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Computation of eddy current losses in the mounting rail of a magnetically levitated conveyor vehicle

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Abstract

Purpose – The paper proposes presenting a transient 3D-FE computation approach of the eddy current losses in the rail and the flux concentrating pieces of a magnetically levitated conveyor vehicle.

Design/methodology/approach – The calculation process is started with a coarse mesh in order to reduce computation time without losing accuracy. Then mesh refinement iterations are performed, based on the estimation of the discretisation error. The results of the post processing are the levitation force, the braking force and the eddy current losses.

Findings – The paper finds that by means of adaptive mesh refinement, the error is significantly reduced with a minimum increase of computation time. The hot spots of eddy current losses can be localised by visualizing the eddy current density. At nominal speed, especially the huge amount of eddy current losses in the flux concentrating pieces must be considered during the development process.

Research limitations/implications – For further development, the linear motor will be modified with the results of FE computations to reduce eddy current losses. Therefore, different materials and a variation of geometry will be considered.

Practical implications – Magnetically levitated systems excite eddy current losses instead of bearing losses. These losses must be taken into account when developing the drive.

Originality/value – It proposes a transient 3D-FE approach for computing eddy current losses accurately with a minimum increase of computation time.

Keywords Eddy currents, Magnetic fields, Finite element analysis, Electric motors

Paper type Research paper

Introduction

Conventional conveyor vehicles, used for luggage transport between airport terminals, are usually mounted on roller bearings. The consequences are mechanical wear, which yields maintenance costs as well as noise and a reduced duty cycle. Moreover, the speed of such systems only reaches 10 m/s, limited by the maximum speed of conventional bearings. Thereby the journey time of the passengers increases by waiting for their luggage (de Neufville, 1995). To avoid these disadvantages, a magnetically levitated conveyor vehicle is developed, driven by a linear homopolar motor. The system can also be used in clean rooms or in food industry due to the contactless operation. The maximum speed is only limited by the power of the driving

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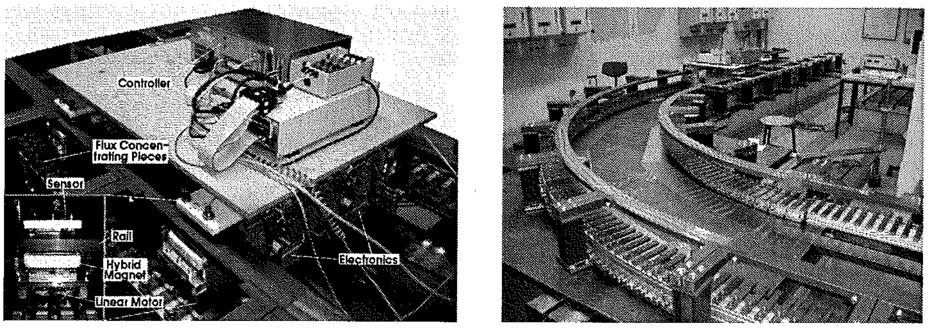
linear motor (Hameyer, 2002; Henneberger, 2001). Figure 1(a) and (b) slow the conveyor vehicle. A levitation/propulsion module is integrated on each corner of the vehicle. The levitation module consists of a hybrid excited magnet, composed of two permanent magnets and two coils, each wound around a U-shaped yoke (Jayawant, 1981). When the vehicle is moving, eddy currents are induced into the massive iron rail and the flux concentrating pieces of the linear motor. The resulting eddy current losses decelerate the vehicle, so these losses must be considered during the development of the levitation/propulsion module. In this paper, the computation of the eddy current losses in the rail and the flux concentrating pieces of the homopolar linear motor as well as the visualization of the eddy current density are presented.

Computation of eddy current losses in the rail

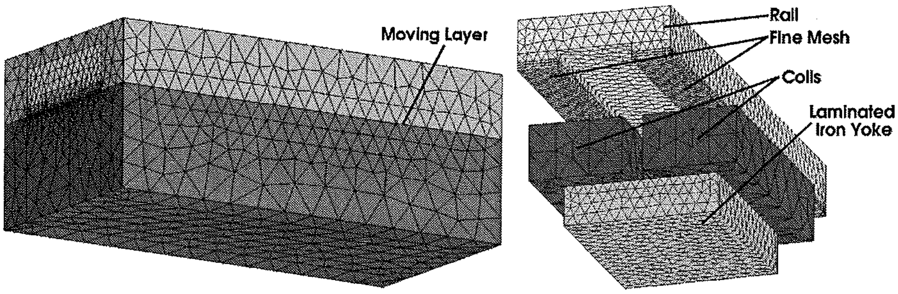
For modelling and meshing the levitation module, the package Ansys (2000) is used. In order to consider relative speed between yoke and rail, a moving layer is defined in the air gap, Figure 2(a). Along this layer, the transient solver disarranges the rail and the levitation module in discret time steps. The eddy currents predominantly appear at the bottom of the rail blades. The maximum penetration depth of the eddy currents inside the rail, which is relevant for the losses, is estimated by equation (1) to about 5 mm at a speed of 5 m/s (Blume, 1994):



(a) Implemented conveyor vehicle

(b) Test track

Figure 1.
Prototype of the conveyor vehicle with test track



(a) Full model including surrounding air and moving layer

(b) Levitation module not including surrounding air

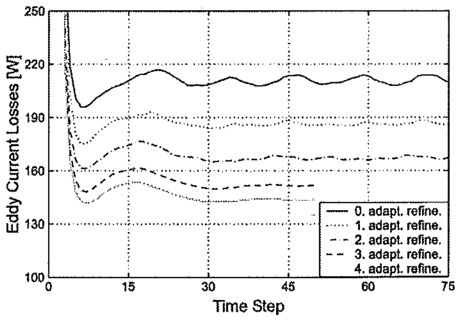
Figure 2.
Finite element model of the levitation module

$$d = \sqrt{\frac{2}{\omega \sigma \mu_0 \mu_r}}. \quad (1)$$

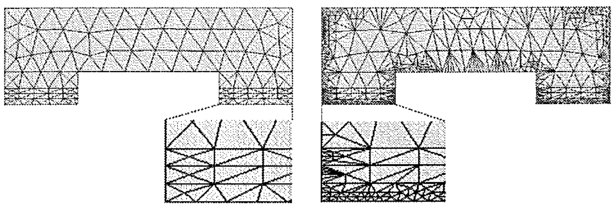
Therefore, the frequency ω, the electrical conductivity σ and the permeability μ_r are required. For slower motion of the vehicle, eddy current losses can be neglected. So for the first meshing process, only the rail blades are finely meshed up to the penetration depth with an element size of 1.667 mm (Kaehler and Henneberger, 2000) to reduce computation time, Figure 2(b).

The eddy current density and losses as well as the levitation and breaking forces are computed with the package *i*MOOSE (van Riesen *et al.*, 2004). The transient effects, induced into the rail by the abruptly activated coil currents, have decayed after about 30 time steps, as shown in Figure 3(a). Especially in the regions close to the surface, the absolute error is significant in regions with a too coarse mesh, because the penetration depth of the eddy currents is described by an exponential function. The error (Kaehler, 2003) is computed by estimating the lack of continuity of the tangential component of the eddy current density (2) and the magnetic field strength (3):

$$\varepsilon_{J,e} = \frac{\int_{V_e} \int \left(\vec{J}_e - \vec{J}_{\text{avr},e}\right) \cdot \mathrm{d}\vec{E}_e \mathrm{d}V}{\int_V \int \vec{J} \cdot \mathrm{d}\vec{E} \mathrm{d}V} \quad (2)$$



(a) Losses vs. adaptive mesh refinement



(b) Original and refined mesh after the 4th iteration

Figure 3.
Adaptive mesh refinement

$$\varepsilon_{H,e} = \frac{\int_{V_e} \left(\vec{H}_e - \vec{H}_{\mathrm{avr},e}\right) \cdot \mathrm{d}\vec{B}_e \mathrm{d}V}{\int_V \int \vec{H} \cdot \mathrm{d}\vec{B} \mathrm{d}V}, \tag{3}$$

$\varepsilon_{J,e}$ describes the local error of one element e, computed by its eddy current density $\vec{J}_e$ and electrical field strength $\vec{E}_e$. V_e is the volume of the element, the variable of the considered region are constituted by $V, \vec{J}$ and $\vec{E}$. $\vec{J}_{\mathrm{avr},e}$ specifies the average current density of element e. Accordingly, the variables of equation (3) are defined.

The average values are computed by:

$$\vec{H}_{\mathrm{avr},e} = \sum_{i=1}^{6} \vec{\alpha}_i \cdot H_i. \tag{4}$$

H_i describes the magnetic field strength in the centre of the element's edge i, resulting from the average value of all surrounding elements in this point. $\vec{\alpha}_i$ considers the form function of element i. The resulting, relative computation error is the sum of both error components (5):

$$\varepsilon_{\mathrm{res}} = \varepsilon_{H,e} + \varepsilon_{J,e} \tag{5}$$

In order to improve accuracy, the mesh is adaptively refined in regions with large error. Thereby, the computation time is moderately increased with a maximum gain of accuracy on the computed losses. This procedure is repeated until the difference between two successive solutions becomes smaller than a given tolerance, as shown in Figure 3(a).

The cross-section of the rail is depicted in Figure 3(b). The computation has been accomplished at a speed of 20 m/s. Regions with higher losses can be recognized at the refined mesh.

The breaking forces and resulting eddy current losses at different speeds are shown in Figure 4(a) and (b). As the ratio of eddy current losses and speed is approximately a quadratic function, especially for high speeds the losses must be considered. At a nominal speed of 20 m/s, the four levitation modules of the vehicle induce about 600 W thermal losses into the rail. These losses must additionally be provided by the motor.

Figure 5(a) and (b) shows the eddy current density at the surface of the rail above the levitation module at 5 m/s and nominal speed. The eddy currents are predominantly induced at the leading and leaving edge of the levitation module. For reducing losses in these regions, the geometry of the rail and the levitation module need to be modified in a next development step by decreasing the blades width.

Eddy currents decrease the bearing force due to Lenz's law, as shown in Figure 6(a). For levitation, the bearing force of each levitation module amounts to 413 N for nominal operation. According to this requirement, the levitation module was dimensioned without motion due to the complexity of computing the decreasing bearing force. The reduction of bearing force between steady state and nominal speed for each levitation module amounts to about 55 N, i.e. 13%. For the compensation of the lack of bearing force, the currents in the levitation module coils must be increased or the air gap between the rail and the levitation module needs to be decreased.

Figure 6(b) shows the number of elements as a function of the adaptive mesh refinement step. The curve is approximately following an exponential function. The

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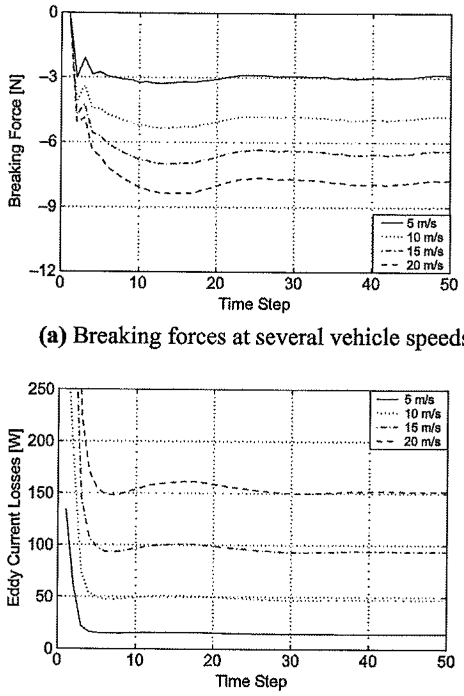
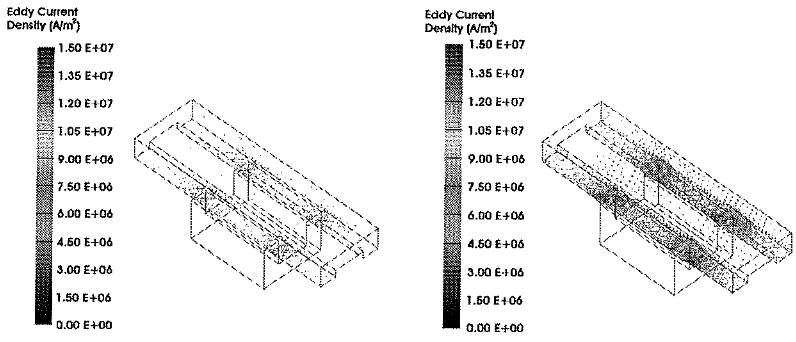


(a) Breaking forces at several vehicle speeds

(b) Losses at several vehicle speeds

Figure 4. Results of computation



(a) Eddy current density at 5 m/s

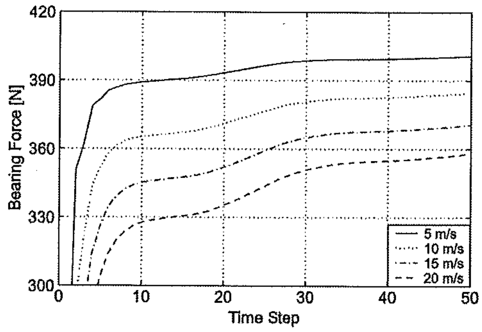
(b) Eddy Current Density at 20 m/s

Figure 5. Eddy current density in the rail above the levitation module

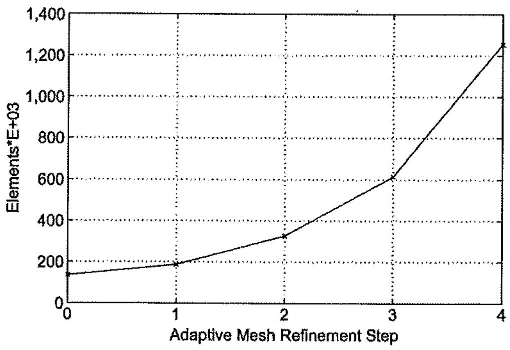
simulation process is stopped after the 4th adaptive mesh refinement step, because the computation time is proportional to the number of elements. After this step, the error also can be accepted, as shown in Figure 3(a).

Computation of the eddy current losses in flux concentrating pieces

In analogy to the rail, a finite element model of the homopolar linear motor is built. Due to the complexity of the geometry, adaptive mesh refinement is not applied. The



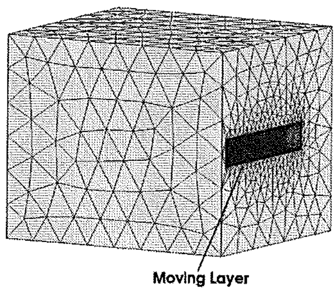
(a) Eddy current density in the rail above the levitation module



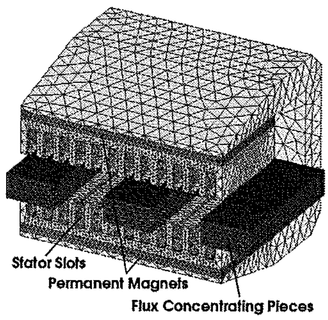
(b) Element numbers of the refined mesh

Figure 6.
Lack of bearing force and number of elements of the refined mesh

magnetic field of the motor, which is excited by permanent magnets, induces eddy current losses into the flux concentrating pieces. Thereby the losses almost only appear in those pieces, which enter or leave the stator of the motor, Figure 8(b). The rest of the losses is induced into the pieces by the slots of the stator, increasing the air gap and the flux alternating, and the commutating currents in the stator windings. On this account, especially the flux concentrating pieces are fine meshed, as shown in Figure 7(a) and (b).

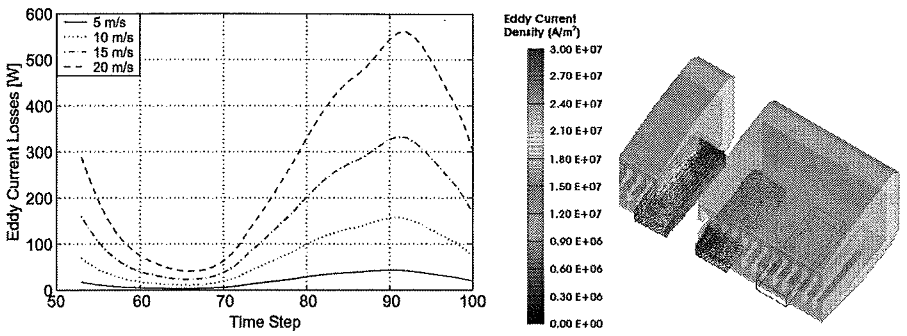


(a) Full model including surrounding air and moving layer



(b) Propulsion module not including surrounding air

Figure 7.
Finite element model of the propulsion module



(a) Eddy current losses vs. position of flux concentrating pieces

(b) Propulsion module without surrounding air in the point of maximum eddy current losses

Figure 8. Computation results of the homopolar linear motor

For a first estimation and reducing the complexity of the modelling, the influence of the commutating stator currents is neglected.

Figure 8(a) shows the eddy current losses in the flux concentrating pieces of one linear motor depending on the speed. Between step 60 and 70, two flux concentrating pieces are moving inside the stator. During this time, the losses are only induced by the stator slots. Around step 90, the losses achieve the maximum value, since one flux concentrating piece is leaving the stator, while a second one enters.

The results of the computation show, that the average value of the entire eddy current losses, induced into the flux concentrating pieces, amounts to about 1200 W at a speed of 20 m/s. Compared to the eddy current losses in the mounting rail, these losses are twice as high. Altogether the eddy current losses amount 1800 W at a speed of 20 m/s.

Conclusion

By means of finite element method and adaptive mesh refinement, the eddy current losses in the rail and the flux concentrating pieces of a magnetically levitated conveyor vehicle have been computed. In order to improve accuracy with a minimum increase of computation time, the mesh of the rail is adaptively refined in the regions with large error. Thereby the error was reduced to about 40%. The adaptive mesh refinement method was not used for the homopolar linear motor because of its complex geometry. For reducing the error, the flux concentrating pieces are meshed fine with an element size, smaller than the eddy current penetration depth. The resulting breaking forces up to 90 N for the vehicle additionally need to be considered during the development process of the linear motor. The decreasing bearing forces at nominal operation amount up to 13%. Additional currents in the coils of the levitation module or a decrease of the air gap between the levitation module and the rail have to compensate this effect, being put down to Lenz's law. In summary, the eddy current losses of the vehicle amount to 1800 W at nominal speed of 20 m/s. Thereby two-thirds of the losses are induced into the flux concentrating pieces. So for further development, especially the motor will be optimised concerning the eddy current losses.

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