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Cogging Torque Analysis of Permanent Magnet Machines using Abaqus/Standard

Abaqus Technology Brief

Summary

Reduction of cogging torque is one of the fundamental goals in designing permanent magnet machines. Finite element analyses are indispensible in analyzing the various design choices for reducing cogging torque and for faster prototyping of the final product.

One of the challenging aspects of computing a cogging torque curve using the finite element method is reducing the numerical noise generated from the mesh. The noise arises due to the complex variation of the magnetic field in the air gap, often leading to numerical cancellation errors that are sensitive to the nature of the chosen mesh.

In this Technology Brief, we show how Abaqus/Standard can be used to compute cogging torque in a permanent magnet generator. To reduce numerical noise, meshing techniques involving a sliding mesh and repeated meshes are realized using the advanced meshing functionality available in Abaqus/CAE.

Background

Permanent magnet machines are used in many industrial applications because of their ability to produce high power densities. However, they have the undesired effect of producing cogging torque, which arises from the interaction of the permanent magnets with the stator teeth or rotor poles. Cogging torque introduces unwanted pulsation in the shaft torque, and can subsequently cause structural vibrations and noise.

Due to the absence of axisymmetry in the rotor geometry, cogging torque varies with the angular position of the rotor. The periodicity is determined by the number of stator slots and rotor poles, while the magnitude is determined by a number of geometric factors such as pole arc angle, magnet dimensions, geometry of the stator teeth, etc.

The cogging variation in the torque may interfere with other components such as position sensors. Vibrations and noise are amplified further when the frequency of the cogging torque matches the mechanical resonant frequency of the stator or rotor. It is therefore essential to evaluate the cogging torque produced by the design choices of a permanent magnet machine.

Geometry and Model

We consider the geometry of the stator-internal permanent magnet generator proposed by Zhang et.al. [1] for wind power generation applications (Figure 1). It has a 10-pole rotor with a pole-arc angle of 10.428°. The 12 stator teeth are split at the top and a bridge is provided at the bottom to support the permanent magnets, which measure 20mm x 5mm. The detailed geometry of each tooth is depicted in Figure 2. The slot opening and thickness of the air gap are assumed to be 1mm and 2mm, respectively. The length of the device is assumed to be 75mm.

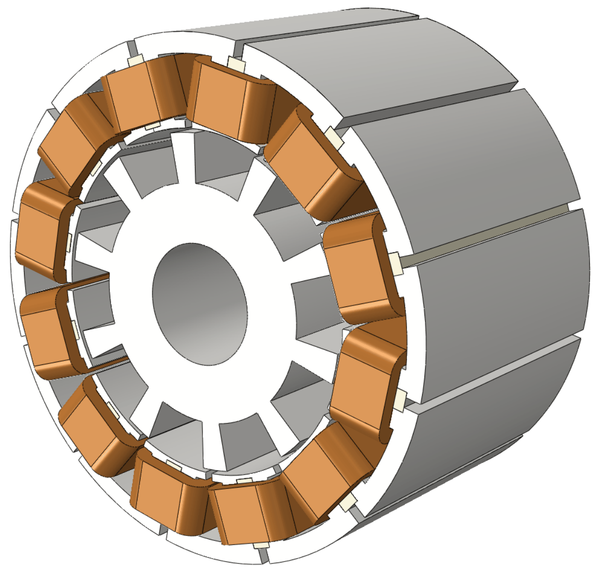

Figure 1: 12-slot, 10-pole stator-internal permanent magnet generator

> **Key Abaqus Features and Benefits**
>
> - Abaqus/Standard capability for analyzing planar magnetic problems allows for faster prototyping of electrical machines
> - Abaqus/CAE meshing functionality facilitates a sliding mesh technique for the rotor, allowing mesh noise to be reduced

Material Properties

The stator, rotor and the shaft are assumed to be made of a 1010 grade steel. To account for saturation, the nonlinear magnetic properties of steel are specified using a BH-curve. The permanent magnets are assumed to have a coercivity of 6.7e5 A/m and a relative permeability of 1.023. The material properties of the coil do not affect the results of the cogging torque analysis.

Mesh

The overall simulation consists of a number of individual analyses, each considering a different angular position of the rotor. Cogging torque computations are sensitive to the nature of the mesh; noise may be introduced if the mesh topology varies in each angular position. The subsequent cogging torque curve can be noisy and the periodicity of the curve may be lost.

To minimize the numerical noise, a sliding mesh technique is employed. With this approach, the stator mesh

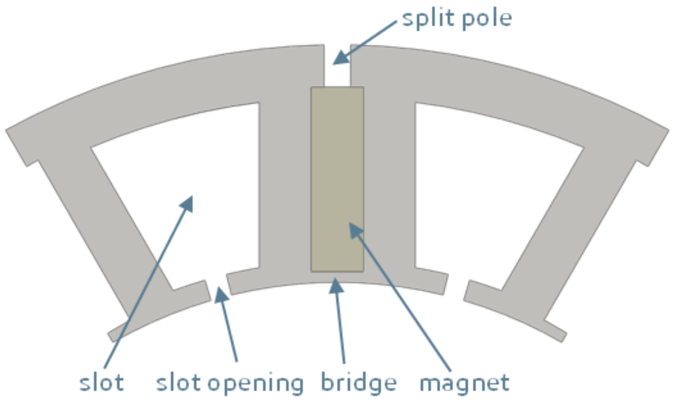

Figure 2: Stator tooth geometry

remains fixed and the rotor mesh is circumferentially repositioned for each individual analysis. The rotor and stator meshes have fixed topologies and their common interface (the center of the air gap) is divided into equally spaced segments; 2160 segments are used so that every angular degree of the interface is spanned by seven equally spaced nodes. This allows the rotor mesh to be moved circumferentially in discrete angular increments for each analysis while maintaining spatially coincident nodes at the interface.

The nature of the mesh in the stator teeth also influences the numerical noise. Abaqus/CAE is used to generate a repeated mesh in the stator teeth, as shown in Figure 3, to help reduce the numerical noise. To maintain mesh quality, controls such as edge seeds and single/double biased edge seeds are used. As shown in Figure 4, the biased edge seeds can be used to generate smaller elements at the stator-air and the rotor-air interfaces in the air gap. Biased meshing helps resolve the field variation at these interfaces as the magnetic flux leaves the stator tooth and enters the rotor poles and vice versa.

The mesh for the entire model is shown in Figure 5. It contains approximately 160,000 hexahedral elements and 320,000 nodes. The two dimensional magnetostatic problem is modeled using an extruded three dimensional mesh that has only one element along the thickness direction.

Analysis Method

A two-dimensional magnetostatic analysis is performed for various angular positions of the rotor. A 2D analysis ignores the end effects and assumes that the field is invariant along the length of the device. This is a reasonable

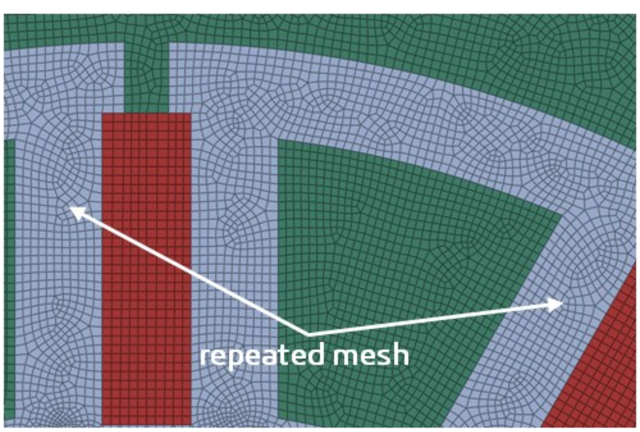

Figure 3: Repeated mesh in the stator teeth

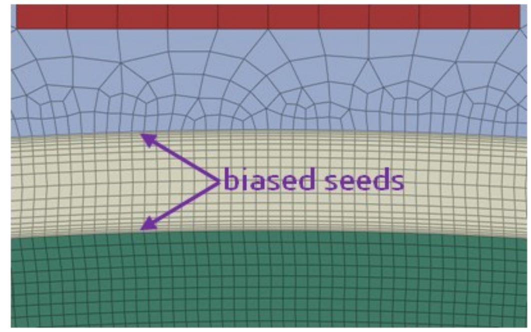

Figure 4: Biased mesh in the air gap region

assumption for many motor applications and allows for fast prototyping of the device. A full 3D analysis of the model can be performed at the end of the design either to confirm or make minor modifications to the design. The angular positions of the rotor considered here range from 0° to 12° with an increment of one sixth of a degree.

For each angular position of the rotor, the magnetic field output is postprocessed to compute the torque on the rotor. The Maxwell stress tensor based approach is adopted to compute the torque. In this approach, the torque is computed as an integral on a surface that encompasses the rotor. For the current analysis, the integration surface is chosen at the center of the air gap to minimize numerical noise.

Results

The contour plot of the magnetic flux density at zero angular rotation of the rotor is shown in Figure 6. Notice that the magnetic field is saturated in the bridge regions. If the analysis did not account for nonlinearity, the magnetic flux would completely pass through the bridge regions and avoid the high reluctance air gap, and hence the rotor, altogether.

For the initial configuration of the rotor, vector plots of the magnetic flux density in the right-most tooth and in the top-half of the problem domain are shown in Figures

Figure 5: Mesh of the entire model

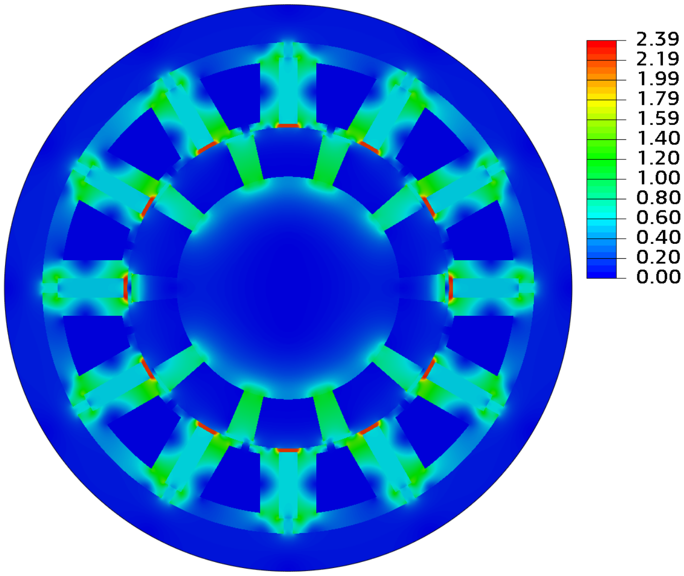

Figure 6: Contour plot of magnetic flux density magnitude

7 and Figure 8, respectively. From Figure 7 we see that when a rotor pole is below a permanent magnet, the flux leaving the North pole of the permanent magnet passes through the air gap and the rotor pole before it reenters the South pole of the magnet through the air gap again. But, when a rotor pole is between two permanent magnets, the flux passes through one rotor pole and comes out of another rotor pole as can be seen from Figure 8.

The cogging torque as a function of angular position is extracted by postprocessing the field output and is shown in Figure 9. The torque curve is very smooth and does not exhibit any noise. For an electrical machine, the periodicity of the cogging torque in degrees is given by 360/LCM (M,N), where, M is the number of stator slots, N is the number rotor poles and LCM signifies the least common multiple. The current model has 12 stator slots and 10 rotor poles and hence the periodicity is six degrees. We can see from the plot that the computed torque curve has the expected periodicity of six degrees.

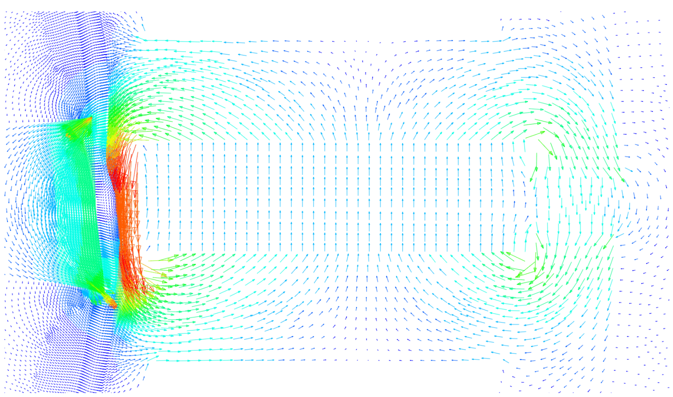

Figure 7: Vector plot of the magnetic flux density in the right-most tooth of the stator

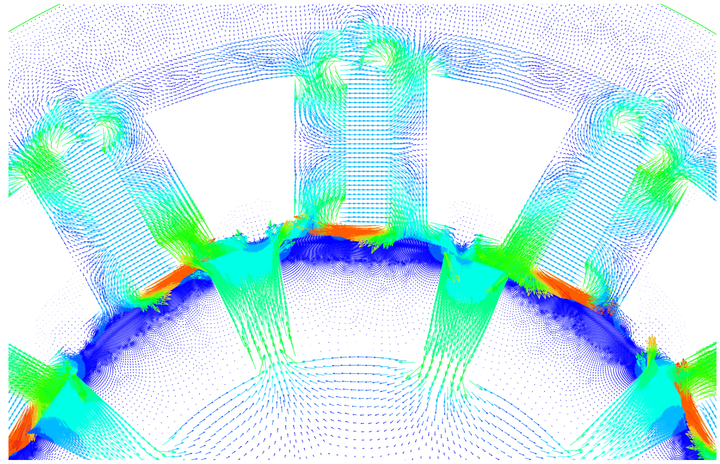

Figure 8: Vector plot of magnetic flux density in the top-half of the problem domain

Conclusions

In this Technology Brief, we have shown that Abaqus/Standard can be used to compute cogging torque in electrical machines. Meshing techniques required to reduce numerical noise are incorporated using advanced Abaqus/CAE meshing functionality. The Abaqus/Standard analysis could also be run in conjunction with Isight to perform parametric optimization with the aim of reducing cogging torque.

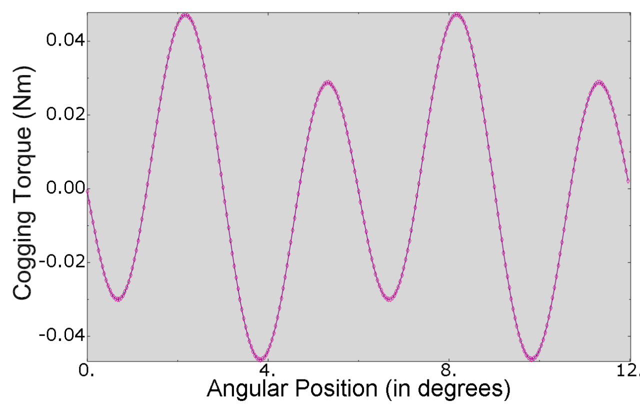

Figure 9: Cogging torque curve

References

1. Zhang, J., Cheng, M., and Chen, Z., "Optimal design of stator interior permanent magnet machine with minimized cogging torque for wind power application," Energy Conversion and Management, 2008 pp. 2100–2105.

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