NUMERICAL SOLUTION OF MAGNETOSTATIC FIELD OF MAGLEV SYSTEM

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Abstract: The paper deals with the design of the levitation and guidance system of the magnetic levitation train Transrapid 08 by means of QuickField 5.0 – a 2D program for electromagnetic fields solutions.

1. INTRODUCTION

Systems working on the principle of magnetic levitation have recently started to be used more widely in various applications. A very prospective area of magnetic levitation is high-speed magnetic bearings. In comparison with conventional types of bearings, they have much longer service life at a reasonable price.

In recent years, most progress of magnetically levitating systems can be seen in the area of high speed railway. Maglev train sets can reach the speeds up to 500 km/h [2]. In order to reach such a speed, the train set has to levitate at a certain height over the track to eliminate friction.

In the future, the application of the maglev system in the area of conveyor belts or cranes is highly probable. For shorter distances, they will use big propelling forces, which can be reached by using the magnetic field. The aim of this work is – under some simplifying conditions – to design a 2D levitation system so that it meets the criteria of the already existing Transrapid 08 set. A check calculation of the electromagnet temperature rise will be carried out at the end of the work.

2. FORMULATION OF THE PROBLEM

The levitation system consists of levitation and guidance electromagnets. Each Transrapid 08 train set consisting of 3 sections carries 46 levitation electromagnets and 36 guidance magnets on the chassis. The levitation electromagnets enable the vehicle to be lifted up to the working position, which is usually 10 mm above the track [6]. Guidance electromagnets prevent the train set from derailing when going round the curve (fig. 1).

The material for producing the stator and electromagnets is classic dynamo sheets of the 0.5 mm thickness made of carbon steel 12 040. The B-H curve values have been obtained from the Škoda Corporation ŠN 006004 Standard (fig. 2).

The total weight of the TR08 train is 188.5 tonnes when all three sections are loaded [7]. The gravitational force that has to be overcome by each levitation electromagnet is as follows:

$$\left|\boldsymbol{F}_{\mathrm{lev}}\right| = m \cdot g = \frac{188.5 \cdot 10^{3} \cdot 9.806}{46} = 40.19\ \mathrm{kN}. \quad (1)$$

Another force affecting the Transrapid is the centrifugal force when going round a curve. The minimal curve radius is determined as 6500 m at the speed of 500 km/h [1]. Due to the curve radius size and the high-speed train dimensions it is possible to consider it as a mass point. Furthermore, let's assume that the function of the guidance electromagnets lies just in the attraction towards the track. The resulting centrifugal force which has to be overcome by one guidance electromagnet (if ignoring the train set tilting) is as follows:

$$\left|\boldsymbol{F}_{\mathrm{gu}}\right| = \frac{\left|\boldsymbol{F}_{\mathrm{cen}}\right|}{18} = \frac{\dfrac{188.5 \cdot 10^{3} \cdot 138.9^{2}}{6500}}{18} = 31.1\ \mathrm{kN}. \quad (2)$$

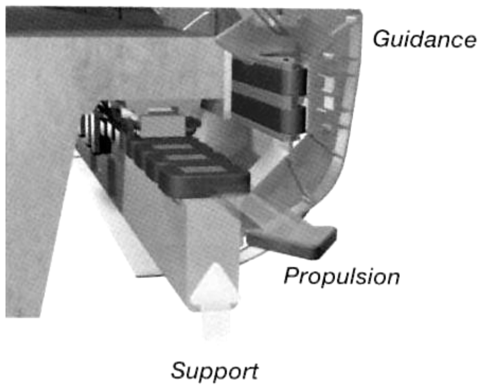

Fig. 1. Levitation and Guidance System of Transrapid 08

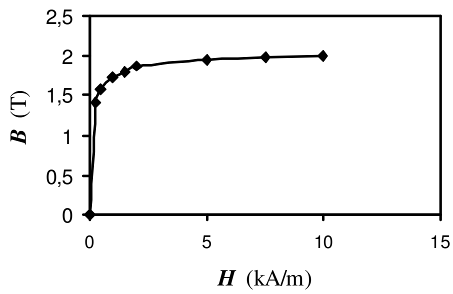

Fig. 2. The B-H curve of the applied steel

3. MATHEMATICAL MODEL

The levitation system design represents a weakly coupled problem. This paper is focused on two physical fields which can affect each other, i. e. the magnetostatic and stationary temperature fields.

3.1 Stationary magnetic field

The entire levitation and guidance system is supplied by a direct electrical current, which creates the stationary magnetic field. Due to the design symmetry it is possible to solve the whole levitation and guidance system at the same time (fig. 3). The design area consists of the following sub-areas:

Ω_1 : carbon steel 12 040
Ω_2 : carbon steel 12 040
Ω_3 : carbon steel 12 040
Ω_4 : carbon steel 12 040
Ω_5 : concrete structure (just to illustrate)
Ω_6 : air
Ω_7 : copper coil
Ω_8 : copper coil
Ω_9 : Teflon insulation.

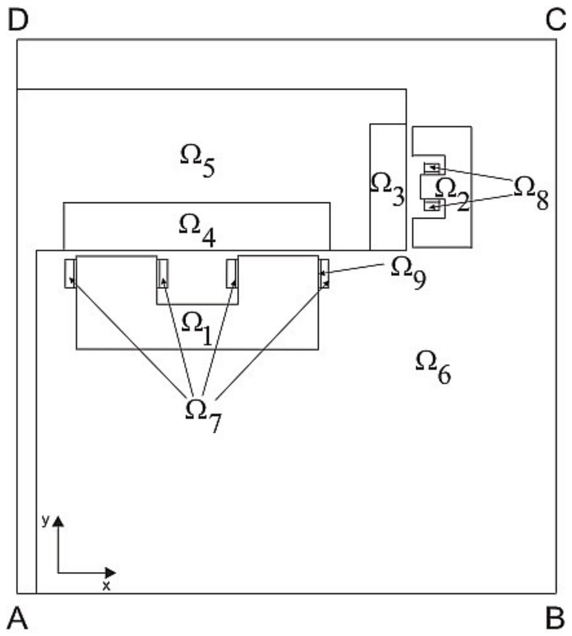

Fig. 3. The individual areas determination

The differential equations describing the stationary magnetic field are listed below.

$$\Omega_{1-4}: \ \mathrm{rot}\left(\frac{1}{\mu_{\mathrm{Fe}}}\,\mathrm{rot}\,\boldsymbol{A}\right)=0\,, \tag{3}$$

$$\Omega_{5-6}: \ \mathrm{rot}\,\mathrm{rot}\,\boldsymbol{A}=0\,, \tag{4}$$

$$\Omega_{7-8}: \ \mathrm{rot}\,\mathrm{rot}\,\boldsymbol{A}=\mu_0\,\boldsymbol{J}_{\mathrm{ext}}\,, \tag{5}$$

where $\boldsymbol{A}$ represents the magnetic vector potential, $\boldsymbol{J}_{\mathrm{ext}}$ is the individual field currents density, and μ_{Fe} is the iron permeability.

The boundary condition along the imaginary boundary ABCD (which represents the infinity) is of the Dirichlet type and $\boldsymbol{A}=\boldsymbol{0}$ applies to it. The boundary DA represents the symmetry axis, along which Neumann´s condition is applied in the form of $\partial\boldsymbol{A}/\partial n=\boldsymbol{0}$, where n represents the outer normal to this part of the boundary.

The force affecting the unit of the magnet length is worked out by means of Maxwell's tensor of the tension modified to the relation:

$$\boldsymbol{F}=\frac{1}{2}\int_S\left(\boldsymbol{H}\left(\boldsymbol{B}\cdot\boldsymbol{n}\right)+\boldsymbol{B}\left(\boldsymbol{H}\cdot\boldsymbol{n}\right)-\boldsymbol{n}\cdot\left(\boldsymbol{H}\cdot\boldsymbol{B}\right)\right)\mathrm{d}S\,, \tag{6}$$

in which the integration is carried out along the magnet boundary.

3.2 Stationary temperature field

The source of the temperature field is the temperature rise of the magnets field coils which are fed with a direct current. As the individual electromagnets are only functional when the train set moves, the temperature rise of the ferromagnetic belt placed in the track is not taken into consideration. It is then possible to calculate each temperature field separately. The determination of the individual areas corresponds to the stationary field calculation.

The differential equations describing the stationary temperature field can be seen below:

$$\Omega_{1-2}: \ \mathrm{div}\,\lambda\,\mathrm{grad}\,T=0 \tag{7}$$

$$\Omega_{7-8}: \ \mathrm{div}\,\lambda\,\mathrm{grad}\,T=-w\,, \tag{8}$$

where w represents specific Joule losses in the given volume of the coils V at the resistance R, which is determined using the relation below.

$$w=\frac{R\cdot I^2_{\mathrm{ext}}}{V}\,. \tag{9}$$

Along the bound of each electromagnet there was determined a boundary condition describing the heat propagation by transfer to the neighbouring area at the temperature of 20°C:

$$-\lambda\cdot\frac{\partial T}{\partial n}=\alpha\cdot\left(T-T_{\mathrm{ext}}\right). \tag{10}$$

In equations (7)–(10) λ denotes the heat conductivity, T is the temperature, α the heat emission coefficient, T_{ext} is the temperature of the external medium and n means the outer normal to the boundary.

4. ILLUSTRATIVE EXAMPLE AND THE OBTAINED RESULTS

The above mentioned mathematical model of the problem was solved using the 2D FEM program QuickField 5.0. The goal of the optimization was to find such dimensions of the levitation and guidance system that would prevent the ferromagnet supersaturation and at the same time would prevent destruction of the applied insulation (Teflon) due to the rise in temperature. The maximum value of the induction reached was 1.8 T.

By means of the optimization, the following characteristics of the levitation and guidance system were obtained:

- Electromagnets length: $l = 0.5\,\mathrm{m}$
- No. of levitation coil laps: $N = 1253$
- No. of guidance coil laps: $N = 1625$
- The field current of the levitation coil: $I_{\mathrm{ext}} = 5.50\mathrm{A}$
- The field current of the guidance coil: $I_{\mathrm{ext}} = 9.43\,\mathrm{A}$
- The coil filling factor: $\chi = 0.785$

4.1 Stationary magnetic field

The stationary magnetic field was calculated by means of the finite element method on the mesh made up of 92742 nodes. Further fining of the mesh has proved to be useless because the problem has already converged with the 1 per cent accuracy (fig. 7). The calculation only took 40 s on the computer with 2 GB RAM and 2.6 GHz CPU.

The magnetostatic field distribution after the dimensions optimization for the levitation and guidance electromagnet is depicted in fig. 4 and 5.

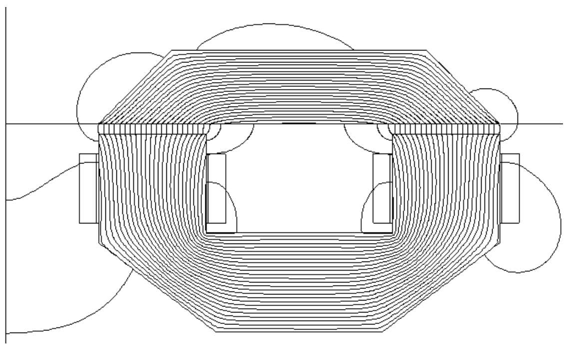

Fig. 4. The cut of the stationary magnetic field distribution in the levitation electromagnet

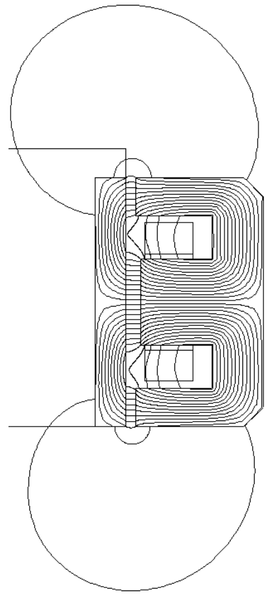

Fig. 5. The cut of the stationary magnetic field distribution in the guidance electromagnet

The dependency of the levitation force on the air space size is shown in the following picture.

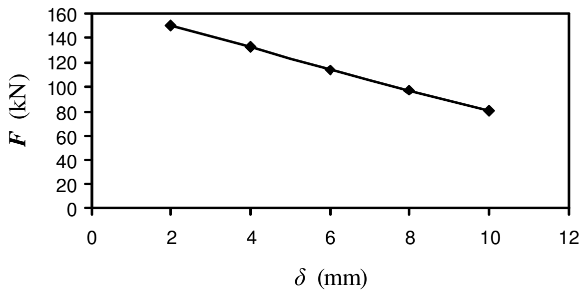

Fig. 6. The dependency of the levitation force on the air space size

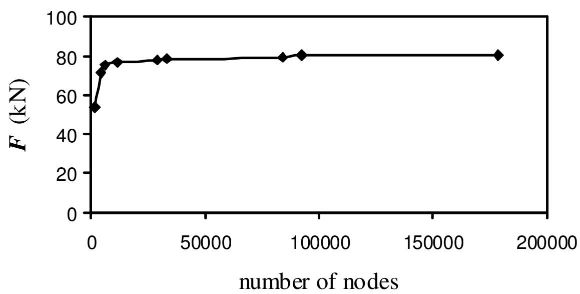

Fig. 7. The dependency of the levitation force on the applied mesh density

4.2 Stationary temperature field

The stationary temperature field was calculated for each electromagnet separately. In case of the guidance magnet it was being determined on the mesh containing 5408 nodes. With the levitation magnet the mesh contained 10210 nodes.

Material constants used when calculating the temperature were:

-The coil thermal conductance:

$\lambda_{Cu} = 303.16\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$

-The Teflon thermal conductance:

$\lambda_{teflon} = 0.24\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$

-The carbon steel thermal conductance:

$\lambda_{12\,040} = 45\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$

-Resistance of one coil lap: $R = 0.0215\ \Omega$.

The heat emission coefficient along the electromagnet bound was roughly determined so that it matched the reality as closely as possible. In case of the levitation electromagnet, the heat emission coefficient was determined as $20\,\mathrm{W \cdot m^{-2} \cdot K^{-1}}$, because the temperature rise happens after lifting the vehicle.

In case of the guidance magnet, two heat emission coefficients were determined. The value of the first coefficient was $20\,\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ for the covered part of the electromagnet and $120\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ for the uncovered one.

When the field current 5.50 A flows through the levitation coil, the coils temperature rises to 231° C and the carbon steel temperature rises to 167° C (fig. 8).

When the field current 9.43 A flows through the guidance coil, the coils temperature rises to 264° C and the carbon steel temperature rises to 97° C (fig. 9).

It is then possible to state that when using teflon as the insulating material, the insulation will not be damaged due to the rise in temperature.

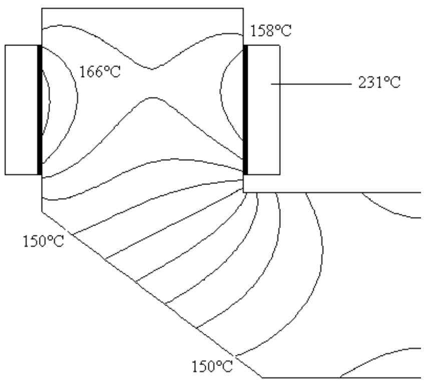

Fig. 8. The distribution of isotherms of the levitation magnet temperature field.

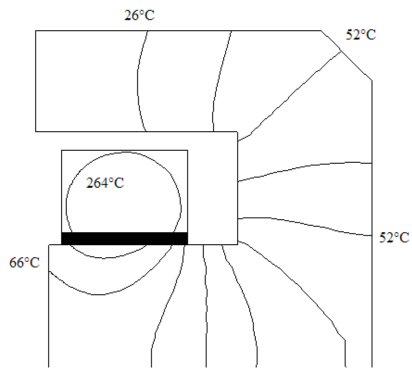

Fig. 9. The distribution of isotherms of the guidance magnet temperature field.

5. CONCLUSION

In practice, the design of the levitation and guidance system means a very complex 3D nonlinear optimizing problem, however, it is solvable. If applying a few simplifying preconditions, it is possible to implement the design in 2D. The aim of the paper was to find a solution to a weakly coupled problem of a magnetostatic and stationary temperature field. In the illustrative example there were presented the results of the optimizing design. The maximum temperature reached in case of the guidance electromagnet was 264° C.

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