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Noise and vibration of a power transformer under an electrical excitation

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ABSTRACT

The noise of electrical machines such as electric motors, power transformers and electrical inductors increasingly interested designers and manufacturers of several industries (automotive, rail, etc.). This interest concerns the reduction of noise caused by these machines in transportation vehicles for example, to provide better comfort to users. In this paper, the noise radiated by an electrical power transformer is predicted using an end-to-end multiphysics modelling solution. The modelling procedure is based on the chaining of three analysis methods. The first one simulates the electromagnetic problem which generates Maxwell forces on the magnetic core of the transformer from electrical excitation. These forces are considered as an input for the mechanical problem solved by the finite element method (FEM) to calculate the acceleration field on the structure. Finally, these accelerations are considered as in input for the acoustic model to compute the noise radiation using the Boundary Element Method (BEM). Two models of the ferromagnetic core are considered. The first is a bloc model where the different laminates are stuck and the second is a laminated model where a small sliding condition is introduced at interfaces between sheets of metal. Numerical results of the mechanical and acoustic models using a laminated core are compared with experimental data and show good agreements with measurements.

1. Introduction

The noise generated by electrical devices and machines such as electric motors, power transformers and electrical inductors increasingly interested designers and manufacturers of several industries (automotive, rail, etc.). This interest concerns the reduction of noise caused by these machines, in transportation vehicles for example, to provide better comfort to users.

In the case of electrical inductors and power transformers, one of the noise sources is the magnetic circuit supplied by an electric current. The prediction of the radiated noise by numerical simulation software tools is an essential step in the design phase of silent systems. Modelling the electro-magnetic noise is a multi-physics problem requiring chaining between electromagnetic, mechanical and acoustic models. Among the authors who have worked on this chaining of multi-physics calculation, we can cite Ait-Hammouda [1] who developed a tool for Vibroacoustic dimensioning (DIVA) of AC machines. This tool was developed in Matlab. The electromagnetic model was validated with the OPERA 2D software, the mechanical model was validated using the ANSYS code, while the acoustic model was validated by comparison with experimental results. In 2010, Le Besnerais [2] used the analytical tool DIVA 2 (re-form of DIVA) to model the electromagnetic, vibro-acoustic and heat transfer behaviours of an electric motor. The electromagnetic, mechanical and acoustic models was validated with the software tools FLUX 2D, IDEAS and Sysnoise respectively. Recently, another software chaining was mounted by Pellerey [3], within the Avelec project, for the simulation of vibro-acoustic behaviour of an electric motor using the Maxwell code for the electromagnetic problem, the MSC.Nastran code for the mechanical model and FFT ACTRAN for the acoustic simulation.

One of difficulties of the mechanical problem is how to model the magnetic laminated core which is a stack of many sheets of metal intercalated by a thin layer of an electrical insulator. Masti [4] have studied the effect of the lamination on the dynamic behaviour of a magnetic core. He modelled this structure by considering the core as one bloc or as a stack of several sheets of metal. Eigen frequencies obtained by these models were compared with measurements. Bouzek [5] have modelled the laminated stator of an electrical motor by considering it as an orthotropic material and

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compared numerical natural modes and frequency with experimental data. By considering a laminated model, each thin sheet of metal have to be meshed separately which generates a very large size finite element matrix system. For this reason, some authors consider the use of homogenization method to reduce the model's size. For example, Dupont [6] developed a method to calculate an equivalent homogeneous material that can be applied to all the structure without meshing every laminate separately.

This work has been realized in the context of dBET project, which is a collaborative research project led by Alstom Transport. The dBET project is aiming to simulate and reduce the noise radiated by electrical equipments of train such as transformers and inductors. In literature, the majority of studies concerning the power transformer's noise, are interested on the load noise caused by Laplace forces on windings [7,8]. However, Alstom noticed that the no-load noise caused by Maxwell forces and magnetostrictive strains of core lamination is more critical than the load noise for its applications. Therefore, in this paper, only the Maxwell forces are treated, and an end-to-end numerical Multiphysics Modelling solution is proposed to predict the noise radiation of a no-loaded power transformer. The modelling procedure is based on the chaining of three numerical analysis methods. The first one simulates the electromagnetic problem which generates Maxwell forces on the magnetic core of the transformer from electrical excitation. These forces are considered as an input for the mechanical problem solved by finite element method 'FEM') to calculate the acceleration field on the structure. For this mechanical problem, the ferromagnetic core is modelled by considering either a stick contact (bloc model) or a sliding contact (laminated model) at the interface between different laminates. Numerical results of each model is compared with experimental results. Finally, the acceleration field obtained by the mechanical FE model is considered as in input for the acoustic model to compute the noise radiation using the Boundary Element Method (BEM).

2. The Multiphysics computing process

The proposed calculation chain is composed of 3 stages as shown in Fig. 1. The first step is an electromagnetic calculation using Flux 3D tool and which has as input the electric current and as output Maxwell forces on the ferromagnetic core's air-gap. The second step is to recover Maxwell forces from electromagnetic solution, which is introduced as a solicitation for a mechanical calculation to obtain accelerations at the nodes of the core. The mechanical calculation is performed by the code VPS [9] (Virtual Performance Solution). The third step is performed with the software tool VAOne using the Boundary Element Method implemented in Rayon solver [10]. This is an acoustic calculation to compute the noise radiated by the structure due to an imposed acceleration. The interface between the two first models is an internal tool developed to ensure the transfer and projection of Maxwell forces field from electromagnetic mesh to the mechanical mesh. This tool is compatible with other electromagnetic software tools used in the project such as ANSYS-MAXWELL and ESI-SYSMAGNA.

Setting equation of the electromagnetic problem is given by Eq. (1) that determines the Maxwell force density F produced at magnetic permeability interface between steel sheets and air.

$$F = b^2/2\mu_0 \tag{1}$$

where μ_0 is the magnetic permeability of the air (steel sheets are considered as a perfect magnetic conducer). The flux density b is obtained thanks to electric current in the windings that produce magnetic flux (shown by flux lines in Fig. 5). In this kind of transformer the current has a 50 Hz frequency in Europe. Thus, according to Eq. (1) forces have a 100 Hz frequency harmonic.

The calculated Maxwell force represents the excitation of the mechanical problem that allows the calculation of the structure displacement field vector W using the finite element method (FEM). The displacement vector satisfies the following algebraic equation (Eq. (2)).

$$(K - \omega^2 M)W = F \tag{2}$$

where K and M are the stiffness and mass matrix of the vibrating structure, ω: excitation angular frequency, and W is the nodal displacement field.

The last step of the computational process is the simulation of the acoustic radiation of the power transformer. The displacement field obtained by solving the dynamic Eq. (2) corresponding to frequency response of the power transformer excited by the Maxwell forces. The acoustic model is conducted using the boundary element method (BEM) which require only the mesh of the external surface of the power transformer.

The solution of the problem is given by the integral equation of the acoustic pressure:

$$P(x) = \int_S \left(-\rho\bar{\gamma}G(x,y) - P(y)\frac{\partial G(x,y)}{\partial n_y} \right) dS_y \tag{3}$$

where, p is the acoustic pressure, ρ is the mass density of the external acoustic media, $\bar{\gamma} = -\omega^2 W$ is the acceleration field defined on the surface, G(x, y) is the free field Green's function defined by $G = -e^{ikR}/4\pi R$, where R is the distance between two points located in the external acoustic domain in R^3 space and k = ω/c the acoustic wave number, where c is the speed of sound in the acoustic domain.

Since the acceleration is imposed at the external surface of the transformer, it is possible to represent the radiated pressure by the indirect Boundary Element Method (10):

$$P(x) = -\int_S \mu(y)\frac{\partial G(x,y)}{\partial n_y} dS_y \tag{4}$$

where the unknown is the jump of pressure μ on the radiating surface of the power transformer, which satisfies the following integral equation:

$$\rho\gamma\gamma(x) = \int_S \mu(y)\frac{\partial^2 G(x,y)}{\partial n_x \partial n_y} dS_y \tag{5}$$

To calculate the jump μ of the pressure, the integral Eq. (5) is solved using the variational boundary element method [11] implemented

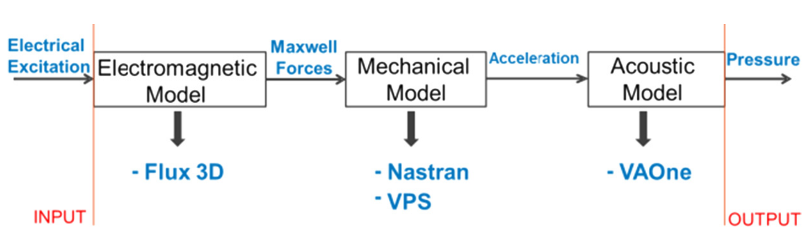

Fig. 1. The Multiphysics modelling process.

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