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Computation Of Eddy Current Losses In The Mounting Rail Of A Magnetically Levitated Conveyor Vehicle

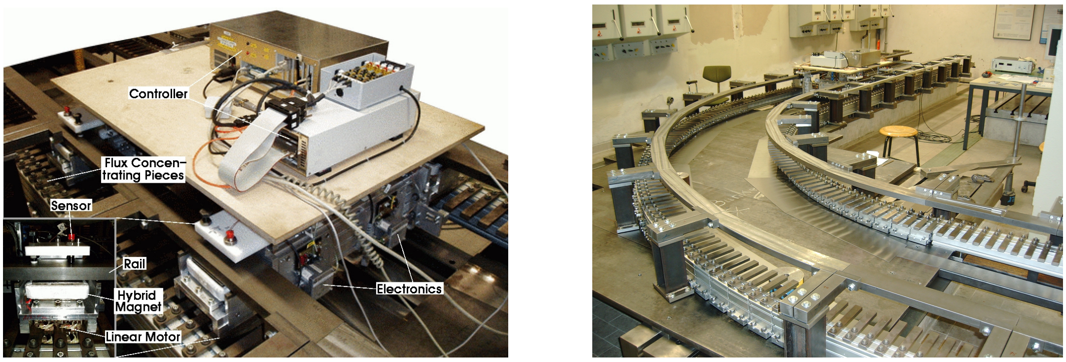
M. Leβmann, K.Hameyer

Institute of Electrical Machines, RWTH Aachen University
Schinkelstraße 4, D-52062 Aachen, Germany
Marc.Lessmann@IEM.RWTH-Aachen.de

Abstract* – This paper presents a FE computation approach of the eddy current losses in the rail of a magnetically levitated conveyor vehicle. The modelling and meshing process of the rail and the levitation module are presented. In order to reduce computation time without losing accuracy, the calculation process is started with a coarse mesh in the rail. Then mesh refinement iterations are performed, based on the estimation of the error of discrete elements. The results of the post processing are the levitation and breaking forces, as well as the eddy current losses. By visualizing the eddy current density, in further development the geometrical dimensions can be optimized to reduce losses.

Introduction

Conventional conveyor vehicles, used for luggage transport between airport terminals, are usually mounted by 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 [1]. 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 linear motor [2,3]. Fig. 1a,b) shows the implemented 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 [4]. While 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.



a) Implemented conveyor vehicle.

b) Test track.

Fig 1: Prototype of the conveyor vehicle with test track.

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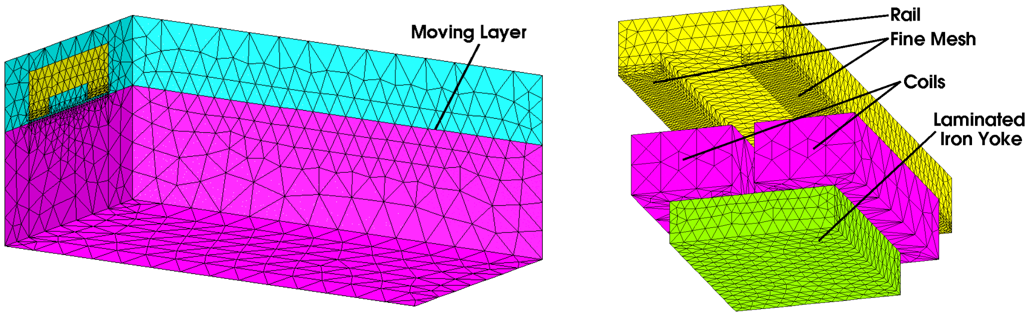
Computation of eddy current losses in the rail

For modelling and meshing the levitation module, the tool package *Ansys* [5] is used. In order to consider relative speed between yoke and rail, a moving layer is defined in the air gap, Fig. 2a). Along this layer, the transient solver disarranges the rail and the levitation module in discreet 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 [6]:

$$d = \sqrt{\frac{2}{\omega\sigma\mu_0\mu_r}}\,. \tag{1}$$

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 5/3 mm [7] to reduce computation time, Fig. 2b).



a) Full model including surrounding air and moving layer.

b) Levitation module not including surrounding air.

Fig. 2: Finite Element model of the levitation module.

The eddy current density and losses as well as the levitation and breaking forces are computed with the tool package *i*MOOSE [8]. The transient effects, induced into the rail by the abruptly activated coil currents, have decayed after about 30 time steps, as shown in Fig. 3a). 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 [9] is computed by estimating the lack of continuity of the tangential component of the eddy current density (2) and the magnetic field strength (3):

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

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

$\varepsilon_{J,e}$ 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 elements volume, the values of the considered region are constituted by V, $\vec{J}$ and $\vec{E}$. $\vec{J}_{avr,e}$ specifies the average current density of element e. Accordingly, the variables of equation (3) are defined.

The average values are computed by:

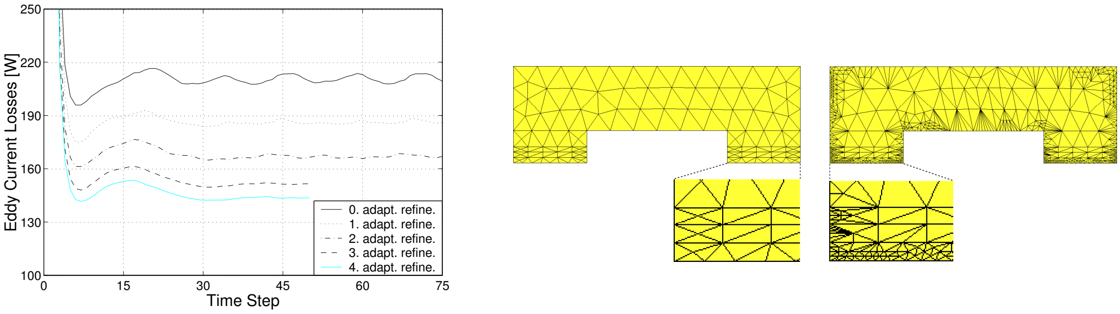
$$\vec{H}_{avr,e} = \sum_{i=1}^{6} \vec{\alpha}_i \cdot H_{i.} \tag{4}$$

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):

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

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 Fig. 3a).

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

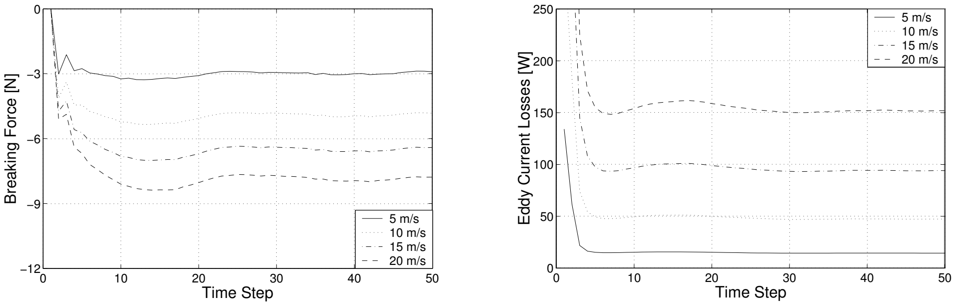


a) Losses vs. adaptive mesh refinement.

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

Fig. 3: Adaptive mesh refinement.

The breaking forces and resulting eddy current losses at different speeds are shown in Fig. 4a,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.

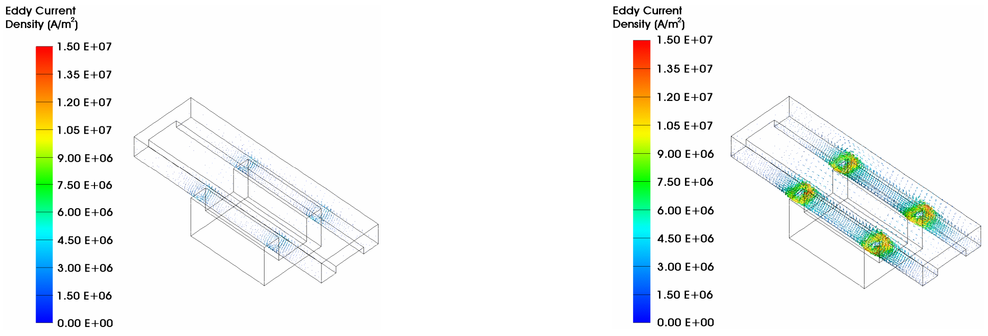


a) Breaking forces at several vehicle speeds.

b) Losses at several vehicle speeds.

Fig. 4: Results of computation.

Fig. 5a,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.

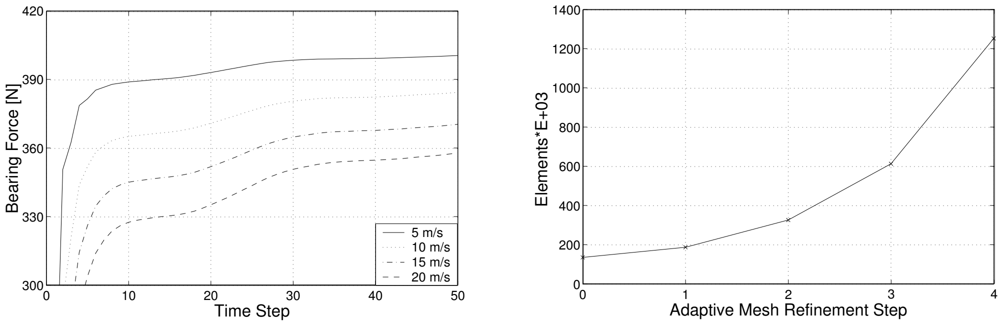


a) Eddy current density at 5 m/s.

b) Eddy Current Density at 20 m/s.

Fig. 5: Eddy current density in the rail above the levitation module.

Eddy currents decrease the bearing force due to Lenz’s law, as depicted in Fig. 6a). 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 stagnation and nominal speed for each levitation module amounts to about 55 N, according to 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.



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

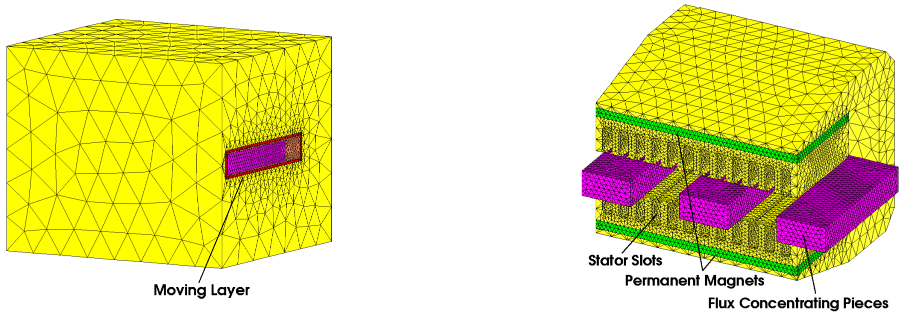
b) Element numbers of the refined mesh.

Fig. 6: Eddy current losses and bearing forces during nominal operation.

Fig. 6b) depicts the number of elements as a function of the adaptive mesh refinement step. The curve is approximately following an exponential function. The 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 Fig. 3a).

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 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, Fig. 8b). 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 Fig. 7a,b). For a first estimation and reducing the complexity of the modelling, the influence of the commutating stator currents is neglected.

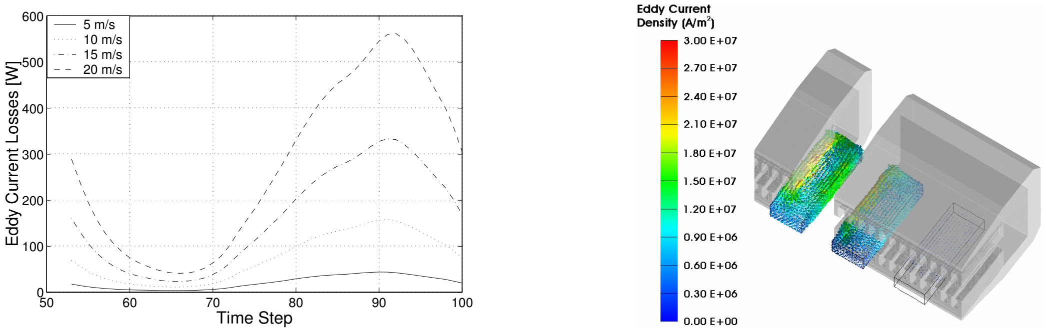


a) Full model including surrounding air and moving layer.

b) Propulsion module not including surrounding air.

Fig. 7: Finite element model of the propulsion module.

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



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

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

Fig. 8: Computation results of the homopolar linear motor.

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 higher. 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 optimized concerning the eddy current losses.

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