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Design and analysis of electromagnetic-hydraulic composite brake based on electromagnetic importing method[1]

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Abstract. The interaction theory of the electromagnetic brake and hydraulic booster frictional brake is analyzed, and structure of vehicle brake mechanism which can be produced the braking torque by the electromagnetic brake and frictional brake, is illustrated. The electromagnetic brake and hydraulic brake can be controlled more flexibly. The problem that the electromagnetic braking torque is too small and difficult to control braking energy diversion can be solved effectively, which provides the conditions for commercial marketing of the electromagnetic-hydraulic composite brake. According to some references, braking torque of the electromagnetic-hydraulic composite brake is proposed. The simulation results show that the torque value is related to the material and current in the field coil, etc. The torque value obtained from the proposed equation approaches the value obtained from simulation.

Key words. Electromagnetic-hydraulic composite brake, electromagnetic importing, design.

1. Introduction

At present, the braking system of passenger car mainly depends on the friction braking powered by hydraulic system. However, with the continuous improvement of engine power and vehicle speed, many problems of hydraulic braking system appear that may be divided into several categories. For example, powder brought about by friction causes pollution of environment, increased wear of hydraulic system leads to higher maintenance costs and, heat fade and thermal failure of hydraulic braking system is an important reason to vehicle accident.

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In order to overcome the above problems of the traditional hydraulic braking system, electromagnetic-hydraulic composite braking system becomes a new research direction. One of the issues to be solved is technical and is connected with reaching a sufficiently high electromagnetic braking torque: this requires a large coil and the space around the braked wheel is too narrow to install there such a coil.

Meanwhile, the front wheels and the electromagnetic-hydraulic composite brake mechanism must be able to move together with the wheel hub. Scholars in China and abroad just basically study the theory of electromagnetic-hydraulic composite brake [1–4], but some problem such as how to design the structure of the composite braking system and how to mount the composite brake on the vehicle are not solved yet. So, after the technology is developed and used in practice, the paper provides a new possibility how to bring magnetic field to vehicle wheels. The task is analyzed theoretically and the results may contribute to successful solution of connected practical problems.

2. Structure and function of electromagnetic-hydraulic composite brake system

In view of the difficulties with installing larger field coil into a narrow space on the wheel, this paper offers an electromagnetic-hydraulic composite brake system based on electromagnetic importing method. Due to different material requirements of electromagnetic braking system and hydraulic braking system, the electromagnetic-hydraulic composite braking system is designed as a dual disc brake. A catheter of high magnetic permeability with low residual magnetism and coercive force is applied to transfer magnetic flux of high density from the field coil to the braking disc.

The aim of technical scheme of the electromagnetic-hydraulic composite brake system is to improve the existing passenger car wheel hub and lengthen the brake disc, thus to ensure that it can be mounted without problems. Another aim is that the electromagnetic brake friction plate with bolt holes, wheel, brake disc and electromagnetic friction brake disc fastening must rotate together with the wheels, which must be realized by the steering wheel via relative rotation of the bearing section.

The basic structure of the electromagnetic - hydraulic composite brake is shown in Fig. 1.

3. Description and theory of electromagnetic-hydraulic composite brake

As shown in Fig. 1, when the vehicle brakes, according to the intensity of braking, the control unit of the braking system starts supplying appropriate current to the field coil 17. The magnetic flux generated by the coil passes through the core 18, pole 16 and catheter 15 into the the electromagnetic guide block 14. Each coil has two electromagnetic guide block, corresponding to the N and S magnetic poles (shown in

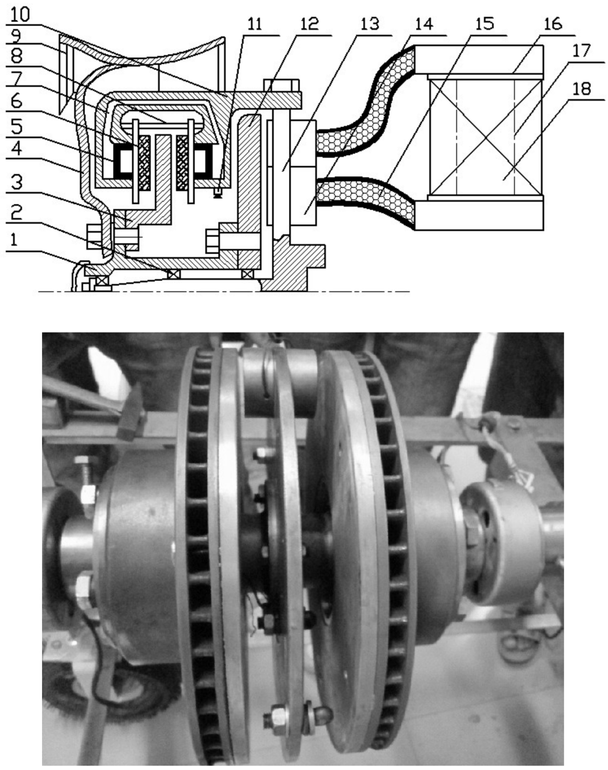

Fig. 1. Structure of electromagnetic-hydraulic composite brake: 1–hub, 2–wheel hub bearings, 3–friction brake disc, 4–wheel rim, 5–piston, 6–brake block assembly, 7–wheel cylinders, 8–guide support pin, 9–wheel plate, 10–clamp bracket, 11–inlet of wheel cylinder, 12–electromagnetic brake disc, 13–steering knuckle, 14–electromagnetic guide block, 15–electromagnetic catheter, 16–magnetic pole, 17–field coil, 18–iron core, 19–guide vane

Fig. 2). The block 14 and electromagnetic brake disc 12 is very close to one another (typically 1 mm). As the electromagnetic brake disc rotates, it will cut the force lines leading from the N-pole of the electromagnetic guide block to the S-pole, which leads to generation of eddy currents of rotational origin that produce the braking torque.

As the electromagnetic brake works, the oil from the brake master cylinder will pass through the oil inlet of the wheel cylinder 11 into the wheel cylinder 7. The cylinder pushes the piston 5 and the brake block assembly 6 starts moving towards the center of the brake pad assembly under the guide of the guide support pin 8. This leads to clamping friction brake disc 3 tightly and achieving the effect of the friction brake.

As shown in Fig. 3, the electromagnetic brake disc closed to the side of the friction braking mechanism is processed with guide vanes 19. The vanes can dissipate the heat generated by the electromagnetic brake. At the same time, the guide vane can also cool the friction brake mechanism. In order to improve vehicle's braking torque

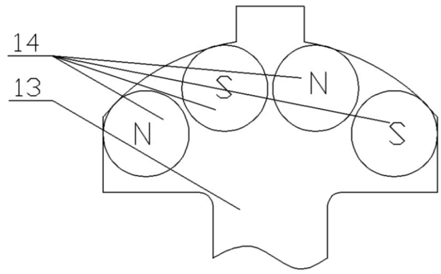

Fig. 2. Arrangement of steering knuckle electromagnetic guide block

at low speed, a copper plate of a certain thickness is installed at the electromagnetic brake disc side.

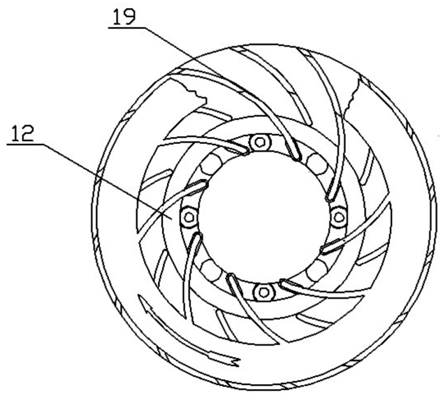

Fig. 3. Structure of electromagnetic brake disc

Figures 4 and 5 show other important parts of the composite brake.

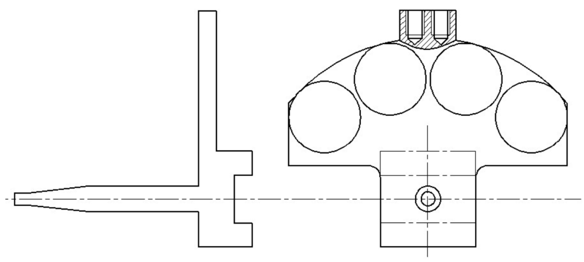

Fig. 4. Steering knuckle of composite brake

The flexible catheter (15) allows the electromagnetic brake disc and field coil to produce relative motion, which does not affect the transmission of the electromagnetic field.

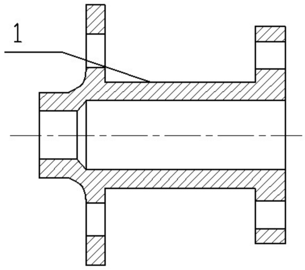

Fig. 5. Wheels hub of composite brake

4. Mathematical model of electromagnetic part of electromagnetic-hydraulic composite brake

Generally, any eddy current disc brake consists of a source of magnetic flux (produced by permanent magnet or, in our case, by electromagnet) and a well electrically conductive disc. The disc driven by an external source of mechanical energy rotates at an angular velocity ω is located very close to the magnetic poles.

The mathematical model of the electromagnetic part of the composite brake may generally be described by the following system of equations:

1. The first equation

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{1}$$

expresses that electric field strength is produced in the electrically conductive disc moving in a time variable magnetic field of magnetic flux density $\boldsymbol{B}$.

2. The occurrence of electric field $\boldsymbol{E}$ in the rotating disc causes currents in the disc whose density $\boldsymbol{J}$ is described by equation

$$\boldsymbol{J} = \sigma \boldsymbol{E}\,, \tag{2}$$

σ denoting the electric conductivity.

3. Relation between magnetic field strength $\boldsymbol{H}$ and produced current density $\boldsymbol{J}$ is generally given by the equation

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}\,, \tag{3}$$

but the displacement currents of density $\partial \boldsymbol{D}/\partial t$ do not play any role here and may be neglected.

4. The relation between the field vectors $\boldsymbol{J}=$ and $\boldsymbol{H}$ can be expressed as

$$\boldsymbol{B} = \mu_0 \mu_{\mathrm{r}} \boldsymbol{H}\,, \tag{4}$$

where $\mu_0 = 4\pi 10^{-7}$ H/m is the magnetic permeability of vacuum and μ_{r} is the relative permeability.

5. The volumetric force $\boldsymbol{f}$ acting in the disc is given (provided that the disc is non-ferromagnetic) by the relation

$$\boldsymbol{f} = \boldsymbol{J} \times \boldsymbol{B}\,. \tag{5}$$

6. Finally, the corresponding volumetric torque $\boldsymbol{t}$ is

$$\boldsymbol{t} = \boldsymbol{r} \times \boldsymbol{f} = \boldsymbol{r} \times (\boldsymbol{J} \times \boldsymbol{B}) \tag{6}$$

and acts against the rotation of the disc, thus decelerating it.

In our case the distribution of magnetic field in the system will be solved in terms of magnetic vector potential defined by the equation

$$\boldsymbol{B} = \mathrm{curl}\ \boldsymbol{A} \tag{7}$$

normalized by the Coulomb condition

$$\mathrm{div}\ \boldsymbol{A} = 0\,. \tag{8}$$

and aalso electric potential φ

The electric field strength $\boldsymbol{E}$ in the investigated domain containing the whole system generally consists of three terms

$$\boldsymbol{E} = -\mathrm{grad}\ \varphi - \frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{v} \times \boldsymbol{B} = -\mathrm{grad}\ \varphi - \frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{v} \times \mathrm{curl}\ \boldsymbol{A}\,, \tag{9}$$

where the first term denotes the component coming from the external source, the second term is produced by time variations of magnetic fields and the third term (existing only in the disc) is produced by its rotation. Symbol $\boldsymbol{v}$ denotes the velocity.

After inserting the above equation into (7), using of simplified equation (3) and (4) provides

$$\mathrm{curl}\ \left(\mu^{-1}\mathrm{curl}\ \boldsymbol{A}\right) = \gamma \left[-\mathrm{grad}\ \varphi - \frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{v} \times \mathrm{curl}\ \boldsymbol{A}\right]\,. \tag{10}$$

which represents the general equation describing the field in the system consisting of the electromagnet (containing the field coil, magnetic circuit, catheter and poles) and disc.

This equation contains, however, two unknowns: $\boldsymbol{A}$ and φ, which means that another, supplementary, equation has to be added. This equation is represented by the zero divergence of the current density at any point of the system, i.e.

$$\mathrm{div}\ \boldsymbol{J} = \mathrm{div}\ \left(\gamma \left[-\mathrm{grad}\ \varphi - \frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{v} \times \mathrm{curl}\ \boldsymbol{A}\right]\right) = 0\,. \tag{11}$$

Both equations must be supplemented with correct boundary condition along a sufficiently distant boundary. The condition for the magnetic vector potential is of the Dirichlet type, the condition for the electric vector potential is of the Neumann type.

In the rotating disc itself, the source currents are zero, so that the field may be described just by the equation containing only the magnetic vector potential in the form

$$\mathrm{curl}\ \left(\mu^{-1}\mathrm{curl}\ \boldsymbol{A}\right) = \gamma\left[-\frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{v}\times\mathrm{curl}\ \boldsymbol{A}\right]. \qquad (12)$$

and in case that the disc is nonferromagnetic and magnetic field does not vary in time, there holds

$$\mathrm{curl}\ (\mathrm{curl}\ \boldsymbol{A}) = \mu_0\gamma\left[\boldsymbol{v}\times\mathrm{curl}\ \boldsymbol{A}\right], \qquad (13)$$

and after using identity

$$\mathrm{curl}\ (\mathrm{curl}\ \boldsymbol{A}) = \mathrm{grad}\ \mathrm{div}\ \boldsymbol{A} - \Delta\boldsymbol{A} = -\Delta\boldsymbol{A}$$

with respect to the Coulomb condition (8) we finally have

$$\Delta\boldsymbol{A} + \mu_0\gamma\left[\boldsymbol{v}\times\mathrm{curl}\ \boldsymbol{A}\right] = \boldsymbol{0}. \qquad (14)$$

Particular steps of the general solution include:

1. Computation of the time-dependent distributions of potential $\boldsymbol{A}$ and φ using (10) and (11).
2. Computation of the time-dependent distribution of magnetic flux density in the disc using (7) and computation of time-dependent distribution of density of induced eddy currents ($\boldsymbol{J} = \gamma\boldsymbol{v}\times\boldsymbol{B}$).
3. Computation of the time-dependent distribution of the volumetric forces $\boldsymbol{f}$ in the radial cross-section in the disc using (5).
4. Computation of the time-dependent distribution of the volumetric torques $\boldsymbol{t}$ in the radial cross-section in the disc using (6).
5. Computation of the total drag torque using the formula

$$\boldsymbol{T} = \int_V \boldsymbol{t}\,\mathrm{d}V\,, \qquad (15)$$

where V is the volume of the rotating disc.

5. Simulation results

As the general 3D model of the braking system is rather complicated to solve, we decided to use a simplified 2D computational arrangement. The model was solved by the code Ansoft Maxwell 2D 10.0.

First, it is necessary to initialize the construct environment, and create a new project name through PROJECTS control in the software. Although the Maxwell software can construct model diagram using its own modeler, it is easier to apply AutoCAD software to build an electromagnetic - hydraulic composite brake model. Through Maxwell module TRANSLATOR controls, the AutoCAD DXF files are transformed into SM document format that Maxwell software can identify.

The principal parameters of the electromagnetic-hydraulic composite brake are:

- The distance r_{ab} from the center of the brake disc to the center of the electromagnetic coil is 0.08,m.
- The thickness of brake disc is 8 mm.
- The distance from the center of the electromagnetic guide block to the center of the electromagnetic brake disc is 2 mm.
- The field coil of the electromagnetic brake is made of copper.
- The brake disc is also of copper.
- The material of the electromagnetic guide block and electromagnetic catheter is NdFe35.
- The properties of soft magnetic material are nonlinear.
- The material of background is air.
- The number of turns of the field coil is 4000.

The simulation results are shown in Figs. 6–9. Figure 6 shows the discretization mesh covering the electromagnetic-hydraulic composite brake. Figure 7 shows the distribution of magnetic field in the system for field current 15 A. In this case, the maximum value of magnetic flux density B is 0.7 T (current density J being $8.78 \times 10^3\,\mathrm{A/cm^2}$). According to the simpler formula (20), the braking torque of the brake $T_{\mathrm{b}} = 1780.61\,\mathrm{N\,m}$, while code Ansoft Maxwell provides the force acting on the brake disc $F_{\mathrm{bs}} = 1780.61\,\mathrm{N}$, so that the simulated torque $T_{\mathrm{bs}} = 142.45\,\mathrm{N\,m}$.

Figure 8 shows an analogous magnetic field distribution for field current 20 A. Now the maximum B is 0.93 T (current density J being $1.24 \times 10^4\,\mathrm{A/cm^2}$), which is more larger than in the previous case. According to (20), the braking torque of the electromagnetic-hydraulic composite brake disc $T_{\mathrm{b}} = 239.72\,\mathrm{N}$,. Ansoft Maxwell provides the force acting on the brake disc $F_{\mathrm{bs}} = 3165.5\,\mathrm{N}$ so the simulated torque $T_{\mathrm{bs}} = 253.24\,\mathrm{N\,m}$.

For comparison, Fig. 9 shows the distribution of magnetic flux density also for field current 20 A, but now the brake disc is made of iron. In this case, the maximum value of B is 0.67 T, which is substantially smaller than maximum value of B in Fig. 8. This suggests that the ideal material for the brake disc is cooper.

Figure 10, shows the dependence of brake torque on the field current. From It is clear that the torque grows with increasing torque. Moreover, the torque calculated from simulation is somewhat higher than the torque determined from the simpler formula (20), but the difference does not extend about 13 % (for field current 10 A).

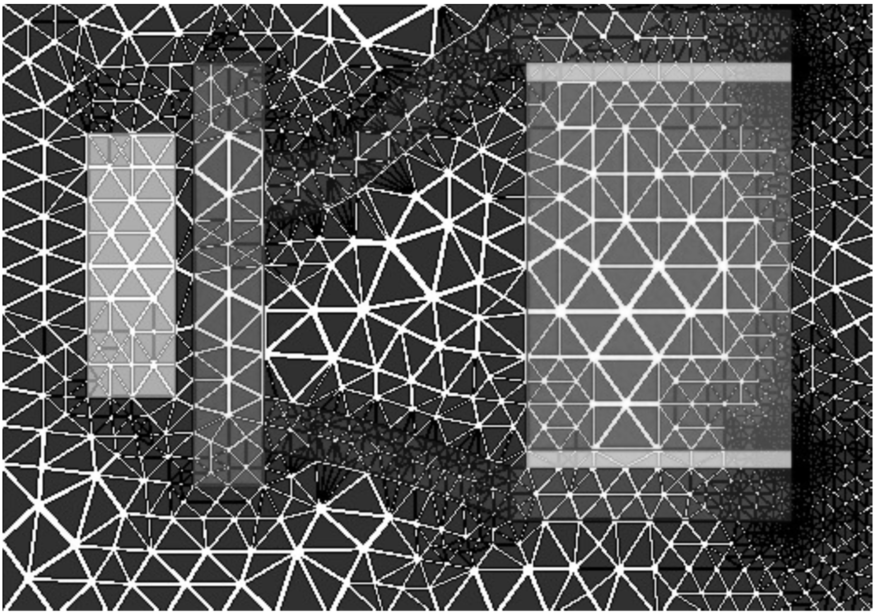

Fig. 6. Discretization mesh

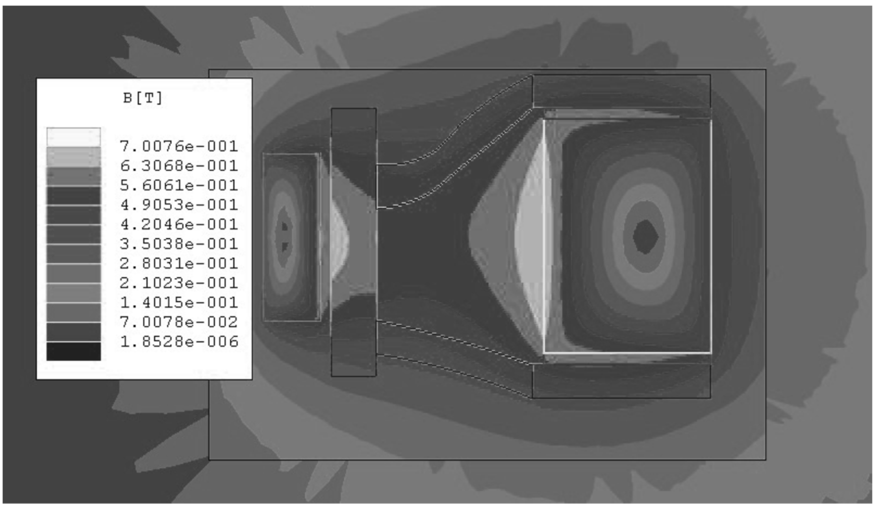

Fig. 7. Magnetic flux density distribution for current $I = 15\,\mathrm{A}$, disc made of copper

6. Conclusion

As the double-disc brakes use different materials, friction brake and electromagnetic brake can exhibit their particular advantages. The electromagnetic-hydraulic composite brake reduces the wear of the brake system, maintenance costs, danger of

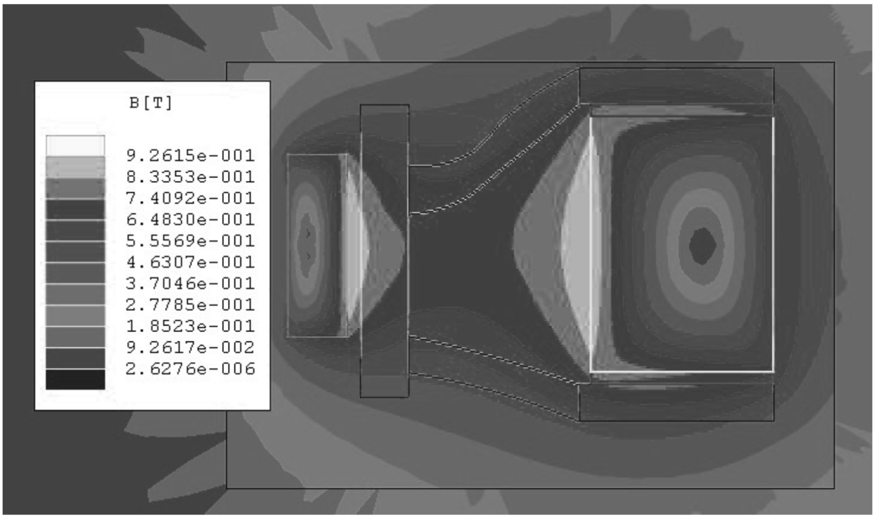

Fig. 8. Magnetic flux density distribution for current $I = 20\,\mathrm{A}$, disc made of copper

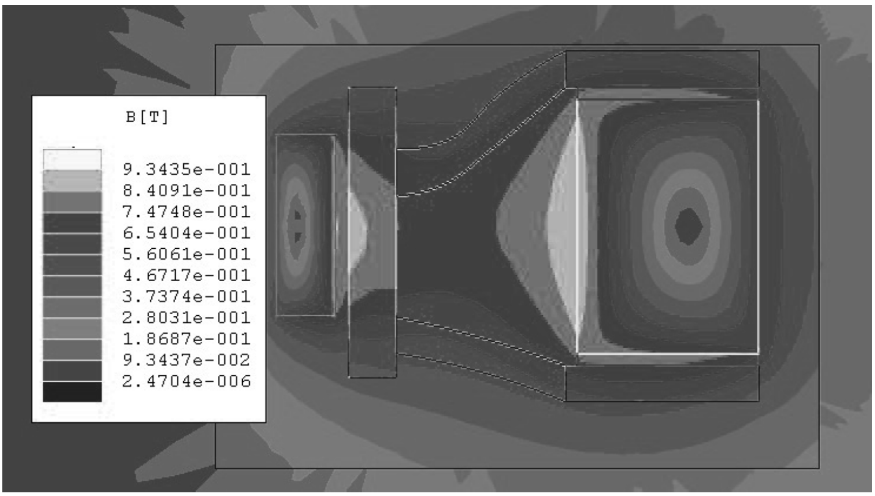

Fig. 9. Magnetic flux density distribution for current $I = 20\,\mathrm{A}$, disc made of iron

the car's thermal failure, rate of water aging and, moreover, it increases security of the braking system.

Thus, overcoming the shortcomings of the existing hydraulic braking systems using the hydraulic system and non-contact electromagnetic brake system made of composite represents the present direction of development of the braking systems.

Based on the mathematical model, the braking torque of the electromagnetic - hydraulic composite brake is calculated. The computations are carried out by applying the software Ansoft Maxwell 2D/3D. The results show that the torque

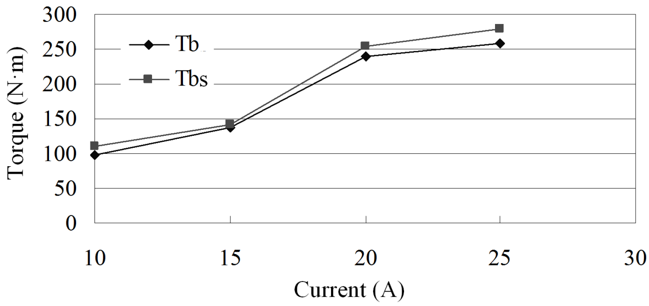

Fig. 10. Torque versus applied field current

grows as the current increases, and the torque value obtained from (20) approaches the value obtained from simulation.

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