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Miniature ball contact sensor for completion of singular points of an energizing magnetic field

The article presents the results of research (obtained by use of a specially developed contact sensor) regarding the completion of singular points of the spatial magnetic field for selected systems of miniature relays controlled by coils and / or permanent magnets. The authors have shown that appropriate formation of the control magnetic field ensures a high degree of integration and miniaturization of the structure of electromagnetic contact systems.

1. INTRODUCTION

Technological progress and material achievements of recent times enable designers and engineers to develop new solutions of electromechanical devices structure with a high degree of miniaturization and integration. These devices include miniature connectors, different contact switches, both so-called "dry" as well as mercury wetted, and various types of valves(hydraulic, pneumatic) and/or electromagnetic attenuators**.** Such miniature components can be controlled manually or as a function of the displacement-actuators, the two- and/ or multi-positioned-switches (sensors), and electromagnetic relays operating both under mono- or multi–stable conditions. Currently this group of devices includes, for example, super-miniature reeds of a glass envelope length of 5-7mm manufactured traditionally [1,2] as well as switches based on the micromechanical device structure (so-called MEMS switches) in which the magnetic system volume does not exceed 2-3 mm^3 [3-5]. The group also includes reeds made of micro-machine technology whose dimensions are of 2x1.4x0.75mm [6]. The MAGNASPHERE company has developed miniature, hermetically sealed switching elements in a metal casing in which the core function and contact performance is executed by a ferromagnetic ball of 2-3 mm diameter [7].

For all these devices the control is accomplished either by means of coils (including electro-deposited) [3] or moving permanent magnets [6,7]. In the latter case, in order to enhance the sensitivity and reduce the size, one has to reduce the so-called "differential movement of the control element". This is basically achieved at the cost of the increase in the magnetic field gradient along the movement direction of the control element [1]. High field gradients occur most frequently in areas close to singular points where the field strength is equal to zero. Therefore the completion of the singular points is very important to properly design the device structure.

2. ANALYSIS OF SELECTED MAGNETIC SYSTEMS, EXPERIMENTAL TESTING AND DISCUSSION

The systems selected for the analysis were magnetic systems with permanent magnets energizing the miniature contact sensor in which both the core and the contact function were performed by a small ball made of a soft ferromagnetic material. Additionally, the ball can be wetted with mercury in order to improve the quality of contact performance under very small values of the contact force. For the purposes of the analysis very small dimensions of the soft magnetic ball (not pre-magnetized) were assumed. If the dimensions of the ball are small enough in comparison with these of the source of the magnetic field (electromagnet or permanent magnet), whereas, the ball is magnetized evenly (uniformly) by an outer magnetic field and will possess a high relative value of the magnetic permeability, then, in order to determine the value of force F_z (acting on it by the external field) along the z-direction, one can use the following formula [9]:

$$F_z = \frac{4\pi}{\mu_0} \cdot R_b^3 \cdot B \cdot \frac{\partial B}{\partial z} \qquad (1)$$

where:

u_0 – is a magnetic permeability of air
R_b – radius of the ball
B – module of a magnetic induction vector B in the reporting point under the absence of the ball.

The application of the above formula with the use of the calculation results of the magnetic field distribution due to the permanent magnet (using the method of the equivalent solenoid [9]) provides satisfactory results, from a practical point of view, both in the case of the induction B and the force F_z values. Figure 1 shows the comparison of the analysis and measurement results of the distribution of vector components B_x and B_z of the magnetic flux density along the x- and z-axis for the axially magnetized ring-shaped permanent magnet made of a 1BI material of the following dimensions: D = 11.5mm, d = 7.5mm, h = 4.4mm (for the selected point at y = 0 and z = 5.2mm). Whereas, Fig. 2 presents the distribution (along the z-axis) of calculated and measured values of the force F_z due to the magnetic field of the billet magnet (11.5 mm x 7mm x11.5mm, material 24BA210) on the steel ball. The curves 1 refer to a ball of radius R_b = 0.5mm (for the selected point at z = 5 mm and y = 0 mm), whereas the curves 2 – a ball of radius R_b = 1.6mm (at the point z = 6.1mm and y = 0 mm) respectively. The curves are indicated in relative values F_z / F_b (referred to the ball weight F_b) to demonstrate the resistance of the ball sensor to external mechanical vibrations.

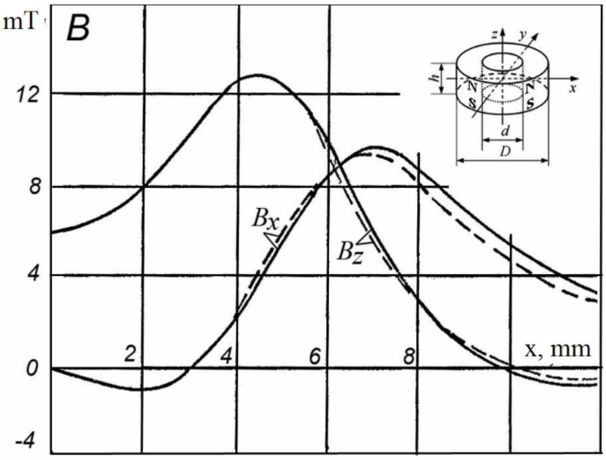

Fig. 1. Distribution of B_x and B_z components along the x-axis due to axially magnetized ring-shaped magnet (made of a material 1BI of dimensions :D = 11.5mm, d = 7.5mm, h = 4.4mm) for selected point at y = 0 and z= 5.2mm (solid lines – experimental data, dashed lines – calculations)

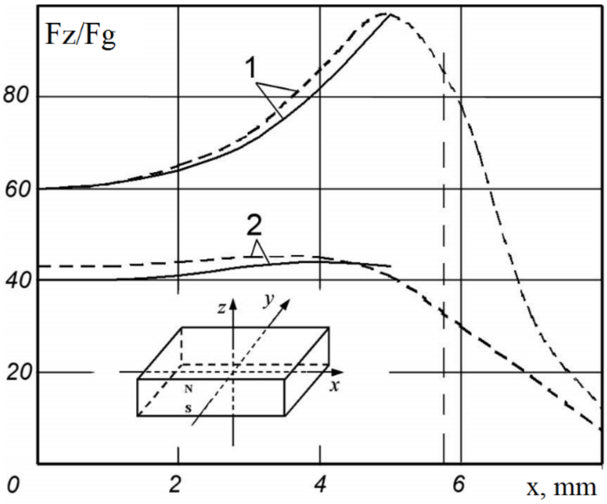

Fig. 2. Distribution of the force F_z value, acting on the steel ball due to the magnetic field of the billet magnet (material 24BA210, 11.5mm x 11.5mm x 7mm). Solid lines – experimental data, dashed lines – calculations, F_g – ball weight

The equation (1) shows that the electromagnetic force acting on the ball is directed toward the increasing induction module and is equal to zero at the points where the induction is zero or reaches its extremum. However, in those points where the maximum occurs the ball is in a stable state, whereas in places where it reaches the minimum (including zero-singular point) it is unstable (during the movement along the z axis). In order to increase the force F_z value, one has to increase either the module or gradient of the magnetic flux density. However, the increase in the induction value is limited due to saturation of flux conducting elements (generated by an energizing electromagnet) or is limited by restriction of magnetic energy of permanent magnets. High gradient, in turn, can be achieved by suitable design of the magnetic circuit structure. This circuit should ensure suitable distribution of the magnetic induction value along the trajectory of motion of the balls with alternately changing values of minima and maxima. It may, for example, be in the form of an annular axially magnetized permanent magnet (Fig. 3) [10]. The figure 3 features only the B_z component since for an axial symmetrical arrangement the component along the z axis is equal to the B vector. If the magnet (1) is fixed to move the magnetic ball contact (2) along the z axis, whereas the centre of ball (3) is located between the singular point A and one of the maxima of the induction module (points 0 and C), for example at point G, the electromagnetic force exerted to the ball is directed toward the point C. In this situation, the ball moves to the right and will close the respective contact (4). On the other hand, while moving the magnet (1) in such a way that a singular point is on the right side of the ball centre, one obtains a change of direction of the force – towards the point 0. In this case, the ball will move in a step way and will close the opposite contact.

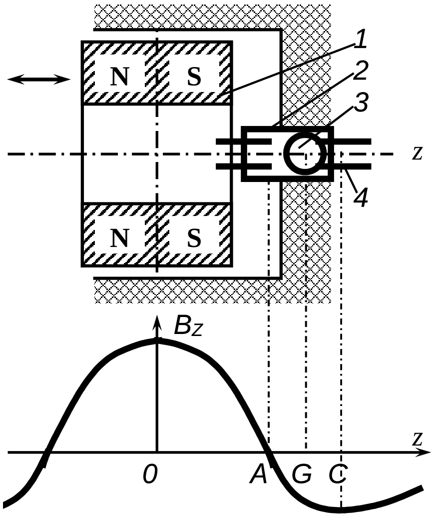

Fig. 3. Controlling the magnetic contact switch by means of a single ring-shaped permanent magnet magnetized axially

The application of the two ring-shaped permanent magnets (1) and (5), magnetized axially but opposite to each other (Fig. 4) [11], allows to increase the magnetic induction gradient in the area of the ball (3). This enables to accomplish a controllable switch with snap action without the necessity to use mechanical spring-return force, due to magnets repulsion interaction.

The required distribution of the magnetic induction value can also be obtained by means of planar permanent magnets. In a system made of two such magnets, (1) and (5) arranged as shown in Figure 5 [12], the distribution of the magnetic induction module with alternating maxima and minima occurs along the x axis. The displacement of the singular point from the A to A' position is done by moving a permanent magnet (1) along the x-axis (shown by dotted lines). Under the electromagnetic force that is directed to the point C (the maximum of induction module), the ball (3) moves to the left. During the operation of such a switch the interaction of permanent magnets (1) and (5) not only provides the snap action of the ball but also results in abrupt displacement of the moving magnet (1) and its placing in extreme positions.

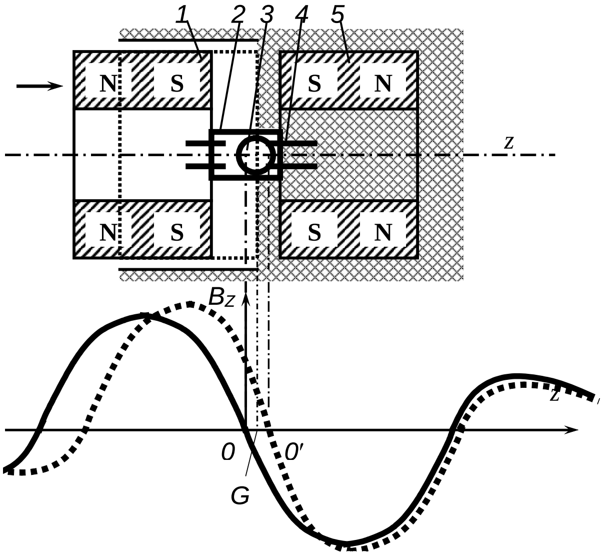

Fig. 4. Controlling the magnetic contact switch by means of two axially magnetized ring-shaped permanent magnets arranged coaxially but opposite to each other

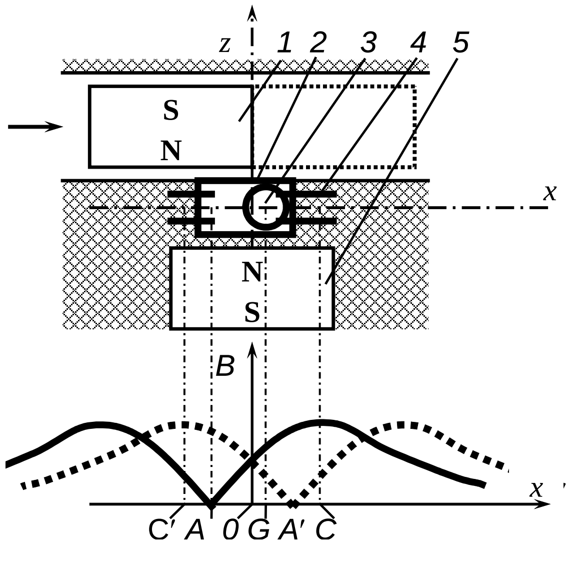

Fig. 5. Magnetic contact sensor controlled by means of two rod-shaped permanent magnets

Figure 6 shows the magnet system in which, through the use of original composition of permanent magnets, a very high gradient is induced in the area of the ball location, which significantly increases the value of the electromagnetic force [13]. The applied permanent magnets (1), (2), (6) and (7) are placed on two opposite sides of the ball contact, along the x axis. Here, each pair of magnetic poles is located opposite to each other and relative to the opposite pair. The pair of magnets (6) and (7) is immovable, and the pair of magnets (1) and (2) moves along the x-axis on either side of the transverse z axis. In the starting position the two pairs of magnets are arranged symmetrically with respect to the z axis. The minimum (zero) module of magnetic induction (singular point) occurs at the point 0. Therefore, the ball (4) cannot keep up at this point of unstable equilibrium and goes to one of the terminal positions, for example, to the right to the point C with the maximum induction closing at this contact (5). If we move a pair of magnets (1) - (2) to the right (dotted line in Fig. 6), the singular point (0') will shift right to the center of the ball (4) (point G). As a result, the electromagnetic force will be directed to the point C with the maximum induction. Therefore, the ball (4) moves to the left and changes over the contact.

After release, the moving pair of magnets (1) - (2) returns immediately to the symmetrical position (multi-function device of bistable operation). Please note, however, that the length of movement of the pair of magnets (1) - (2) should be less than the dimension of one magnet along the x-axis. Otherwise, automatic return to the starting magnets position will never occur.

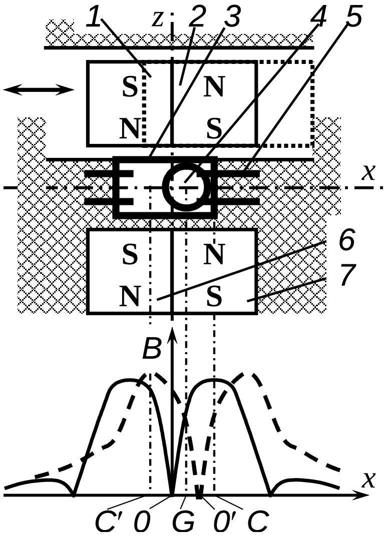

Fig. 6. Magnetic contact sensor controlled by means of four rod-shaped permanent magnets

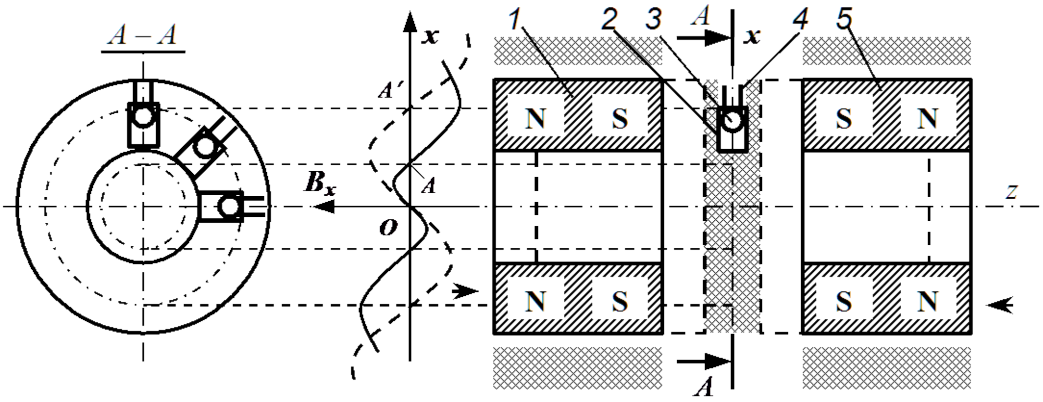

Fig. 7. Multicontacts switch controlled by means of two coaxial oppositely disposed ring-shaped permanent magnets magnetized axially

A multiple contact switch shown in Fig. 7 consists of two movable (along z-axis) ring-shaped permanent magnets (1) and (5) and a number of stationary reeds (2) laid out along the periphery [11]. In this case maxima and minima of the magnetic induction module appear after the each other along the x axis; while the x axis is any radial axis passing through the center of the gap between the magnets (1) and (5). The curves passing through points A-A' represent (in 3-dimensional space) the geometric location of the singular points. In the initial position of the magnets, the area corresponding to the singular point A is shifted from the ball (3) to the z-axis, whereas the electromagnetic force – in the opposite direction (towards the maximum value of induction). When approaching the magnets (dotted lines) the singular point and its periphery move towards the A' location and are situated on the other side of the ball centre. The electromagnetic force also changes direction thereby displacing the balls.

The utilization of the above discussed control principle of the contact ball sensor enables to design and to assembly any electromagnetic relay [14]. The source of the driving force in this case can be both flat and / or 3-dimensional coils. The required position and desired displacement of singular points is thus performed by proper selection of current values in the energizing windings.

3. CONCLUSIONS

Proper design and fabrication of any electromagnetic contact device with a high degree of integration requires both an appropriate value and space distribution of the driving magnetic field with suitable completion of singular points. Adequate positioning of the singular points can be achieved either by respective shaping of an energizing permanent magnet, selection of its dimensions and magnetic material parameters and/or by the arrangement of the magnets relative to each other, either by current waveform selection in the driving coil performed by any technique including this of an electron beam evaporation. The various modern structures of both miniature contact switches and electromechanical relays can be implemented by employing a miniature ball contact sensor and its control principle.

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