Effective electromagnetic force calculation for NVH simulation in electric vehicle traction drives

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Electric vehicle traction drive motors are a major application area for electromagnetic simulations. More attention is being paid to complete drivetrain analysis using multi-physics simulations. Multi-body dynamic mechanical simulations rely on export of accurate electromagnetic force and torque values. The authors demonstrate methods that improve accuracy. The benefit of determining the effect of geometric deformations by repositioning mesh nodes rather than meshing a new geometry is shown. Errors caused by different discretization in each tooth are calculated using averaging algorithms for concentric configurations and used to reduce discretization errors in deformed geometry results. Improvement is also obtained by minimizing cancellation errors.

Index Terms—Electric vehicles, Electromechanical systems, Finite element analysis, Magnetic forces

I. INTRODUCTION

Progress in development and deployment of electric vehicle traction drives has been accelerating in the last decade. However, design of the traction drive system is still a complex exercise requiring considerable understanding of the performance of electric motors, gearboxes, bearings and connecting shafts. In particular, the mechanical interaction of the motor and the rest of the drivetrain requires extensive investigation to ensure that the vehicle meets noise, vibration and harshness (NVH) requirements. A key element of this is accurate calculation of motor electromagnetic force and torque, which are passed to multi-body dynamic analysis to understand the influence of the motor on vibration and vice-versa [1].

One of the important work packages within the EDISON (Electric Drive Integration by Simulation and OptimisatioN) project [https://gtr.ukri.org/projects?ref=103363] requires integration of electromagnetic effects computed by SIMULIA Opera with a multi-body simulation. Studies within the project have shown the importance of minimizing small inaccuracies in electromagnetic force calculation associated with meshing, which can introduce spurious mechanical harmonics.

The authors describe the experience gained in EDISON in addressing this aspect of the work. Following brief descriptions of export requirements from Opera and the sensitivity studies performed to show how different mechanical deformations affect system performance, the second section discusses options for introducing these deformations and compares the reliability of two different methods. The remaining sections describe techniques introduced to further minimize errors associated with discretization, the impact of motor winding on one of these methods and the issue of cancellation.

II. REQUIREMENTS AND SENSITIVITY STUDIES

The outputs required from the electromagnetic simulations are time series of mechanical values (forces acting on each tooth and rotor torque) over one 360° revolution of the motor under the required load. Methods to calculate torque are well established and, within EDISON, torque has been calculated by virtual work integration using an annular band of elements lying at the center of the air-gap [2], [3].

Methods for calculation of the force on individual teeth are less well established. Integrating Maxwell stress along an arc at mid air-gap radius opposite the tooth and half of each slot on either side is common, but this is, strictly, incorrect, as the Maxwell stress contour should be closed [4]. In the results presented here, the body force density of each element in a tooth and corresponding core back has been calculated and a volume integration performed to calculate the force components. Fig. 1 shows example radial and axial forces.

![Typical tooth radial and tangential force components of an 8-pole IPM](image)

Fig. 1. Typical tooth radial and tangential force components of an 8-pole IPM

Electric motors are designed to operate with concentric round geometry, but manufacturing tolerances, assembly and external forces lead to deformation. A series of sensitivity studies was devised to investigate common deformations including stator ovalling, tooth rocking and rotor “whirl”.

III. INTRODUCING DEFLECTIONS

To introduce deformations to the concentric geometry, two possibilities exist: geometry can be reconstructed with the deformations and a new mesh created, or node coordinates of the concentric model can be modified to the required geometry.

Fig. 2 shows the advantage of the second method for a simplified example of a tooth rocking model. In a tooth rocking study, the teeth behave as though they are cantilevered from the motor core back with maximum displacement at the tip nearest the rotor and zero displacement where the tooth joins the core.
back. Forces calculated are small and the first method produces more significant changes due to the modified mesh than the (expected) changes shown by the node displacement method.

Consequently, the node displacement method was used for the sensitivity studies wherever possible. For example, one of the sensitivity studies performed was stator ovalling. Nodes of the stator mesh were modified such that the air-gap of the machine reduced in one axis and enlarged in the orthogonal axis. A full description of the findings from all these sensitivity studies will be provided in the paper, showing smooth progression of the effect of increasing displacement.

IV. AVERAGING ALGORITHMS

As shown in Fig. 3, because the test motor is operated as a synchronous machine in the simulation and uses a short-pitched double layer stator winding, the force pattern on each tooth for the concentric model should be effectively identical, but phase shifted by the electrical angle between teeth.

However, small differences are observable, due to slightly different discretization of each tooth, which contribute spurious harmonics to the mechanical analysis. To help overcome this, waveforms for all teeth in the concentric model are shifted in phase, averaged, and shifted back to initial phase, allowing error for each tooth due to non-uniform mesh to be calculated. When a deflected motor is modelled, the error waveform is subtracted from the computed waveform before processing in the mechanical software. Further adjustment to the averaging algorithm was necessary for single-layer windings. Teeth lying between different phase bands of the winding will experience a different waveform to those lying between 2 coils of the same phase. Both algorithms will be described in more detail in the full paper.

V. REDUCING CANCELLATION ERRORS

Unlike the preceding static deformation cases, modelling of whirl produces large variations of tooth force during each rotation, as the rotor minimizes the air-gap opposite each tooth in turn and maximizes the air-gap on the diametrically opposite tooth. Consequently, the rotating unbalanced magnetic pull was expected to dominate the mechanical behavior. However, even after averaging, spurious harmonics were still found. This was traced to extreme cancellation errors due to arbitrary element orientation from Delaunay triangulation. Fig. 4 shows tangential force density variation on an arc through the tooth tip (in orange on the insets). Cancellation error can be reduced by using uniformly sized and oriented elements. The tooth tip was re-meshed with regular hexahedral elements using mapping, giving the improvement also shown in Fig. 4.

VI. CONCLUSIONS

Accuracy of values required for export of electromagnetic forces to multi-body dynamic mechanical simulations for deformed EV traction drive motors is vital. Improvement is obtained by modifying the mesh from the concentric rotor and stator model, rather than creating the deformed geometry and re-meshing. Discretization differences for each tooth can be mostly overcome using averaging algorithms to establish errors in the concentric model. Cancellation errors produced by arbitrary element shapes from Delaunay triangulation can be reduced by meshing significant force production volumes with a mapped, regular mesh.

REFERENCES