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# MAGNETIC SPRING AS THE ELEMENT OF VIBRATION REDUCTION SYSTEM

*SUMMARY*

*The paper presents the operating principle, experiments and calculations of a magnetic spring. Force exerted by the magnetic spring is a result of interaction of magnetic fields formed by magnets and coils. The stiffness of the spring can be modified by changing the current in coils. The paper presents FE model of the spring. Static characteristic of the spring were determined using results of FE method calculations and experiments. The magnetic spring with switched stiffness was employed in one degree of freedom system.*

***Keywords****: magnetic spring, vibration control, switching stiffness*

*SPRĘŻYNA MAGNETYCZNA JAKO ELEMENT UKŁADU WIBROIZOLACJI*

*W pracy przedstawiono zasadę działania, badania eksperymentalne oraz symulacyjne układu z wykorzystaniem sprężyny magnetycznej. Siła oddziaływania sprężyny magnetycznej jest rezultatem oddziaływania pola magnetycznego wytworzonego przez magnesy oraz cewki. Zmiana sztywności sprężyny uzyskiwana jest za pomocą zmiany natężenia prądu w cewkach. Opracowano model MES sprężyny. Charakterystyki statyczne sprężyny zostały wyznaczone przy użyciu symulacji MES oraz potwierdzone na podstawie badań eksperymentalnych. Sprężyna magnetyczna ze zmienną sztywnością została zastosowana w układzie o jednym stopniu swobody.*

***Słowa kluczowe****: sprężyna magnetyczna, sterowanie drganiami, układy przełączające*

## 1. INTRODUCTION

Mechanical springs made of steel are usually applied in vibroisolation systems. They have prescribed stiffness and usually small damping coefficient. Therefore dampers or rubber pads should be mounted parallel or in series with springs in vibroisolation systems [Kowal 1996]. Springs are basic elements of vehicle and machine suspensions.

In controlled magnetic spring the stiffness can be changed. Variable stiffness is also a feature of shape memory alloys springs (SMA) (Raczka 2006). One of the ideas of application the magnetic field in vibroisolation system was ‘magnetic-levitation’. In this idea the stability of equilibrium position was the main problem. For example, the design of Mizuno (Mizuno 2003) is unstable in vertical direction, and that of Choi (Choi 2003) uses singular magnets which do not scale well with volume (Robertson 2005).

Main principles of vibration isolation have been developed in detail. For example in one degree of freedom system, the reducing of stiffness causes the lowering of resonance frequency. Damping reduces the amplitude of the resonance peak but increases amplitudes at higher frequencies in relation to amplitude of vibration without damping (Robertson 2009).

According to frequency response curve, the system should have small stiffness. Small stiffness can be realized in mechanical supports, but only for local range of displacement. Since the ‘zero stiffness’ is not a global property these devices are usually called ‘quasi-zero stiffness’ springs (Robertson 2007).

In a conventional mass–spring system, the static deflection increases when the stiffness of the support is reduced, and a lower limit of the stiffness is imposed by allowable displacement. Special type of supports can exhibit stiffness that is a nonlinear function of displacement. Some of these “zero stiffness” supports are presented in (Robertson 2009).

This study focuses on design of controlled magnetic spring, which may be applied in vibration reduction system of machine operator’s seat.

## 2. MECHANICAL CHARACTERISTIC OF MAGNETIC SPRING

This stage of paper contains: operating principle, the FE method determination and experimental determination of magnetic spring parameters. The electromagnetic FE method permits users to calculation of physicals value as: magnetic flux density, magnetic field strength and forces. The aim of calculation was to determine the mechanical characteristics of magnetic spring. To make certain the results of the FE method simulations were conducted experiments.

### 2.1. Operating principle of magnetic spring

Schematic sketch of the magnetic spring is shown in Figure 1. Main parts of the magnetic spring are: magnetic core, magnets and coils, shaft and covers.

Two upper neodymium magnets (1) are fixed to the end of the shaft (7) and the next two magnets (2) are fixed to the lower magnetic core (5) in the spring axis. Magnetic circuit consists of: four side magnetic cores (3), an upper magnetic core (4) and a lower magnetic core (5). Four coils (6) are installed on side magnetic cores (3). A linear motion of the shaft (7) is realized by a linear bushing (8). Adequate posi-

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tions of all elements are provided by an upper cover (9) and a lower cover (10). The covers are fixed by a four stability rods (11). Currents in the coils (6) have an influence on magnetic field in the space between the magnets (1, 2) and simultaneously on the spring force.

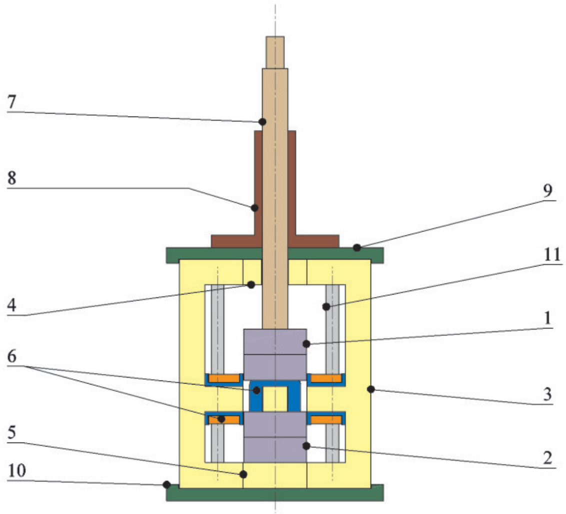


**Fig. 1.** Schematic sketch of magnetic spring

## 2.2. Determination of parameters by FE method

Since the magnetic spring structure is complex, analytical calculations are practically useless. In order to perform a more accurate calculation of magnetic field distribution and spring forces the FE model was prepared. The program ANSYS (ver. 11.0) was used in modelling and calculations. The spring FE model and its section are shown in Figures 2 and 3.

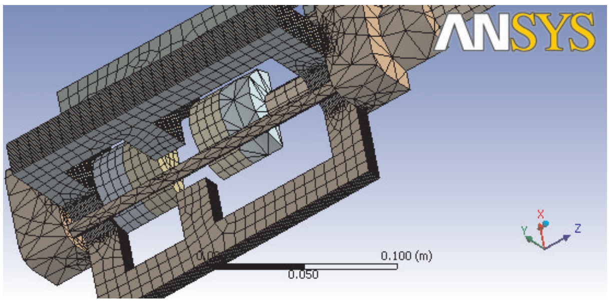


**Fig. 2.** FE model of magnetic spring

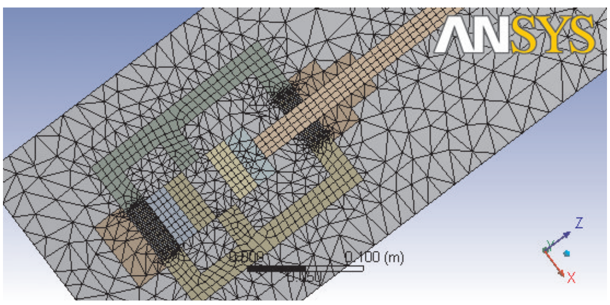


**Fig. 3.** ZX section of the spring FE model

The construction of the proposed magnetic spring has a lot of detail e.g. chamfers, bypasses which can be ignore in FE model because their influence on results of calculations is negligible. The model has two symmetry planes – the XZ plane and YZ plane. The property of symmetry simplifies the model and calculations. The symmetry of magnetic spring with respect to XZ plane was avoided in calculations. In order to determine the characteristic of the spring the following parameters of magnets were assumed: coercion of neodymium magnets $H_c = 9.24{\cdot}10^5$ A/m and residual flux density of neodymium magnets $B_r = 1.28$ T. Magnetic flux density, magnetic field strength and forces acting on components of magnetic spring were determined by FE method. Calculations were done at various positions of the shaft, so that the static characteristics of magnetic spring could be prepare. Selected results of calculations are presented in Figures 4 and 5 (distance between magnets is equal to 25 mm).

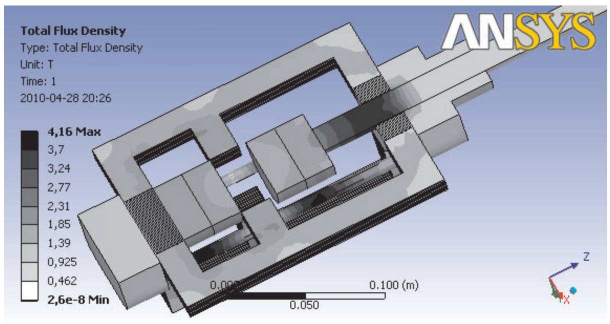


**Fig. 4.** Magnetic flux density

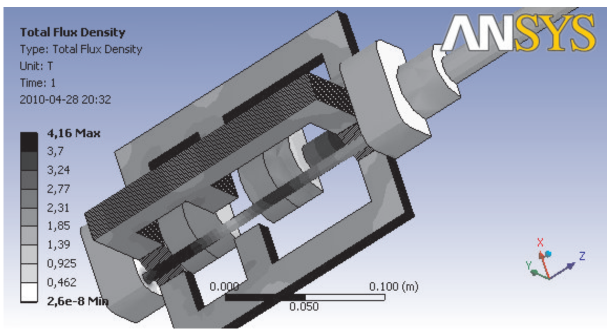


**Fig. 5.** Magnetic flux density

The largest value of magnetic flux density occurs in stabilizing rods and in shaft in the place where the magnets and the linear bushing are linked. In these places the value of the flux density is over 3 T. The largest value of magnetic field strength (above $9{\cdot}10^5$ A/m) occurs in the space between the magnets. The main goal of calculations was to estimate the value of the force acting on shaft. The result of calculations is shown in Figure 6. The force is a non-linear function of distance between magnets. As it was expected the force is higher for smaller distance between magnets.

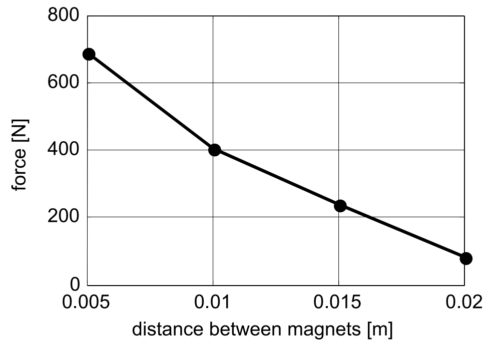


**Fig. 6.** Resulting force vs distance between magnets

### 2.3. Experimental determination of spring parameters

The prototype of magnetic spring was made and a lot of tests were done in the Laboratory of Dynamic Structures and Systems in Department of Mechanical Engineering and Robotics AGH in Cracow. The aim of experiments was to determine the realistic characteristics of prototype. They are necessary to further calculations. The experimental set-up is presented in Figure 7 and the prototype of magnetic spring is shown in Figure 8.

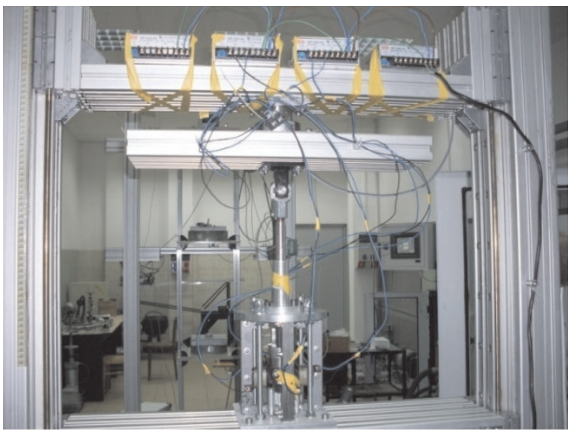

**Fig. 7.** Experimental set-up

**Fig. 8.** Prototype of magnetic spring

Displacement of the shaft was realized by hydraulic system and it was assumed as a triangular signal of amplitude 7 mm, and frequency 0.1 Hz. The force acting on the shaft was measured. Currents in coils were switched according to assumed sequence. The influence of current switching on the spring force was investigated. It was considered current switching in one, two and four coils. In subsequent considerations the coil in which the current is switched on is called ‘active coil’. The current was the same in each coil and it was equal to 7 A. Selected results of experiments are presented graphically. Displacement of the shaft is shown in (Fig. 9) and corresponding force is shown in Figure 10.

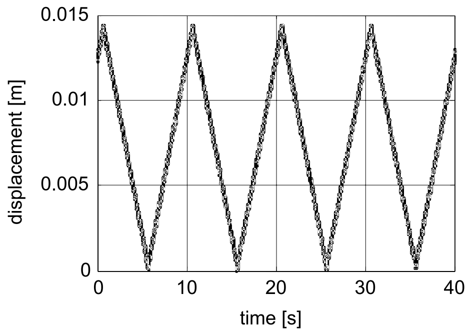


**Fig. 9.** Displacement of the shaft

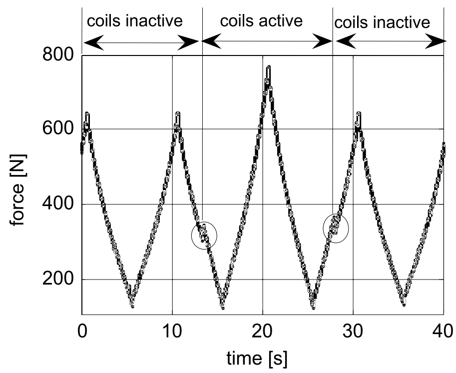


**Fig. 10.** Spring force

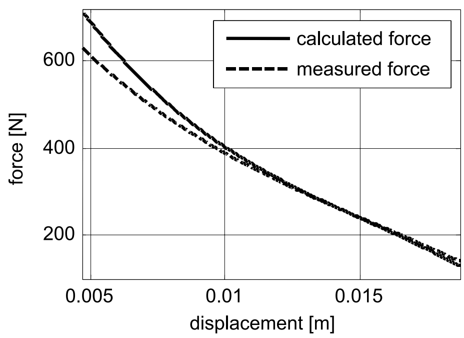


**Fig. 11.** Comparison of calculated and measured force (coils inactive)

Displacements and forces measured for various sequences of active coils were the base to perform magnetic spring characteristics. Results of experiments and calculations were compared (Figs 11 and 12). Calculated force was approximated by a third degree polynomial (Fig. 11). The relative error (Fig. 12) does not exceed 13%. The highest value of error is obtained for small value of displacement between magnets. Taking into account the simplifications done in FE model, the result is satisfactory.

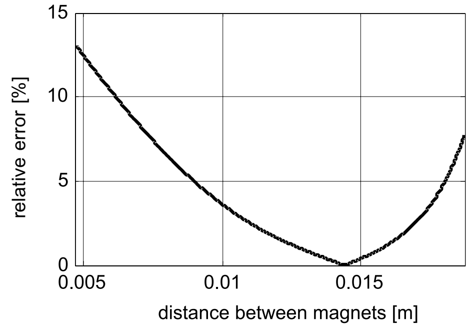


**Fig. 12.** The relative error of calculations

## 3. APPLICATION OF MAGNETIC SPRING IN VIBROISOLATION SYSTEM

The coordinate system introduced for presentation of measured force (Fig. 11) was replaced with a new more convenient coordinate system. The origin of the new coordinate system was placed at the positions of the end of the shaft when the distance between magnets takes the maximum. The relation between force and displacement for various sequences of switched coils in new coordinate system is shown in Figure 13. Depending on direction of current, the active coil increases or decreases the magnetic field strength.

In vibroisolation system, proposed in this work, the principle of operating resolves to appropriate switching between two characteristic of the spring. As a result in each period of oscillation the energy of the system decreases. The scheme of considered system is presented in Figure 14.

Depending on the velocity sign the switching system chooses the appropriate characteristic of magnetic spring. The equation of motion can be written in the form:

$$m\ddot{x} = mg - F(x, \dot{x}) \tag{1}$$

where:

$m$ – mass (in calculations it was assumed 30 kg),
$g$ – gravitational acceleration.

The force of magnetic spring $F(x, \dot{x})$ depends on switching function $f(\dot{x})$ which takes the value 1 (when $\dot{x} < 0$) or 0 (when $\dot{x} > 0$). This function is used to select of spring characteristic. Finally, the force can be calculated from the following formula:

$$F(x, \dot{x}) = f(\dot{x}) \cdot F_1(x) + (1 - f(\dot{x})) \cdot F_2(x) \tag{2}$$

where:

$F_1(x)$ – the “feebler” characteristic of magnets,
$F_2(x)$ – the “steadier” characteristic of magnets.

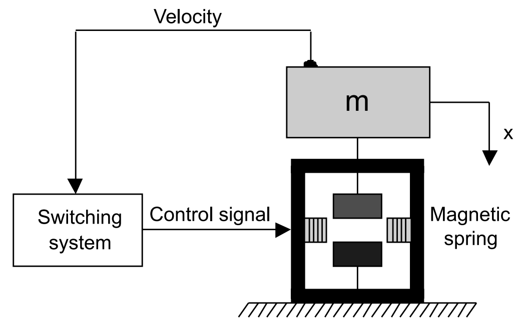


**Fig. 14.** Scheme of vibroisolation system with magnetic spring

The algorithm was adopted to “switch on” or “switch off” the current in one, two or four coils. As a result, vibration energy was reduced in each cycle. The program MATLAB version R2009b was used in simulations. Results of simulations were shown in Figures 15–17.

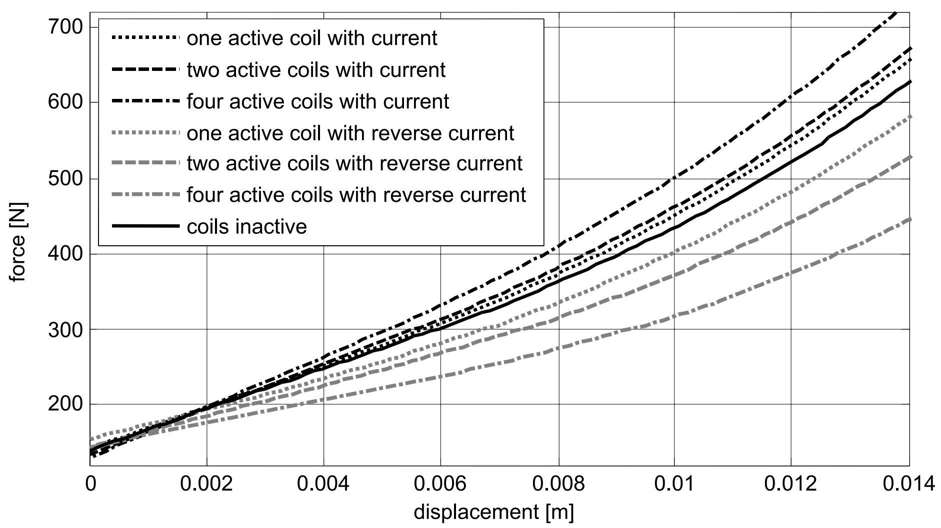


**Fig. 13.** Force as a function of displacement for various combinations of active coils

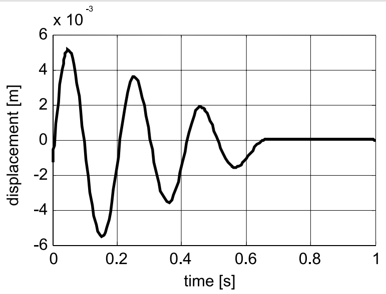


**Fig. 15.** Displacement of the system (one active coil)

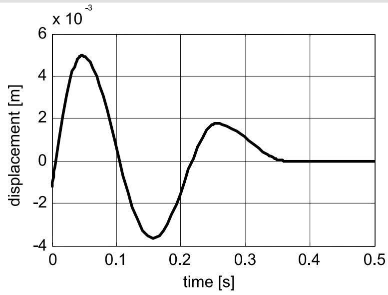


**Fig. 16.** Displacement of the system (two active coils)

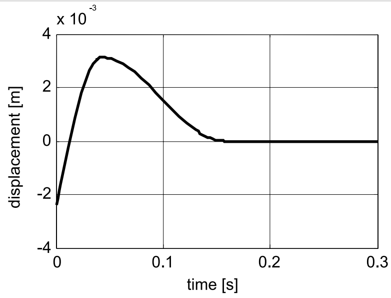


**Fig. 17.** Displacement of the system (four active coils)

Depending on the number of active coils the system comes to a stop after three cycles (Fig. 15), one and half cycle (Fig. 16) or half cycle (Fig. 17). Properties of damping can be identified by drawing the envelope of displacement. Envelopes are shown in Figures 18–19.

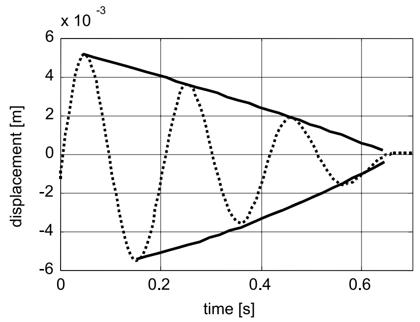


**Fig. 18.** Envelope of displacement (one active coil)

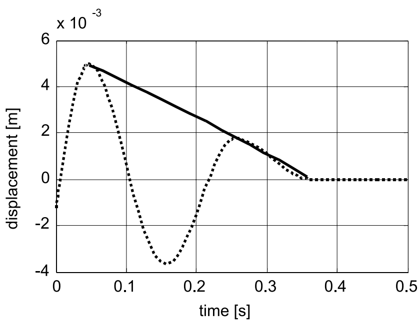


**Fig. 19.** Envelope of displacement (two active coils)

The equivalent damping coefficient as a function of amplitude can be determined by using envelopes (Figs 18–19). They are shown in Figure 20.

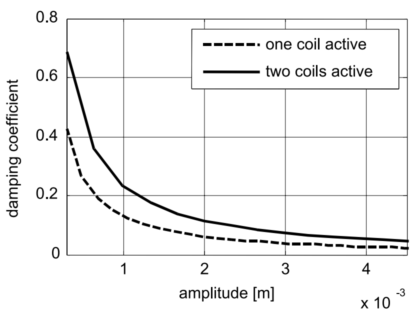


**Fig. 20.** Non-dimensional damping coefficient

As it was expected the damping coefficient increases for small amplitude. This feature is independent on the number of active coils. The damping coefficient increases in result of switching the larger number of coils.

## 4. CONCLUSIONS

In the paper the new construction of magnetic spring was considered. From results of calculations the following conclusion can be formulated:

- The force depends on sign of the current and the number of active coils. The switching of the current in one, two or four coils allows changing the force between 444 and 733 N. The largest force occurred when four coils were used.
- Comparing results of measure and calculation the relative error is small. The relative error for the distance between magnets from 11.5 to 16.5 mm is less than 2%, while for the distance equal to 4.7 mm the relative error is equal to 13%.
- Proposed magnetic spring can be applied in active vibroisolation systems. In such systems the magnetic spring can be controlled by simple switching system.

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