A SIMPLIFIED MODEL FOR SIMULATING STRUCTURAL AND ACOUSTIC RESPONSES OF ELECTRIC MOTORS

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In this work, we will address a simplified model for simulating the dynamic behavior of electric motors, more specifically, the acoustic response of stators. Targeting this application, both structural and acoustic responses are calculated by the finite element (FE) and boundary element (BE) methods, respectively. The FE model consists in a geometric simplification in which the stator is discretized by curved and straight beam elements (body and teeth) and concentrated mass elements (wiring representation). This particular set of simplifications was chosen to facilitate the use of an already well developed MATLAB tool called NuSim. An emulation of the dynamic forces acting on the stator teeth was also taken into consideration, although its amplitudes were approximated. The structural representation was validated by using the commercial software ANSYS®, achieving satisfactory results. Later on, the acoustic part was modeled by the direct BE method, using values for areas, normals, coordinates and velocities from the previously described FE part. Therefore, this algorithm was built to obtain both sound pressure level and radiated sound power (calculated by ISO 3744), respecting the FE model and the forces of arbitrary magnitude prescribed on the stator teeth. Finally, this acoustic part also was validated by comparing the calculated sound pressure levels with commercial software that uses acoustic FE as a solution method. The results of NuSim supported the idea that this simplified model is suitable for a frequency range up to 3.8 kHz, and reduces the time of this analysis type by approximately 60x.

Keywords: finite elements method, boundary elements method, simplification, electric motors, acoustic response

1. Structural Model

NuSim is a simulation software that was previously an algorithm built to calculate the insertion loss of curved beams, by the wave propagation approach, using the FE Method. It was designed with a modular concept, in which every part should work independently, in order to facilitate further additions to its functionality. NuSim already has several working modules available, despite being a work in progress. Some of these are depicted in Fig. 1.
Thus, the beam formulations built in NuSim were used in this new application, focusing on simulating a simplified version of stators of electric motors. Therefore, the stator’s curved sections were modelled by curved beams and its teeth were modeled by straight ones. NuSim also allows the user to prescribe a value for concentrated mass elements to be distributed over the teeth nodes, so that the wiring mass can be considered.

Beam elements do not consider the rotary inertia or the shear deformation, and their formulation was better explained in our previous work [1, 2, 3, 4, 5, 6].

All the extra stator geometric properties, which are not defined by the mesh dimensions, were considered in the beams’ cross-sectional dimensions. All cross-sections were thought to be rectangular, so their width and height would intend to be the stator’s axial and radial thickness. Figures 2 (a), 2 (b), and 3 show how each geometric property was programmed to allow these adaptations.

Furthermore, material properties can be adapted to equivalent ones, so that the behaviors of orthotropic properties or highly damped areas can be better represented. Even with the algorithm allowing such approximations, typical values of mechanical properties were used in the simulations in this paper, since an extensive experimental analysis should be performed to determine these values properly.

So, value of Young’s modulus used in the simulations was 207 GPa, with a Poisson’s coefficient of 0.3, and a density of 7800 kg/m$^3$.

In addition, the stator’s outer diameter measured 200 mm, with a radial thickness of 20 mm and an axial thickness of 50 mm. It had eight teeth, each 30 mm long and 15 mm wide. The wiring mass was 10 g per tooth in the structural validation, but this was neglected in the acoustic validation, because of the mesh differences.

Even more, the algorithm required a “force editor” (Fig. 4) in order to emulate the magnetic forces acting on the real stators. As this is a tool that is still under development, only the base code was built to
Figure 2: (a) Schema of how the stator mesh was built. (b) Geometric properties of a typical stator. roughly emulate an electromotive force behaviour.

Figure 3: NuSim’s interface for editing the stator geometric properties.

1.1 Structural Validation

With that being said, the first validation was carried out by performing a harmonic analysis in a similar model with ANSYS®. The mesh was built through APDL (ANSYS® programming design language), with elements of type BEAM188, which considers both the rotary inertia and the shear deformation. Figure 5 shows that the results were almost identical to each other, supporting the idea that the structural part of NuSim is working as intended.
Figure 4: NuSim’s interface for editing the force properties.

Figure 5: NuSim structural validation, while comparing displacement results with the same model simulated in ANSYS®.
2. Acoustic Model

In this chapter we introduce the acoustic part, which was modeled using the BE method. This was chosen since it is easily scalable for numeric applications, and it will not significantly suffer from acoustic FE mesh size or analytical sensibility to the order of magnitude of its variables.

The direct BE Method for acoustic analysis relies on the Helmholtz integrals to obtain the pressure information at a given point in space. Here, we will show only its basic formulation for the sake of simplicity. If more detailed information is required, please refer to [7].

With that being said, the Helmholtz integral equation can be written as follows:

$$cp(R) = \int_S \left[ p(R_o) \frac{\partial g}{\partial \hat{n}_o} - g(|R - R_o|) \frac{\partial p}{\partial \hat{n}_o} \right] dS,$$

(1)

where $\hat{n}_o$ stands for the normal vector pointing toward the fluid, $p$ stands for the pressure, $g$ is Green’s space function, which will be introduced next; and finally $c$ is a variable that takes four different values as follows

$$c = \begin{cases} 
1, \text{inside the fluid} \\ \frac{1}{2}, \text{on a smooth surface} \\ \frac{\Omega}{4\pi}, \text{on a non-smooth boundary}; \Omega \text{ is the solid angle}. \\ 0, \text{outside the fluid}. 
\end{cases}$$

(2)

Hence, knowing Green’s space function:

$$g(|R - R_o|) = \frac{e^{-jk|R-R_o|}}{4\pi|R-R_o|},$$

(3)

and the following relations:

$$v = \frac{j}{\rho_o \omega} \frac{\partial p}{\partial \hat{n}_o} \rightarrow \frac{\partial p}{\partial \hat{n}_o} = -j\rho_o \omega v,$$

(4)

allows rewriting Eq. [1] introduced previously as

$$cp(R) = \int_S \left[ p(R_o)\bar{g} + j\rho_o \omega v g(|R - R_o|) \right] dS,$$

(5)

with $\bar{g} = \frac{\partial g}{\partial \hat{n}_o}$. By discretizing Eq. [5] we achieve

$$cp_i - \sum_{i=1}^{N} p \int_{S_j} \bar{g}dS_j = j\rho_o \omega \sum_{i=1}^{N} v \int_{S_j} gdS_j,$$

(6)

with $N$ being the number of mesh nodes to be considered, which allows us to introduce

$$\begin{cases} 
\bar{H}_{ij} = \int_{S_j} \bar{g}dS_j, \\
G_{ij} = \int_{S_j} gdS_j 
\end{cases}$$

(7)

facilitating the task of developing a numerical algorithm with these abstractions. Therefore, the BE problem to be solved becomes a matrix problem as in

$$\begin{cases} 
H_{ij} = \frac{1}{2} \delta_{ij} - \bar{H}_{ij}, \\
[H]\{p\} = j\rho_o \omega[G]\{v\}. 
\end{cases}$$

(8)
Therefore, for a suitable direct BE model, only the areas, normals and mesh coordinates are needed along with the desired response coordinates and prescribed mesh inputs in the form of pressure or velocity.

For the application presented in this paper, besides the stator being modeled with beam elements, another simplification was applied on the acoustic part: Only the stator faces farthest from the center (i.e., located on the outer diameter) were considered in the BE model, since the teeth and axial velocities are very small, and can be neglected. In addition, the areas closest to the center, located on the inside of the stator, are sufficiently small compared to the ones on the outside, so they can be neglected as well.

### 2.1 Acoustic Validation

This part was also validated with ANSYS®, but with a slightly different setup in the commercial software. First, the mesh was built with tetrahedral elements for both structural and acoustic parts. ANSYS® Acoustics ACT addon was used so the acoustic body was configured as FLUID220 and FLUID221. The fluid-structure interaction interface was determined by the addon “fluid structure interaction interface” (or FSI interface), and the teeth forces were prescribed as pressures, since they should act equally over the whole extension of the section’s area. Due to the computer’s limitations, the finest mesh achievable was with elements that had edges of 15 mm minimum, allowing a feasible simulation up to 3800 Hz. Both meshes can be seen in Figs. 6(a) and 6(b).

![Figure 6: (a) ANSYS® stator mesh used in validation with tetrahedral elements. (b) ANSYS® fluid mesh used in validation with tetrahedral elements (sliced in half for better visibility).](image)

The mechanical properties of the stator used in this simulation were the same: Young’s Modulus = 207 GPa, Poisson’s coefficient = 0.3, and density = 7800 kg/m³. The air properties were as follows: sound speed = 341 m/s, and air density = 1.21 kg/m³.

The computer that we used had an Intel Core i7 4770K 3.50 GHz processor, mounted on a Gigabyte H87M-D3H motherboard with 16 GB DDR3 RAM (1333 MHz) in dual channel, plus a GeForce GT 630 graphics card.

The complete mesh had around 135000 elements and a little less than 190000 nodes and took around
10 GB of RAM and 2 h to be fully calculated. MATLAB’s NuSim only took 2 min, hence an enhancement of roughly 60x performance-wise. In addition, the resulting file size was around 180 MB in comparison to almost 10 MB with NuSim, again a much lighter solution.

Figure 7 shows that, even with different element formulations, the results are mostly similar, especially for frequencies below 1 kHz. The comparison of pressure values also showed a similar behavior, with a good agreement between the two models on lower frequencies, as can be observed in Fig. 8.

![Displacements (node #6)](image1.png)

![Pressure values](image2.png)

Figure 7: ANSYS® validation of structural displacement with tetrahedral elements.

![Sound Pressure in Axial Direction](image3.png)

![Sound Pressure in Radial Direction](image4.png)

Figure 8: Pressure validation in both radial and axial directions, 200 mm far from the center of the stator.
It could be argued that the discrepancy in the higher frequencies can be decreased by increasing the discretization of the NuSim model. However, as the chosen simplification was a beam representation of the stator, there are vibration modes that are impossible to obtain, such as flexure on the axial direction, aligned with the stator ring center axis. These higher order frequency modes would always be poorly represented by this choice of simplification.

However, it is safe to say that this approximation can feasibly simulate a typical stator and its structural and acoustic behaviors. In addition, because of its high performance, it is suitable for optimization algorithms.

3. Conclusions

In this study, a simplified model was successfully built and validated by comparing its structural and acoustics results using ANSYS®.

The limitations of this approach lie in the structural representation of the stator by beam elements, since it cannot fully describe higher order modes in the axial direction.

However, it was shown that the acoustic results were satisfactory, since they follow the same behavior of the more detailed model.

Furthermore, the improvements in performance and resulting file size were considerably large, with a decrease in the solving time of 60x and a reduction of the file size from 180 MB to around 10 MB.

Since NuSim is a tool that was specifically built for this type of simulation, its interface for editing the stator’s geometric properties and emulating the magnetic forces that act on the stator’s teeth is substantially easy to use.

Finally, it is good to remember that this tool is still under development and there are several parts that need to be improved, such as the solvers in MATLAB that could be compiled in another language to make it faster or to use GPU parallelization. In addition, the force emulation interface needs some rework in order to fully calculate the real electromotive forces acting on the stator.

References