

Electromagnetics, Structural Harmonics and Acoustics Coupled Simulation on the Stator of an Electric Motor

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ABSTRACT

Electric motors and generators produce vibrations and noise associated with many physical mechanisms. In this study, we look at the vibrations and noise produced by the transient electromagnetic forces on the stator of a permanent magnet motor. In the first stage, electromagnetic simulation is carried out to calculate the forces per tooth segment of the stator. The harmonic orders of the electromagnetic forces are then calculated using Fourier analysis, and forces are mapped to the mechanical harmonic analysis of the second stage. As a third stage, the vibrations of the structure are used to drive the boundary of acoustic domain to predict the noise. Finally, optimization studies are made over the complete system to improve the motor design and reduce noise. A simulation environment (ANSYS Workbench) is used to integrate a seamless workflow.

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INTRODUCTION

Electric motors are widely used in a variety of industrial applications. They can be found in compressors, industrial fans, pumps, household appliances, machine tools, etc. Noise and mechanical vibrations are of the main sources that may lead to a breakdown of an electric motor [Shen et al. 2012]. It is therefore very crucial to assess the vibration mechanical performance of electric motors to avoid mechanical failures. Vibrations and electromagnetic noise are induced due to electromagnetic forces within the air-gap between the rotor and the stator. The existence of an air-gap eccentricity also affects the magnitude and imbalance of the produced electromagnetic forces, which will lead to an extra level of vibration noise [Rodríguez et al. 2008]. Air-gap eccentricity can be indirectly calculated by calculating the produced electromagnetic forces. Consequently, vibration levels can be precisely predicted.

It is essential to understand the fundamental and harmonic frequencies of the electromagnetic force in order to avoid the natural frequency of the motor stator. It is therefore important to study the modal analysis of the motor structure to obtain its natural frequencies; otherwise, resonance may occur while in operation, leading to a mechanical failure. The Discrete Fourier Transformation is used to obtain the harmonic indices of the electromagnetic forces. Prior to ANSYS Maxwell R15.0, a user had to manually perform a Fourier transform outside of the software to obtain the frequency data (export data, analyze, re-import data). The built-in feature of duplicating periodic data,

allows the smallest, most efficient magnetic simulation to lead to accurate, full 3D harmonic and acoustic analyses. More details on the fundamental theory are given in section I.

In this manuscript, a seamless workflow to model the acoustic noise and vibration of an electric motor using the Finite Element Method is presented. As a new feature in ANSYS Maxwell R15.0, harmonic indices of electromagnetic forces can be automatically calculated using Fourier Transform. 2D and 3D analyses are adopted and harmonic indices can be calculated in both cases. The workflow will start by (1) electromagnetic force calculation using Maxwell, (2) the calculated forces are then easily mapped to ANSYS Mechanical 15.0 in a harmonic analysis environment, (3) velocity profiles are calculated and mapped to an acoustic run to predict the noise level.

ELECTROMAGNETIC FORCE MAPPING

Finite element analysis is a useful simulation technique for solving magnetic field distributions for arbitrary geometries, and has been utilized and validated for electric machine applications specifically. These simulations can be performed in 2D (assuming constant geometry, fields, and excitations in the extruded Z-dimension) or in 3D, and will take into account rotor rotation [Zhou et al. 2008]; nonlinear, anisotropic materials [Lin et al. 2005]; arbitrary circuit connections and control [Zhou et al. 2006]; and include the field-effects of core loss [Lin et al. 2008]. For the purposes of the present study,

these electromagnetic fields are required to determine the electromagnetic forces acting on the stator teeth, which cause the vibrations to be studied.

Electromagnetic forces are initially calculated within Maxwell as distributed force densities on the stator. We spatially integrate these distributed force densities to provide lumped forces and torques on the tips of the teeth that experience the majority of the electromagnetic forces. We provide two alternatives for calculating these lumped forces and torques:

1. an integral of surface-force density on the exposed edges of the tooth tips (using a Virtual Work force calculation for surface-force density F_u et al. 2004, Ren et al. 2001), and
2. an integral of the Maxwell Stress Tensor (MST) force on a small arc in the air gap in front of each tooth (the arc from slot-center to slot-center adjacent to each tooth).

The integrated forces provide a “0th moment” representation of the force density distribution, which is largely sufficient for the structural response because the laminations are stiff and the presumed deformations are small (which are also assumptions for the linear structural harmonic analysis). The torques are calculated with reference to the centroid of the tooth tip, and provide a “1st moment” representation of the force density distribution, which accounts for any twisting of the teeth around the centroid that is not included in the integrated forces.

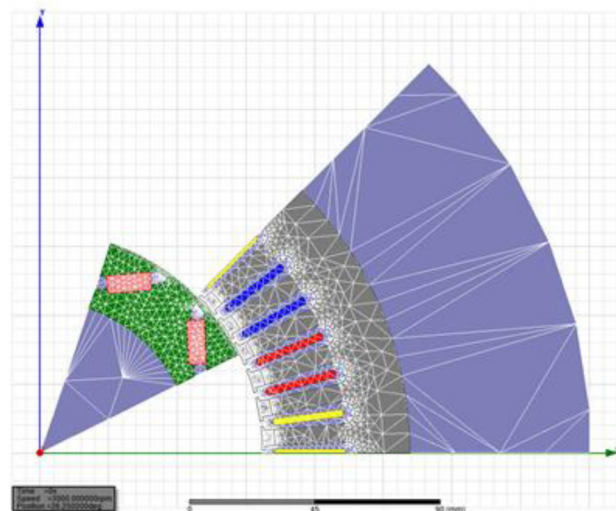


Figure 1. Mesh of 1/8th motor model, showing separate tooth-tip objects.

To further describe the force calculations and compare the methods, we look at fields and transient forces from a Maxwell2D example studied later in this paper. The model is an 8-pole IPM, and we study here the forces on the first tooth tip counter-clockwise from the x-axis. The tooth tips are split into separate objects - disjoint, but touching the stator back-iron - and are well-meshed to accurately resolve fields and forces (mesh shown in [Figure 1](#)). With this process, the radial and tangential forces can be well defined from the front surface of the tooth tips, as well as contributions from the sides. The

instantaneous force densities on the first tooth tip are illustrated as vector plots in [Figure 2](#) using both methods and are representative of the forces on the tooth tips when the direct axis is passing underneath - predominantly radial, with some deflection and variation. The image in [Figure 2a](#) is using the fields in the air gap to calculate the forces, which includes the contribution from the tooth tip, the adjacent coils, and arbitrarily effects from the adjacent tips (strictly speaking, the MST force density should use a closed surface around the object for force calculation, but we take this liberty here because motor fields are most dominant in the air gaps). In [Figure 2b](#) the forces are calculated on the surface of the tooth tip object, but excludes the surface touching the stator back-iron (which would provide a large force pulling the tooth tip to the back-iron), and the spatial integration occurs over only the surfaces not touching the stator back-iron. The integrated instantaneous forces on this first tooth for these vector plots in [Figure 2](#) are provided for reference in [Table I](#). The comparison of transient integrated forces is provided in [Figure 3](#) for an electrical cycle under steady-state conditions, where the radial and tangential forces exhibit similar magnitudes and transient waveforms between the two methods: integration of surface force density, and Maxwell Stress Tensor calculation. Either force calculation method is suited for a model representation of electromagnetic force on the teeth-tips of electric machines, and both methods are available in Maxwell 2D/3D by either selecting the teeth tip objects, or arc segments, and the appropriate force calculation is performed automatically by Maxwell.

The frequency domain harmonic force data is taken from the Maxwell transient force results by the following steps:

1. Use a sliding window to obtain the last $\lceil p/2 \rceil$ electrical cycle(s) of data for F_x , F_y , F_z , and M_x , M_y , M_z , where p is the number of poles included in the periodic simulation (only 1 pole in the example), $\lceil \cdot \rceil$ is the integer ceiling function, and F and M are the integrated force and torques (moments).
2. Perform a Discrete Fourier Transform (using interpolation if non-uniform time-steps were required) to obtain real and imaginary frequency data (magnitude and phase) for F_x , F_y , F_z , and M_x , M_y , M_z .
3. Replicate tooth forces for remaining periodic geometry so that radial and tangential forces are in phase for all replications of periodic teeth.

This is the most efficient way to produce discrete frequency data of electromagnetic forces for steady-state operation. Yet the setup allows removing the periodicity assumption for the model to look at non-periodic forces, such as rotor eccentricity, tooth damage, rotor asymmetry, or unbalanced windings/ excitations. There are inherent assumptions about this calculation for steady-state operation, which will be generalized in the future, as this methodology has more general applications as well.

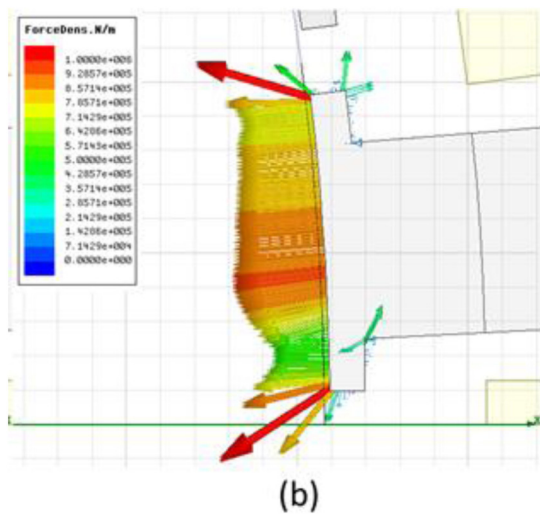
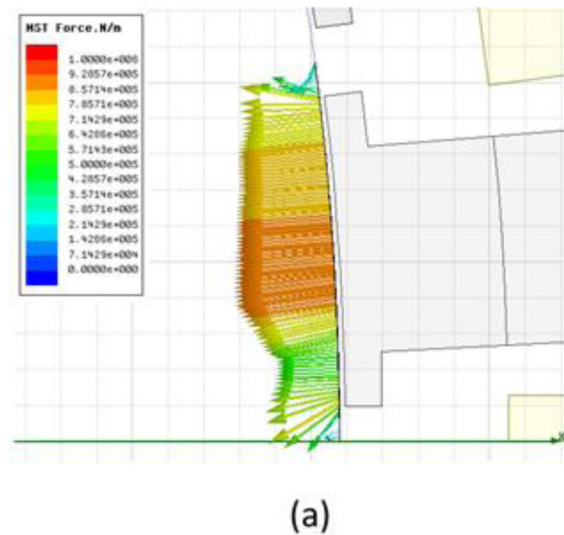


Figure 2. a) Vector plot of Maxwell Stress Tensor force density on arc in air gap in front of first Tooth Tip (from slot-center to slot-center). (b) Vector plot of surface force density on edges of the tooth tip.

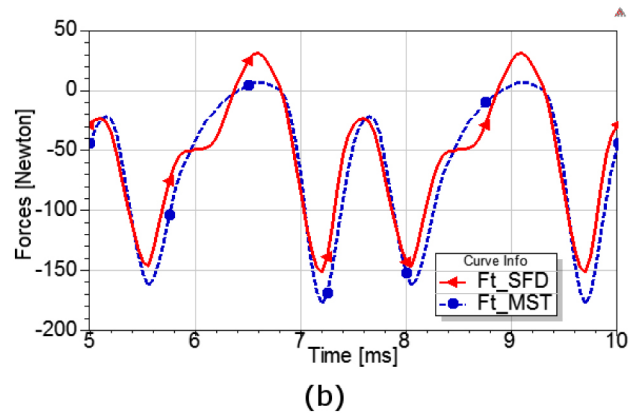
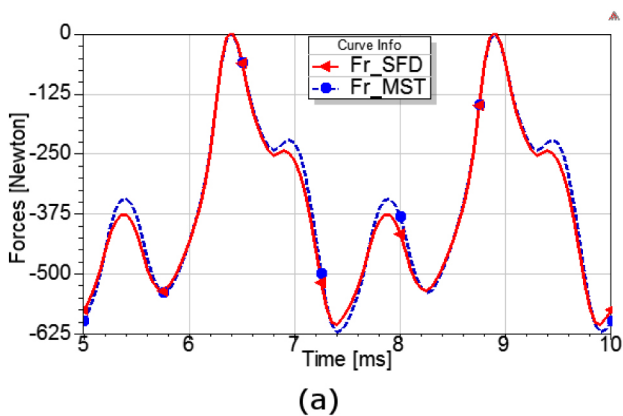


Figure 3. (cont.) Comparison of transient integrated tooth-tip forces in steady-state: (a) Radial force. (b) Tangential force.

Table 1. A comparison of integrated force calculations for an instantaneous force corresponding to the vector force densities in Figure 2, including the axial length scaling of 83.82mm.

	F_{radial} [N]	$F_{\text{tangential}}$ [N]
MST Force	-572.7	-28.0
Surface Force	-597.5	-44.6

MOTOR FINITE ELEMENT MODEL

Maxwell Setup

The motor design that we use for this study is the 2004 Toyota Prius [Hsu et al. 2004], operating at 3000rpm. We assume a synchronous 3-phase sinusoidal input current with peak magnitude 250A. There are 8 poles, 48 stator teeth, 3.3in lamination stack length, and under the assumed operating conditions the average output power is 75kW. This is a standard example motor design in Maxwell and is documented in the ANSYS training material. For this example we use a 2D model using a 1/8th model containing a single pole.

The 5 changes that are recommended for proper setup of the force calculation, different from a standard simulation of rated operation are the following:

1. Aligning the stator rotation so that the periodic master/slave boundaries are centered in the coil slots and not centered in the middle of the stator teeth. This allows the force calculation to occur on complete tooth tips and not partial tooth tips split by the periodic boundaries.
2. Either creating separate objects for the stator tooth tips, or creating arcs in front of each tooth tip (from slot-center to slot-center).
3. Increasing the mesh fidelity on the surfaces of the tooth tips to obtain a better force result.
4. Decreasing the simulation time-step to best resolve cogging effects and obtain higher-frequency harmonic results.
5. Selecting the option within the Maxwell software to enable the harmonic force calculation. This enables the Fourier calculation of the transient forces from within Maxwell and creates necessary data as input files for the structural analysis.

Figure 3.