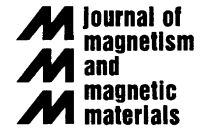




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Simulation of motional eddy current phenomena in soft magnetic material

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Abstract

The finite element simulation of conductors moving in a magnetic field at elevated speeds, yields oscillatory solutions. To overcome the effect of the huge convection terms, the partial differential equation is stabilised by adding artificial diffusion. Accurate results are obtained by applying adaptive mesh refinement. A rotational magnetic brake with a solid ferromagnetic rotor is simulated. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Eddy currents; Ferromagnetism; Finite element method; Numerical simulation

1. Introduction

A conductive body moving in a magnetic field experiences eddy currents. Similar to eddy current effects due to time-varying fluxes, the skin depth is defined as the thickness of the skin in which majority of the induced currents appear. Motional eddy currents, however, are pushed towards the direction of the motion (Fig. 1) [1]. As they are excited by an exterior field, they mainly occur at the sides of the body that are submitted to the magnetic field. For elevated speeds, the eddy currents are pushed towards the surface of the conductor, yielding high magnetic flux densities there. High flux densities are, however, prevented if soft magnetic material is applied. A part of the flux is pushed towards the interior of the moving body or appears as leakage flux around the body. Hence, the behaviour of a moving body is largely dependent on the saturation of the soft magnetic material. Moreover, the flow path of induced currents is restricted to the actual geometry of the device. This makes a finite element model of the device necessary, but also cumbersome. This paper considers finite element models of devices in which soft magnetic conductors move at high speed in a magnetic field.

2. Working principle

The range of applications contains electrical machines, electromagnetic brakes, electromechanic dampers and magneto-hydrodynamic devices. Here, as an example, a rotational magnetic brake is presented (Fig. 1). The brake has four electromagnetic poles, excited by a DC current. The pole shoes are designed to spread the magnetic flux into a large area on the surface of the conductive, soft magnetic solid iron cylinder. The geometry and the excitation of the device enable the application of a two-dimensional model. A finite element discretisation of the geometry is numerically coupled to an electric circuit modelling the electrical connections at the front and rear of the device. A formulation in terms of the magnetic vector potential is set up. The braking torque is computed by integrating the Maxwell stress tensor along a contour in the air gap of the device.

3. Adaptive mesh refinement and upwinding

The governing differential equation contains a motional (convective) term $\sigma \mathbf{v} \times \nabla \times \mathbf{A}$ with σ the conductivity, \mathbf{v} the speed and \mathbf{A} the magnetic vector potential. The differential equation is discretised applying linear triangular finite elements related to a mesh with characteristic mesh size h . If at a certain speed, the Péclet

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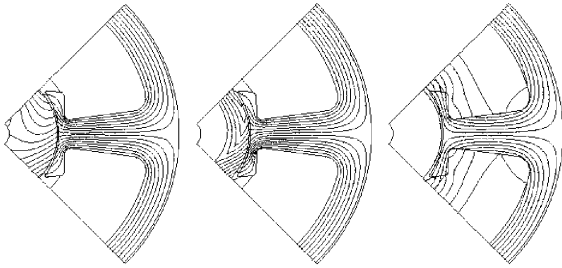


Fig. 1. Magnetic flux line plot for the magnetic brake rotating at 1, 10 and 100 rad/s.

number $Pe = h\sigma|v|/2v$ with v the reluctivity, exceeds 1, the discretised convective term becomes dominant over the diffusive term. The numerical scheme becomes unstable and non-physical oscillations are detected in the finite element solution [2]. The mesh is not sufficiently fine to resolve the steep fronts occurring in the exact solution for the magnetic field. The Péclet criterium is equal to requiring a mesh size being smaller than the skin depth. The criterium indicates two remedies: decreasing h and/or decreasing the ratio $\sigma|v|/2v$. The first remedy may yield large meshes and unacceptable computation times whereas the latter alters the physics of the problems. Here, both principles are combined in an adaptive refinement algorithm relying upon stabilised intermediate solutions. A stable solution on a rough mesh is ensured by artificially augmenting the diffusion in the differential operator. The error estimator detects the highly convective areas in the model. The refinement algorithm cuts the corresponding elements. This approach only refines area's in which a transition layer may occur yielding an accurate solution at the lowest computational cost (Fig. 2).

4. Newton iteration

To cope with the non-linear ferromagnetic materials present in the model, a Newton linearisation is applied. Adaptive relaxation is applied to enhance the convergence of the non-linear iterations.

5. Application

A magnetic brake has the advantage over mechanical brakes that a braking torque is obtained without mechanical contact and thus without being subject to wear. A disadvantage of magnetic braking is the inability to excite a holding torque at standstill. For the rotational brake, considered here, the dependence of the braking torque upon the excitation current is computed. For

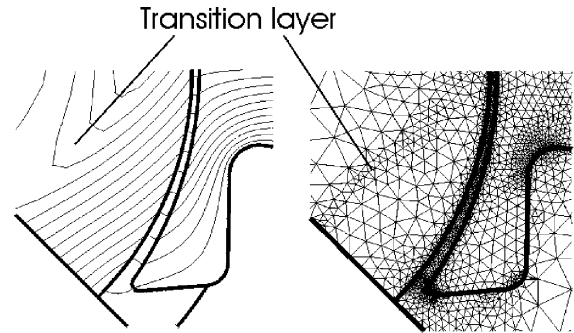


Fig. 2. Detail of a transition layer in a magnetic flux line plot corresponding to an adaptively refined mesh.

enlarging excitation currents, the torque generated by the true model exceeds the torque of a model featuring a linear soft magnetic material. This indicates that the non-linearity of the material is advantageous for this application. The speed–torque characteristic of the device establishes saturation. For increasing speeds, the torque does not increase accordingly. This effect is related to the increasing leakage of the applied flux at high speeds.

6. Conclusions

The adaptive refinement relying upon stabilised solution on rough meshes combined with a relaxed Newton non-linear iteration, enables the simulation of high-speed magnetic brakes featuring a non-linear soft magnetic, highly conductive solid iron rotor. The performance of the device is substantially influenced by the geometry and the non-linearity of the materials.

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