NUMERICAL CALCULATION OF ELECTROMAGNETIC FORCES IN MAGNETIC ACTUATOR FOR USE IN ACTIVE SUSPENSION SYSTEM FOR VEHICLES

Željko Hederić, Damir Šoštarić, Goran Horvat

Original scientific paper

The aim of this work is the dynamic calculation of the necessary electromagnetic forces for positioning of the vehicle at different mass loads. Numerical calculations of magnetic fields and obtained forces are based on finite element method. Comprehensive solutions have been applied to the development of a parametric modelling. The paper defines the basic model for further modelling and the possibility to observe the behaviour of a given model using different types of materials and loads. Types of magnetic materials and their selection for particular parts of the model are explained. These results provide insight into the magnetic field, dependence of default coil current and power of the levitate part of the model. Using these results a mathematical model can be developed. State space model calculation can be utilized as a preparation for automatic regulation of the dynamics of the suspension.

Keywords: electromagnetic forces, levitation, numerical calculation, pre-calculated mathematical model, vehicles suspension

Numerički izračun elektromagnetskih sila u magnetskom izvršnom članu za uporabu u aktivnom ovjesu vozila

Izvorni znanstveni članak

Cilj rada je dinamičan izračun potrebnih elektromagnetskih sila za pozicioniranje vozila na različitim masama opterećenja. Numerički proračuni magnetskih polja i dobivenih sila temelje se na metodi konačnih elemenata. Sveobuhvatna rješenja su primijenjena na razvoj parametarskog modeliranja. U radu se definira osnovni model za daljnje modeliranje i promatrana mogućnost ponašanja određenog modela koristeći različite vrste materijala i opterećenja. Objašnjene su vrste magnetskih materijala i njihov izbor za pojedine dijelove modela. Rezultati daju uvid u magnetsko polje, ovisnost struje zavojnice i snage levitirajućeg dijela modela. Korištenjem ranije navedenih rezultata, matematički model može biti razvijen. Izračun modela u prostoru stanja može poslužiti kao priprema za automatsku regulaciju dinamike suspenzije.

Ključne riječi: elektromagnetske sile, levitacija, numerički izračun, prethodno izračunati matematički model, ovjes vozila

1   Introduction

Magnetic levitation is the process of maintaining objects in free space, without contact with the ground, using a magnetic field. Different models of levitators are designed using basic principles and knowledge regarding magnetic fields. To achieve levitation by applying laws of physics an interaction between two separate magnets is necessary. Depending on the model used a deflecting or attractive force between the poles of magnets can be used. The first attempts were carried out using permanent magnets. Earnshaw's theorem (1839) proved mathematically that it is not possible to perform magnetic levitation in any combination with permanent magnets. There is a possibility to bypass Earnshaw's theorem by modification of its basic assumptions using diamagnetic materials, Meissner's effect, oscillation, rotation (Levitron), and feedback by an electromagnet which is regulated with a magnetic field [1].

In this paper a model that uses the appearance of repulsive forces between the poles of magnets and electromagnets to achieve levitation is shaped and described. The materials and their interaction with the magnetic field are defined. In the model [2], where diamagnetic materials were used to stabilize levitation model dynamic calculations of magnetic force required for stabilization were derived. Dependence between the coil current, magnetic field and the resulting force was numerically calculated using finite element method and three-dimensional display in several different levitator positions compared to zero (reference) position. Developed model allows a further study of the impact of different types of materials, electricity and load on the resulting force.

The paper provides the ability to create models with pre-calculated values of the state space automatic control of the dynamics of the suspension.

2   Basic principle

The levitation systems can be divided in two basic principles: electrical subsystem and mechanical subsystem [3]. Electromagnetic levitation is based on the phenomenon that when ferromagnetic materials are located in foreign magnetic fields, they seek to reduce the magnetic resistance of the magnetic circle, so between them appears attractive force. The diamagnetic material effect is just opposite (Fig. 1).
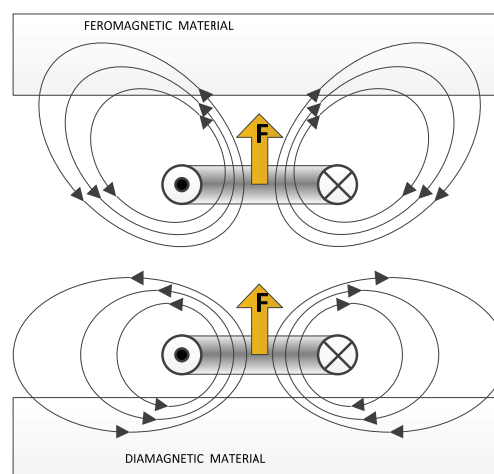

Figure 1 Display of the static magnetic fields effect on ferromagnetic materials and effect of the dynamic magnetic fields on diamagnetic material

Parallel motion of the electromagnet above the diamagnetic plate at certain velocity causes emerged eddy currents within. Those eddy currents acting in the way to suppress this phenomenon. Consequently, that leads to repulsive forces. Due to the need of motion this system is named electro dynamical.

The main task of the magnetic actuator as an integral part of the suspension vehicle system is to provide a neutral (reference) position regardless of the size and orientation of external forces vector. Forces can be decomposed into a vertical component (the dominant force up-down) and a horizontal component (force left – right). Since the gravity of the vehicle and the moving part of the actuator as a vector are aimed vertically downwards (vector G in Fig. 2), it is obvious that the magnetic force (vector F_{mag} in Fig. 2) must be predominantly oriented in the opposite direction from that.

From the standpoint of regulation there is a neutral position, without the action of external forces (vector F_{meh} in Fig. 2), in which magnetic forces must annul the effect of gravity (Fig. 2a). Under the action of external force, position can be shifted downward, where the magnetic force must be increased for the amount of external force (Fig. 2b). The third case is when the position moves upward or external force is greater than the gravity and the opposite direction, so the magnetic force must support the gravity (Fig. 2c). The above descriptions refer to the displayed images on which there are only static forces present (without the presence of dynamic forces). Considering the speed ($\dot{x}$) and acceleration ($\ddot{x}$) change in the system position becomes dynamically demanding from the point of regulation [2, 3]. In the case of dynamic balance of forces components of the force occur caused by the dynamic change of position: acceleration, damping and spring forces. Eq. (1) describes II Newton low for Fig. 2c), with a positive change of position upward ($x > 0$) caused by the action of external forces (F_{meh}):

$$m \cdot \ddot{x} + d \cdot \dot{x} + k \cdot x + F_{meh} = m \cdot g + F_{mag} , \qquad (1)$$

where is mechanical system represented by mass (m), damping constant (d), spring constant (k) and gravitational constant (g).
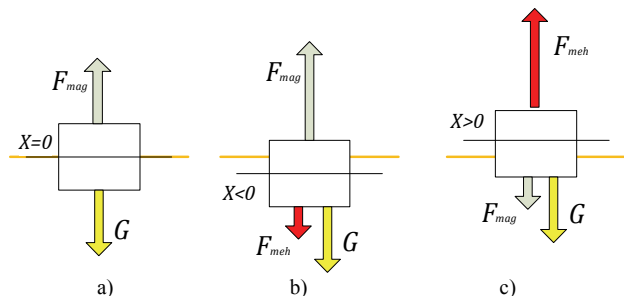

Figure 2 Disposition of forces on moving part of the actuator: a) neutral position $x = 0$, b) under the neutral position $x < 0$, c) above the neutral position $x > 0$.

When vehicle suspension unit system has more magnetic actuators which all have a role of depreciation and maintenance of the default height (position as the default value of the control system), each of them is a separate unit whose work must be controlled to ensure the overall stability. The regulator required for suspension system is very demanding in regard of adjusting and control.

Fig. 3 shows the magnetic field of coils on a magnet, which is in the model of the actuator mounted centrally above the coils. The total resultant force acts upward, and such action of magnetic force overcomes the action of gravity and provides a basic neutral position (levitation in a neutral position).
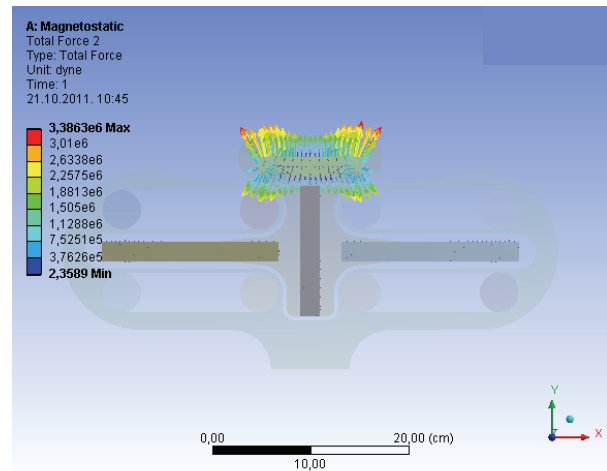

Figure 3 Forces view of the coils flown by current on permanent magnet that is positioned centrally in the upper movable part of the actuator

If the moving part of the actuator was shifted horizontally, obviously this would reinforce the opposite component of magnetic force and therefore, it would result in system returning to the neutral position. Since the entire movable part is solid, the magnetic force of the magnet is the force of the whole body. By changing the direction of current through the coils the change in orientation of magnetic force is ensured as is explained in Fig. 2c).
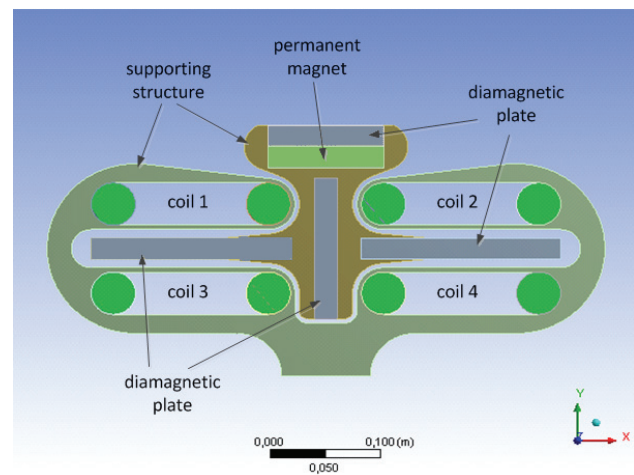

Figure 4 Distribution of the diamagnetic panels

As previously shown in Fig. 2, apart from the action that provides levitation in a static position it is necessary to ensure the action on dynamic behaviour of the moving parts of an actuator (Fig. 1). This action must be dynamic

and always provide suppression in the way of a periodic response. Additionally in the dynamic system besides the horizontal force components there are also vertical components, where higher harmonic behaviour results in larger amounts of regulated resultant force.

In an attempt to achieve this experimentally, many different solutions have been developed [3]. On the model that was chosen here, sets of the diamagnetic material plates in two directions are proposed [2]. Fig. 4 shows two horizontal plates placed between coils 1 and 3 as well as coils 2 and 4. This provides dynamic stability in the vertical direction. For horizontal stability the third panel was mounted centrally located and placed vertically. The fourth panel of diamagnetic material which is above the permanent magnets ensures that the entire system does not come to saturation.

In this case magnetic properties of the system and the force required for levitation would be drastically reduced. Effect of magnetic field of coils on diamagnetic materials is shown in Fig. 5. It must be noted that the amount of magnetic activity is much lower than the effect on the permanent magnet presented in Fig. 2. The ratio of these amounts indicates to a ratio of force required to levitate (default position $x = 0$) and the force required to stabilize the dynamic behaviour (speed and acceleration). This ratio must not deceive because at intense dynamic behaviour the ratio would decline, while the magnetic levitation force would not change.
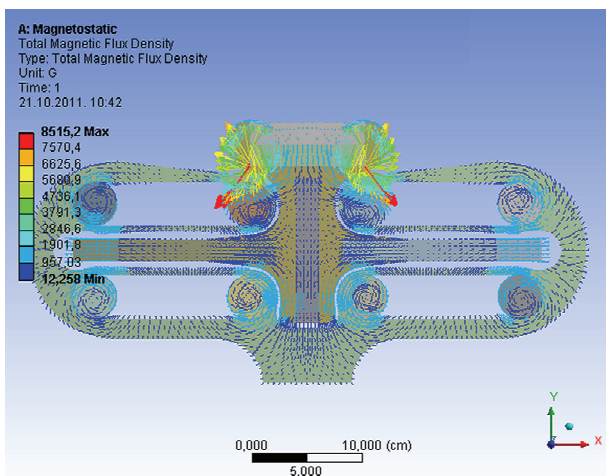

Figure 5 Display of magnetic effect on nonmagnetic materials of the model

3   Numerical modelling

Magnetic vehicle suspension is composed of two systems of coils positioned as to provide vertical and horizontal support vehicles. Directions of coils current (Fig. 6) were determined so that they provide the magnetic force required for the system levitation, but also at relative motion it provides the appearance of electrodynamic force. Indication of the coils current directions and the resultant magnetic force required to levitate are assumed and in this way the designed model is created. Arrangement of coils, permanent magnets and diamagnetic plates provide force couples which with their joint action, always seek to keep the system in a neutral position in both axes perpendicular to the direction of

movement of the vehicle. Because of smaller Joule losses and benefits of the system, the material for coils is made of superconducting materials [4, 5]. During the modelling, great importance should be added to define the dimensions of individual parts of the model [7]. Changing the distance between the coils (coil diameter) significantly affects the magnetic field generated by electromagnets, so optimal distance of the winding should be determined. Frame body of conductive paths and of levitators should have to bear all the possible load of vehicles, including the weight of the vehicle. Permanent magnet in combination with electromagnets provides the necessary force for lifting and it must be set on the least possible distance from the electromagnet.
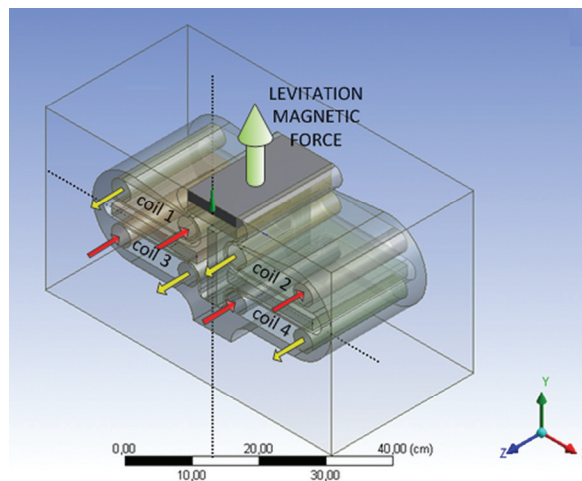

Figure 6 Space display of the magnetic actuator

Approaching a permanent magnet to the coils reduces the required current of coils for achieving an equal lift force, but with it alters the possibility of the model regulation. Previously it was stated that a major role and impact on the required lift force is material selection. To bypass the Earnshaw theorem, altering its basic assumptions it is required to choose the material type of each geometry part separately.

Frame body of the coil must be made of adequate strength and antiferromagnetic, nonconductive materials. Frame body of levitators differs from coil material only for electrical conduction. Plates of the diamagnetic material (Fig. 4) are used to achieve stable horizontal and vertical levitation, and the need to use the Earnshaw theorem is avoided. Change of structural materials of the body greatly affects the amount of force. Replacing the material with ferromagnetic material, the force of permanent magnets is increased up to an amount that overcomes the gravity force and levitation is possible. If we remove diamagnetic plate, the Earnshaw theorem is not avoided and therefore stable magnetic levitation is impossible.

Finite element method is used to model a wide class of problems disassembled on elements of simple shape for the calculations [8, 9, 10]. Suitable interpolation of polynomials is used to approximate the unknown function within each element. After the selected form of the function, it is possible to program a computer to solve the calculation for the given complicated geometry. For a range of elements human intervention is required to

ensure a reliable solution to the problem. Choosing a particular kind of elements which would be well used for the calculation of electric/magnetic fields is essential for obtaining accurate solutions for the solution of three-dimensional problems in electromagnetics.
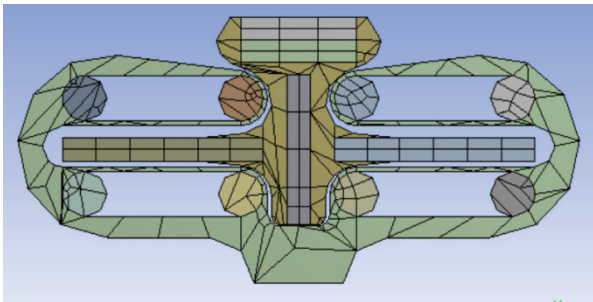

Figure 7 Example of bad model discrediting (automatic mesh is nonsymmetrical)
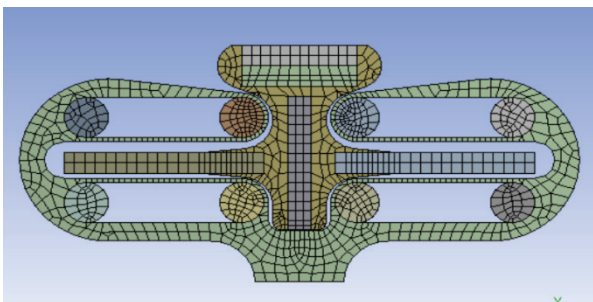

Figure 8 Example of good model discrediting (symmetric mesh with smaller elements is space with larger field derivation)

Fig. 7 and Fig. 8 show the importance of choosing quality mesh to achieve more precise calculation of three-dimensional characteristics of the magnetic field.

4   Result of numerical calculation

Magnetic fields and forces are calculated as a function of changes in the amount and direction of currents of electromagnets, and for a variety of positions of the moving parts. Materials and their properties are retained and unchanged in all segments of the calculation. Due to the inability of field observations of behaviour in all positions and amounts of electricity, we had to limit (make discrete) possible positions of the moving parts and the amount of electricity. The amount of the current was changed from –15 A to +15 A in increments of 3 A, and the position of the moving parts changes from –3 mm to +3 mm with a millimetre displacement, where $x = 0$ denotes the reference position.

It is assumed that there is only the vertical component of the disturbing force (F_{meh} shown in Fig. 2) so the amounts of current through both upper coils are equal, and the currents through both lower coils are of equal amount. The total matrices of magnetic force on the moving part are defined as a function of three variables: $I1$ – upper coil current, $I2$ – lower coil current, x – vertical position of the movable parts. According to the increments of currents and position the total matrices have $7 \times 7 \times 7$ dimensions.

For every discrete value of position, and for every discrete value of currents through the upper coils, the current through lower coils was changed in increments

from –15 A to +15 A. Amount of magnetic forces was shown by creating one of $7 \times 7 \times 7$ situations for each of FEM calculations. Such a procedure can create a state space from which can be explored the changes in the magnetic forces in dependence on all three variables and can be derived process model. Considering the force balance equation (1), it follows that for every dynamic change of position due to disturbance force (left side of equation) through dynamic response by changing of magnetic force (right side of equation) compensation of position changing toward reference neutral position can be made.

Fig. 9 shows the effect of changes of the lower coil current ($I2$) for different vertical positions of yoke (x). Because of clearness a relative change is shown in power in logarithmic scale with respect to the value of the force in the reference position with equal currents in all windings; (in this case it is at: $I1 = I2 = 0$ A, $x = 0$). It can be seen that the presented system is designed to provide a linear change of magnetic force proportional to the current change of the lower coils. Gradient of force changing is larger due to current change than due to changing of the position. It is well because it provides more precise controllability.
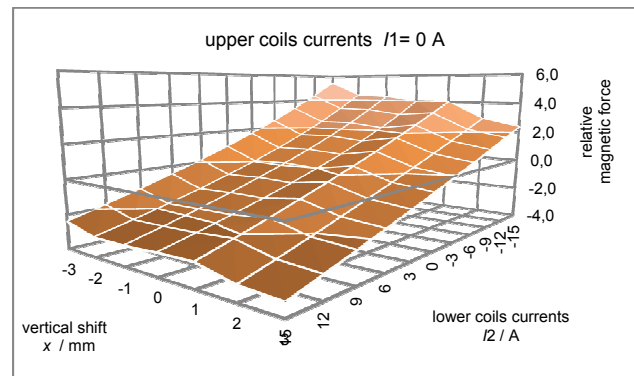

Figure 9 Display of relative magnetic force changes due to changes of lower coils currents and vertical shift

In Fig. 10 is presented the relative change of the magnetic force at upper coil current value $I1 = 15$ A. In this case, it is evident that the gradient of the magnetic force has smaller changes as the results of reaction of opposing forces of the upper and lower coils. It should be noted that the absolute amounts of force in extreme cases are even twice of the maximum value shown in Fig. 9.
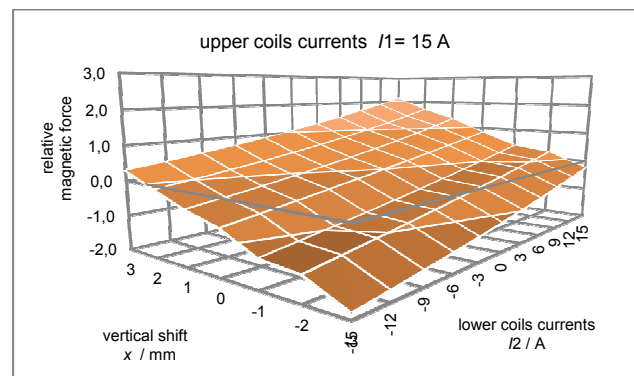

Figure 10 Display of relative magnetic force changes for constant positive value of upper coils currents due to changes of lower coils currents and vertical shift

Fig. 11 shows the situation when all coils currents act mainly downward. In cases where the current in the upper coils has a certain value, as shown in Fig. 10 and Fig. 11, the vertical position of forces annulment is shifted toward the coils with smaller currents. The null value contour is rotated according to that. In Fig. 10 at current values of the lower coils of $I2 = 6$ A, it can be seen that the force equalization is present at the position which is below the reference position at $x = -2$ mm.
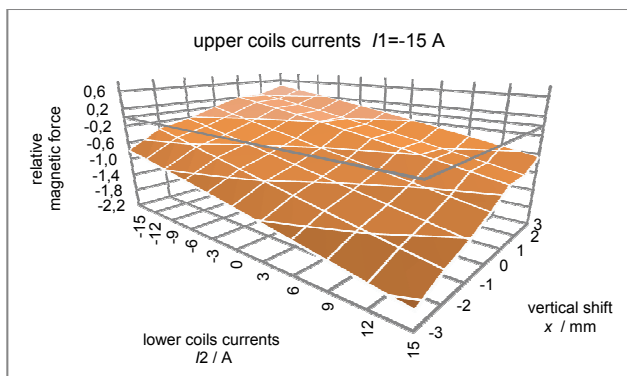

Figure 11 Display of relative magnetic force changes for constant negative value of upper coils currents due to changes of lower coils currents and vertical shift

From discrete data obtained by FEM calculations using mathematical numerical methods, the gradients of force are calculated as a function of all three input values (two current and position). Based on that are formed the surfaces as shown in Figs. 9 ÷ 11. Stacking all surfaces in 3-D images can be created a state space, whose density indicates the critical points. Close by areas of those critical points need to be further calculated with FEM calculation using smaller discretization step size.

5　Conclusion and future work

This paper defines the basic model geometry for further modelling, and the ability to observe the behaviour of a given model using different types of material load. The possibility of observing the magnetic field dependence of the current coils and forces on levitate part of the model is provided.

Results of calculated force characteristics are presented in tables and three-dimensional graphs. Thereby the ability is provided to create models with pre-calculated values, as well as preparation for automatically controlling of the dynamics of the suspension. Numerical calculation gives the possibility to solve various problems by simplifying the large number of complex mathematical equations, giving the opportunity to study the behaviour of each model prior to construction. Future work is conceived in the direction of passive and active control, as well as design of the real device. The presented suspension system is designed for implementation in vehicles. Therefore, integration of passive or active automatic regulation is considered. Active regulation would then be designed for microcontroller embedded control systems that have sensors and actuators. As a conceptual solution for the sensor Hall's probes and three-axis magnetometer are considered. By placing multiple measuring points in sensor places, the system becomes more precise and stable, reducing the overall measurement error. Closed-circuit regulation is realized by feedback connections and installation of a controller/regulator such as PID, Pole Placement.

6　References

[1] Moon, F. C. Superconducting Levitation: Applications to Bearing & Magnetic Transportation. // Adobe E-Book, November 2008.
[2] Miericke, J. Magnetically Suspended Trains. // Cryogenics and Industrial Gases, October, 1969, pp. 19-24.
[3] Goodall, R. The theory of electromagnetic levitation. // Physics in Technology, 16, 5(1985), pp. 207-213.
[4] Thompson, M. T.; Thornton, R. D. Flux-Canceling Electrodynamical Maglev Suspension: Part II Test Results and Scaling Laws. // IEEE Transactions on Magnetics, 35, 3(1999), pp. 1956-1963.
[5] Ma, K. B.; Postrekhin, Y. V.; Chu, W. K. Superconductor and magnet levitation devices. // Review of Scientific Instruments, 74, 12(2003), pp. 4989-5017.
[6] Cansiz, A. Static and dynamic analysis of a diamagnetic bearing system. // Journal of Applied Physics, 103, 3(2008), pp. 034510-034510-5.
[7] Slavek, N.; Lukić, I.; Köhler, M. Software Process Measuring Model. // Tehnički vjesnik - Technical Gazette, 19, 1(2012), pp. 11-17.
[8] Vladić, J.; Đokić, R.; Kljajin, M.; Karakašić, M. Modelling and simulation of elevator dynamic behaviour. // Tehnički Vjesnik – Technical Gazette, 18, 3(2011), pp. 423-434.
[9] Hederić, Ž.; Štefanko, S.; Barukčić, M. Finite elements method calculation of circular magnetic flux emerged by eccentric position of rotor. // Tehnički vjesnik – Technical Gazette, 15, 4(2008), pp. 9-13.
[10] Nikolić, V.; Dolićanin, Ć.; Radojković, M.; Application of finite element analysis of thin steel plates with holes. // Tehnički vjesnik - Technical Gazette, 18, 1(2011), pp. 57-62.

Authors' addresses

Prof. Željko Hederić, PhD.
J. J. Strossmayer University of Osijek
Faculty of Electrical Engineering
Department of Electromechanical Engineering
Kneza Trpimira 2b, 31000 Osijek, Croatia
E-mail: zeljko.hederic@etfos.hr

Damir Šoštarić, M. Eng.
J. J. Strossmayer University of Osijek
Faculty of Electrical Engineering
Department of Communications
Kneza Trpimira 2b, 31000 Osijek, Croatia
E-mail: damir.sostaric@etfos.hr

Goran Horvat, M. Sc.
J. J. Strossmayer University of Osijek
Faculty of Electrical Engineering
Department of Communications
Kneza Trpimira 2b, 31000 Osijek, Croatia
E-mail: goran.horvat@etfos.hr