort is an increasingly important factor at the design stage of reactors [1, 2 and 3]. The Maxwell forces in the air-gap and the magnetostriction effect are the causes of structure deflection at the origin of acoustic noise radiated by magnetic circuits (figure 1).

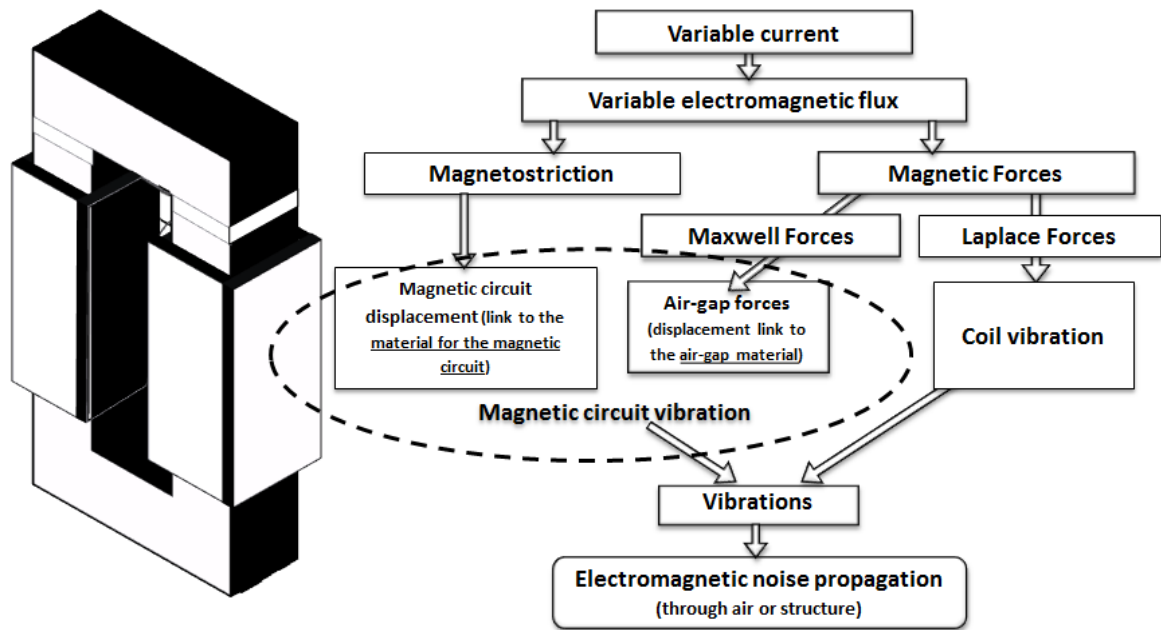
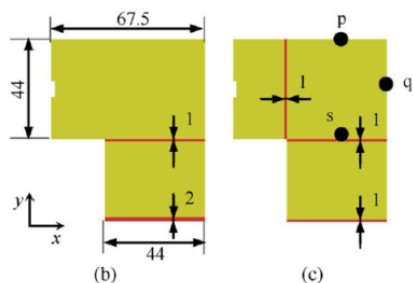


Figure 1: Origin of electromagnetic noise and vibrations

In some cases, for the railway domain, during the start-up phases, the global sound power level is dominated by the magnetic noise radiated by integrated magnetic components (transformer + reactor), the reactors and electrical machines. This noise can be quickly annoying as its spectrum contains high tonalities. Few papers [4, 5] give different solutions (figure 2) in order to reduce electromagnetic noise for the low power structure.

In Figure 2 - case 1 [4], by choosing the hard gaps for the reactor and adding a gap in the yoke of the core, the normal component of displacement on the surface of the yoke, where displacements are the largest, can be reduced. For this topology, the magnetostriction effect is not negligible and the electromagnetic forces are evaluated. Currently, many papers on the consideration of magnetostrictive effects appear and many researchers are interested in these issues to integrate these forces in finite element calculations [6, 8, 9,11] essentially for the transformers or for the sheet characterizations.

In Figure 2 - case 2, the shape of the reactor is a triangular core. With this shape, there is no specific direction with specific vibration characteristics, and so a lower noise level can be expected.



Case 1: two topologies with adding air-gap [4]



Case 2: triangular reactor [5]

Figure 2: New configuration of reactors in order to reduce electromagnetic noise

These structures are used for the low power and this study focuses on industrial reactor design applied to railway domain. PWM and sinusoidal supply are taken into account and the electromagnetic force and vibration of the reactor are analyzed. For a frequency range between 500 and 2 kHz (the switching frequency is relatively low in the railway domain), different prototypes with different materials in the air-gap are built. The results are described here after.

The aim of this study is to analyze and detail the origin of the electromagnetic noise due to the breathing mode, in order to reduce vibration and noise of reactors. This breathing mode is the most important. A detailed analysis by finite element simulation and experimental measurements of breathing free-free mode or forced mode under electrical excitation was conducted to interpret the vibrations of the structure.

II. REACTOR DESIGN AND TEST BENCH

A structure of reactor has been realized (figure 3). This one permits to change easily the air-gap material. A second one has been done without air-gaps so that the magnetic core is no cut. Experimental results are compared with numerical models for the two structures. Weight of the magnetic cores equal 50 kg. To hold the magnetic core with air-gaps, the core is prestressed using threaded rods (figure 3).

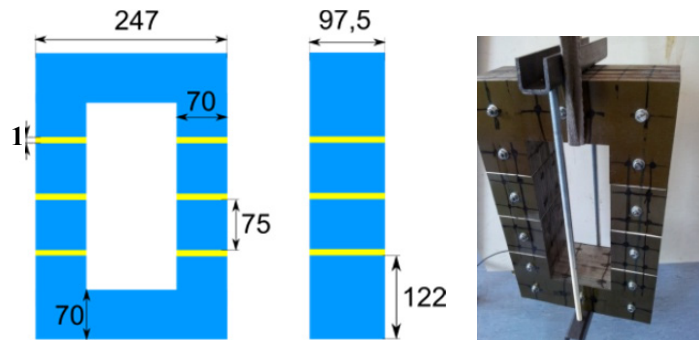


Figure 3: Dimensions of our reactor with six air-gaps

The reactor is electrically excited using a two phase inverter (figure 4). IGBT are driven using a dSPACE board to generate PWM signals. Fundamental amplitude and frequency of PWM parameters are easily editable. As sinus current are generated in the range of 0-1kHz, the PWM frequency is set to 10 kHz to produce sinus without harmonics. Thanks to dSPACE, sweep frequency in current is possible to generate spectrograms. Measurements are done using a Pulse system from Bruel & Kjaer and modal analysis use a modal hammer to excitate the structure (fig. 4).

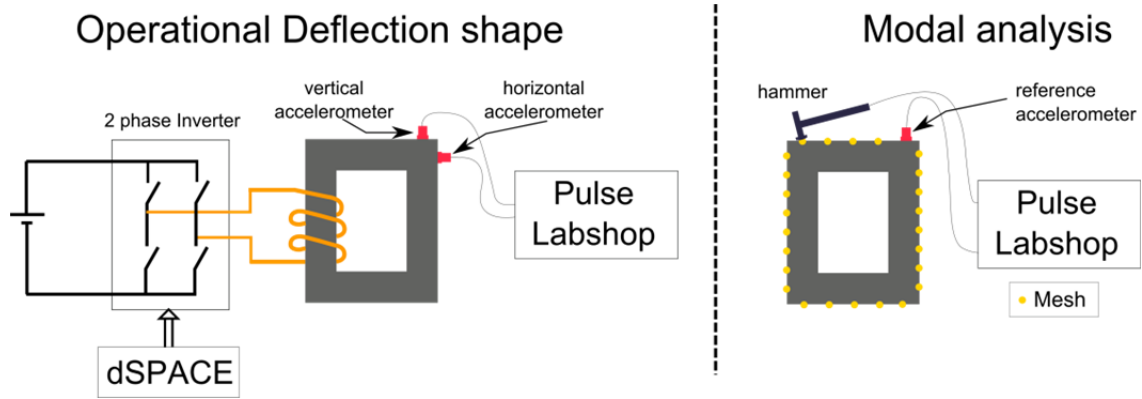
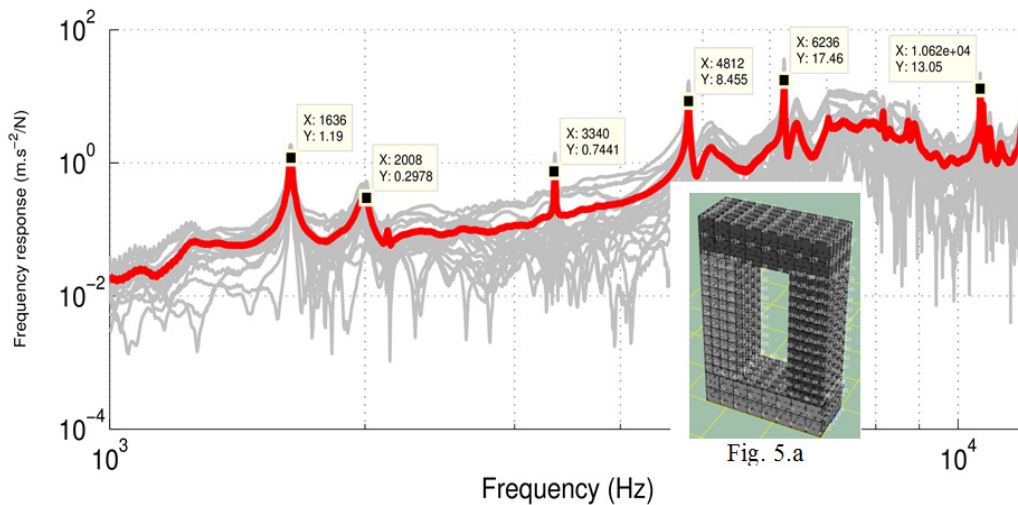


Figure 4: Test bench for operational deflection shape and modal analysis

III. MODAL ANALYSIS

Modal analysis is performed on different magnetic cores.

a) First, a solid core (without air-gaps) is studied. Then, in III-b, a cut core will be used with different materials in the air-gaps. Experimental and Finite Element modal analysis are presented. F.E. Modal analysis is performed in 2D. Experimental measurements are done by meshing the core with accelerometers as shown in figure 5.a.

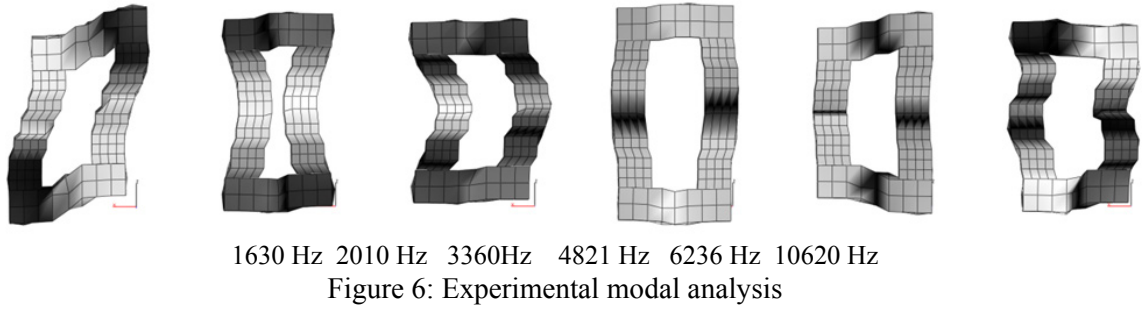


5.a : Mesh for the experimental measurement (solid core)

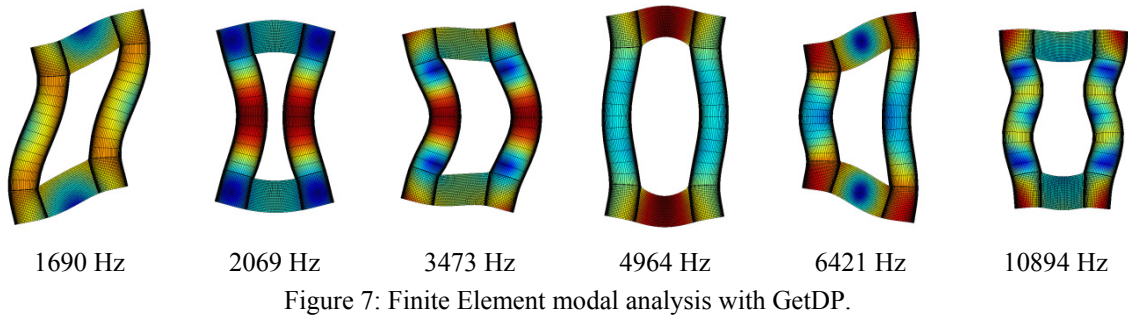
5.b : Frequency Response

Figure 5: Modal analysis for the solid structure

Frequency response of each node is represented on the fig 5.b in grey and R.M.S FRF is computed in red to extract resonances. Resonances are clearly visible and marked on figure 5.b. First resonance is observed at 1636 Hz. The deformation of each resonance is presented on fig.6 and breathing mode is observable at 4812 Hz and 4964Hz for the experimental measurement (fig.7).



A modal analysis using GetDP [9, 10] of the magnetic core gives the following results (figure 7). Core material is considered isotropic with a Young's modulus of 210 Gpa, a Poisson's ratio of 0.3 and a density of 7650 kg/m³. Isotropic assumption is done because the lamination phenomenon occurs only in the perpendicular direction which is not modeled. Frequency and mode shape are identical with a maximum error of 3 %.



b) Impact of the air-gaps:

Air-gaps are added into the magnetic core (3x2 mm per column). A modal analysis is done in the range of 0-1kHz. 6 resonances appear (Circle in figure 8) but some of them represent double modes and are probably due to dissymmetry in the experiment. Thanks to the meshing, modal shape can be extracted and the deflection shape of each resonance is represented on the figure 9. Same kind of deflection is obtained compared to the solid core. But frequencies are lower and order of appearance is different. In addition, the breathing mode does not clearly appear at $f = 645$ and 795 Hz, we will talk about vertical deflection mode (or vertical deflection).

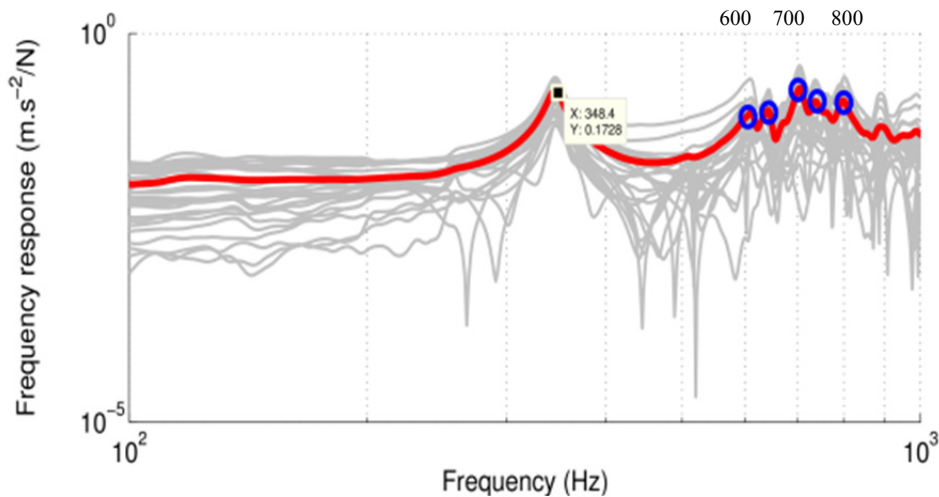


Figure 8: Frequency response for the structure with air-gaps

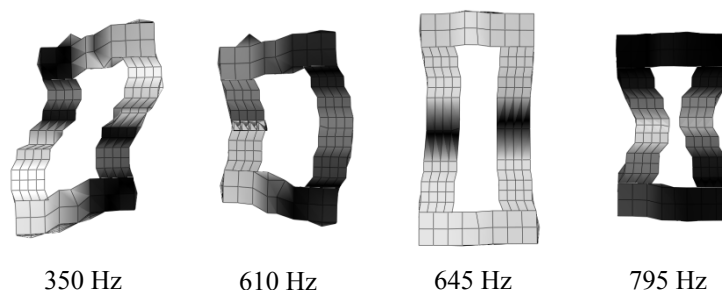


Figure 9: Experimental modal analysis for the structure with air-gaps

Using finite element method, modal analysis is performed (figure 10) for the core with air-gaps. Double modes are not obtained because the numerical model is symmetric. But Frequency and modal shape are consistent compared to the experimental measurement and error doesn't exceed 6%.

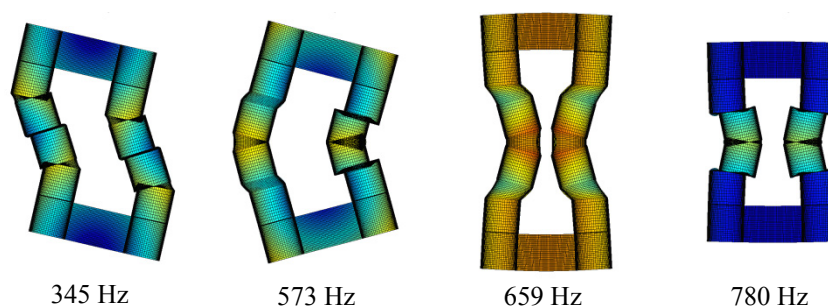


Figure 10: F.E. modal analysis

IV. FREQUENCY RESPONSE AND OPERATIONAL DEFLECTION SHAPE (ODS)

The mechanical structure of the reactors can resonate at many frequencies with different modal shapes as seen previously. But a resonance can be excited electrically only if magnetic force distribution and frequency are consistent with the different resonances. To observe resonance that can be electrically excited, a frequency sweep of current is applied to the reactors, so that the flux density remains constant inside the core. This is done by implementing a U-F Control. This control is implemented inside the dSPACE board (figure 4).

Spectrogram of the current is shown on figure 11.a. Some remarks can be done. Firstly, harmonics are very weak compared to the fundamental. Secondly, current is constant except at low frequency where the resistivity is predominant over inductivity.

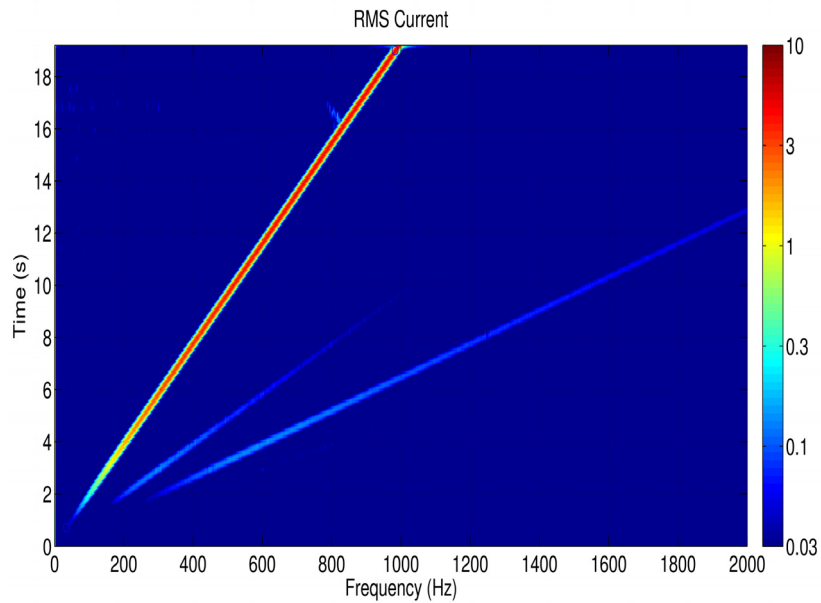


Fig. 11.a: Current

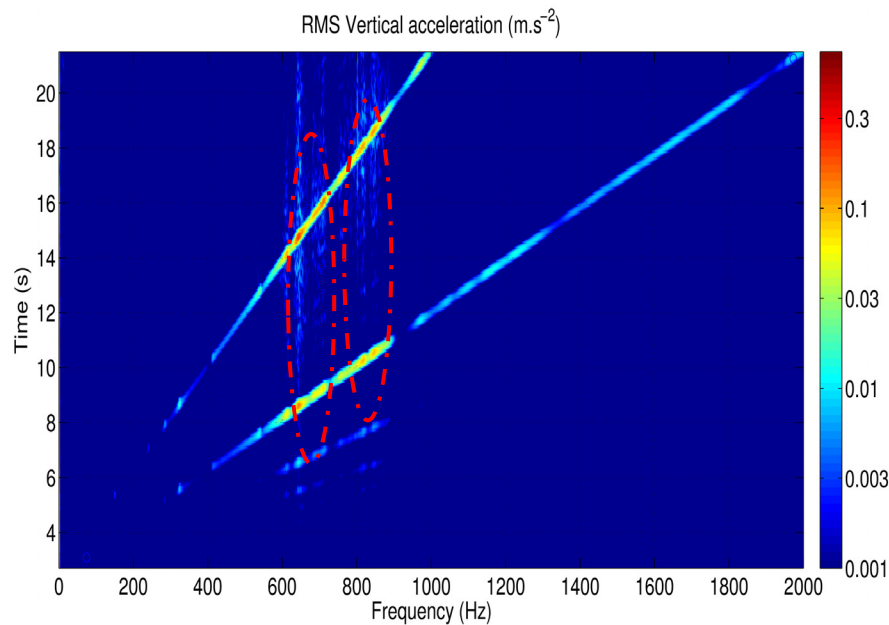


Fig. 11 b: Vertical acceleration

Figure 11: Spectrogram of the current and the acceleration (sweep of frequencies 0 to 1 kHz)

A sweep of frequencies is applied to the reactor with six air-gaps from 0 to 1 kHz. As magnetics forces are quadratics, the deflection frequency is twice as much (0 – 2 kHz). But in the experiment, the inverter injects also DC components, so that the core deflection evolves also at the same frequency as the sweep. Spectrogram of vertical acceleration is represented in the figure 11.b. As mentioned before, the deflection evolves mainly at f and $2f$. Resonances are visible around 600 to 800 Hz and linked to the breathing nearly mode or the vertical deflection mode at 645 and 795Hz. Slice is done on $2f$ for the vertical and horizontal deflection (figure 12) according to the bench test (figure 4). The vertical deflection is strongest compared to the horizontal. ODS have been done for the resonances

at 320 Hz and 820 Hz (figure 12) thanks to an electrical frequency of respectively 160 and 410 Hz.

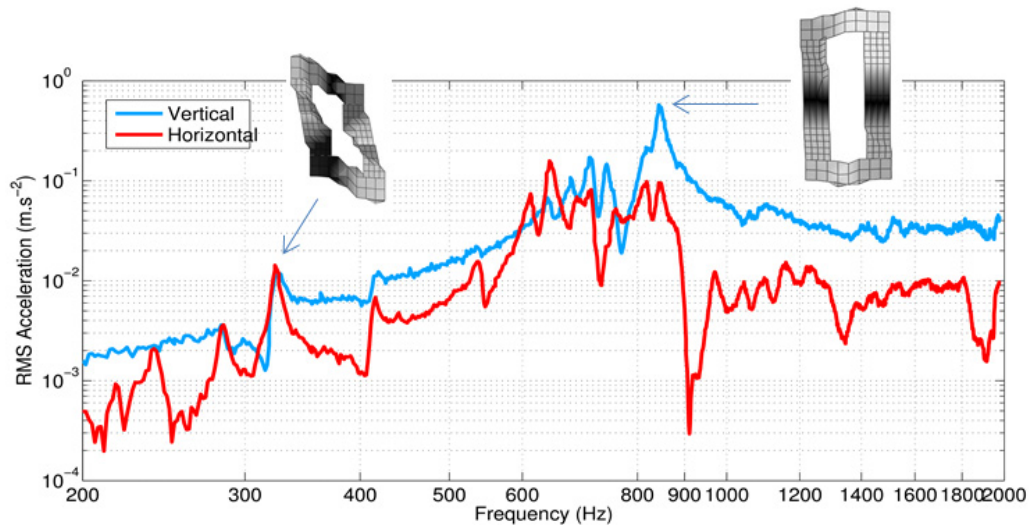


Figure 12: Vertical and horizontal measurement and ODS for 2 resonances

The frequency response of the reactor (figure 12) shows that the mode (820Hz) is the most important in term of acceleration. But acoustic noise depends of the deflection speed. The integration of the curve keeps this mode as the most important for this frequency band.

a) Air-gap material modification

Three different kinds of air-gap material have been tested and the frequency responses of the deflection are represented on the figure 13. The three materials have a different Young's modulus. At low frequency (<2 kHz), the deflection is the smallest for the lowest Young's modulus. Resonances for high and medium material are approximately the same. But due to the high damping factor of the low material, resonances have been completely removed. From this graph, it can be deduced that a material with a small Young's modulus is beneficial and high damping material can be useful to avoid resonance problems.

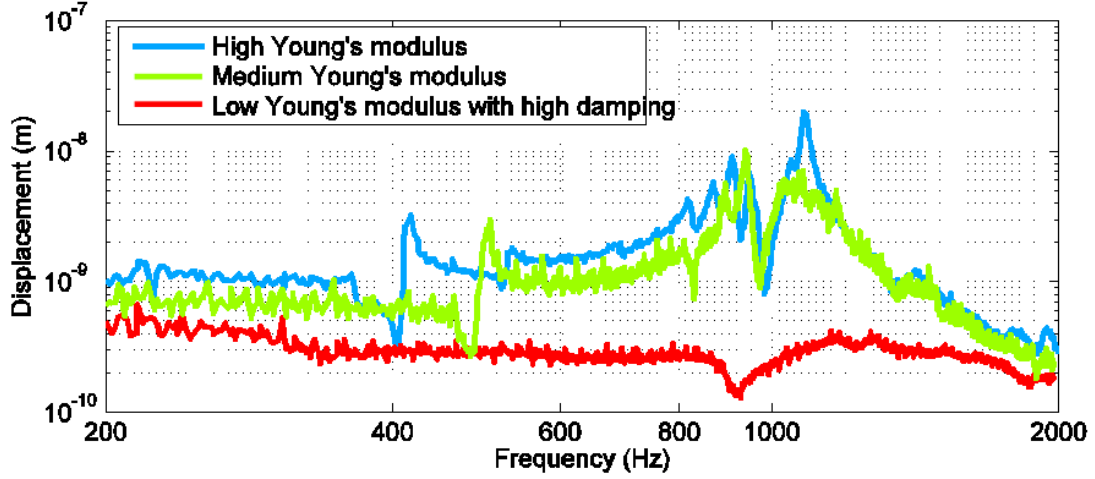


Figure 13: Air-gap material impact: measurement of the displacement for three structures

In [4], the author concludes that increasing the stiffness of air-gap is favorable. In our case, conclusion is opposite. To understand the reason, computation is done on the vertical deflection using an analytical model which takes into account the magnetostriction and Maxwell forces [11].

Discussions : In order to observe trends and the impact of magnetostriction effect, we propose a simplified model (equation 1) [10] in the case of purely vertical deflection with: Δy the vertical deflection [m], $\lambda_T(B)$ the magnetostriction curve [$\Delta l/l$] which depends of B , the flux density [T], n the number of air-gaps, E the Young's Modulus of air-gaps [Pa], H_c the column height [m] and e the thickness of air-gaps [m].

$$\Delta y = \lambda_T(B)H_c - n \frac{B^2}{2\mu_0 E} e \quad (1)$$

By comparing [4] and the inductance described in this paper, the two reactors have a total air-gap of 6 mm per column, but shapes are clearly different. Column height is smaller (150 mm compared to 400 mm) so that magnetostriction is lower on the reactor from [4]. Moreover in [4] stiffness of air-gaps is also smaller than our component. In this way Maxwell forces are higher on the reactor presented in [4]. Results on fig. 14 show that magnetostriction is predominant on our reactor (circle at 400 mm), whereas on the reactor from [4] (circle at 150 mm), Maxwell forces are the most important. To reduce the vertical deflection of both reactors, stiffness of air-gaps should evolve in opposite way.

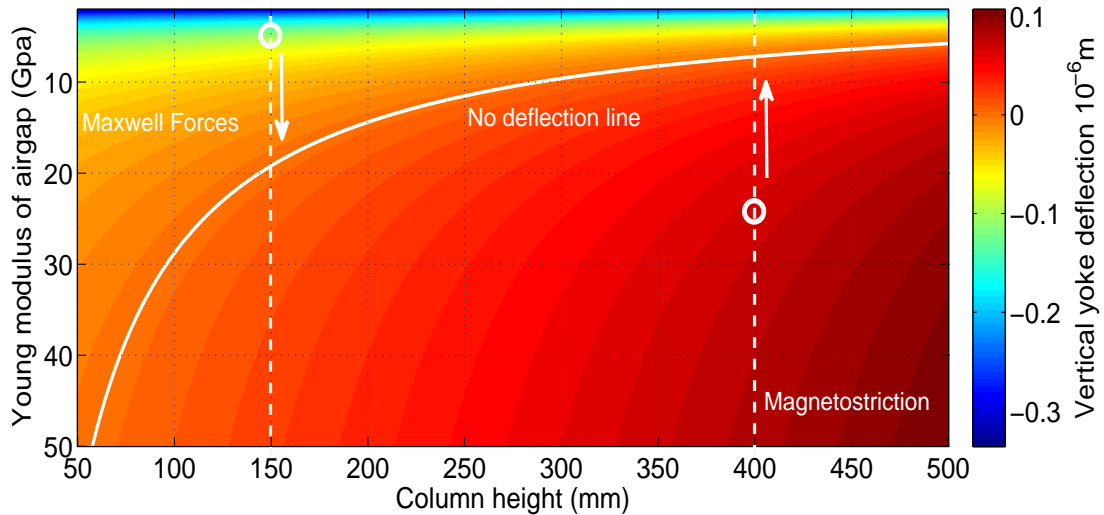


Figure 14: Effect of Young's modulus on two reactors with different column height

From the fig. 14, a compromise between column height and young's modulus is visible. On the no-deflection line, magnetostriction and Maxwell forces compensate each other.

V. CONCLUSION

Experimental measurements have been presented on reactors to understand the mechanical behavior of 2 column reactors. The modal analysis shows the different kind of resonances of the magnetic core which have been compared with a finite element simulation. The operational deflection shapes show that only few resonances can be electrically excited. The vertical deflection is clearly the most problematic mode.

Changing the air-gap material is beneficial for the deflection of the reactor. But it has been presented that, following the shape of the reactor, it is beneficial to reduce or increase the stiffness of the material depending on the column height. For a fixed Young's modulus air-gap, a ratio Column height / air-gap thickness exists which make it possible to cancel the deflection.

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