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CHANGE IN THE MAGNETIC SPRING DESIGN AND ITS INFLUENCE ON THE SPRING FORCE CHARACTERISTICS

The potential energy capabilities of magnetic springs have been estimated. The theoretical limit of the magnetostatic energy accumulated in the spring, which can be converted into mechanical energy, has been calculated. A comparative analysis of the force characteristics of two magnetic spring models – the basic model "two permanent magnets" and a magnetic spring with a magnetic core instead of an external permanent magnet) has been carried out. The prospects of using the magnetic spring design with a magnetic core have been shown.

Keywords: magnetic spring, theoretical limit of magnetostatic energy, force-displacement ratio.

1. Introduction

Permanent magnets and soft magnetic materials are widely used in almost all fields of science and technology. One of their main application sites includes magneto-mechanical devices, where they are used, in particular, as magnetic springs. It should be noted that magnetic springs that are based on permanent magnets differ very much from one another. As a result, the application of that or another magnet in the structural design of a magnetic spring is determined by technical requirements to the force characteristics of the magneto-mechanical device [1].

The use of springs with permanent magnets is quite promising and has a number of undeniable advantages over conventional mechanical springs. For example, magnetic springs are built into precision positioning actuators for passive gravity compensation, as well as precision vibration isolators to reduce dynamic stiffness [2].

Unlike ordinary mechanical springs, permanent magnet springs can be used at lower temperatures, at which spring steels already lose their mechanical properties, whereas the characteristics of magnetic springs remain unchanged and even slightly are improved, as the temperature decreases (for example, the retraction force increases a little).

By applying, in springs, magnetically hard materials based on the Sm-Co system, it is possible to significantly enhance the corrosion resistance of magnetic springs [3]. Such springs can operate for a very long time without changing their mechanical characteristics in aggressive environments, seawater, or various technological fluids in oil wells.

On the basis of a magnetic spring [4], we developed a magnetic return valve, which is successfully used as a component of standard mining equipment in the oil fields of Azerbaijan. The application of the spring on permanent magnets has solved the problems with the return valve on the ordinary mechanical spring that arose because of the service duration and the aggressive environment.

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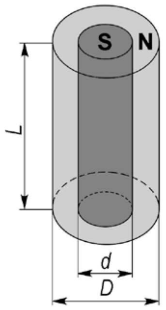

Fig. 1. Basic model of the magnetic spring "two permanent magnets". S and N are the magnet poles, D is the diameter of the ring magnet, d is the diameter of the inner magnet, and L is the length of both magnets

Another significant advantage of magnetic springs over mechanical ones is the variety of their forms and the possibility of adapting their power characteristics to specific applications. It is rather simple to increase the length of the spring travel. For example, two standard permanent magnets in the form of rings (with the same diameters but different heights) are stacked end-to-end, and the inner magnet also increases in length (it can be either combined or integral). It is possible to obtain a fairly large range of magnetic springs using standard rings produced by industry from permanent magnets (hard magnetic ferrites, and neodymium or samarium-cobalt magnets). In other words, magnetic springs can be assembled as a meccano, by adapting them to a specific application.

The designing of complex magnetic springs is carried out, as a rule, on an individual order by plotting the "force-displacement" curves.

To assess the potential of magnetic springs, we calculated the upper theoretical limit of the energy that can be stored in a magnetic spring. The theoretical evaluation of the hard magnetic material is carried out on the basis of its energy product (BH).

Earlier [4], we have already considered several promising models of magnetic springs. For example, Fig. 1 demonstrates the basic model of a magnetic spring "two permanent magnets". To reduce the demagnetizing factor for both permanent magnets in the initial state and, as a result, to use more potential energy of the permanent magnets, this design can be supplemented with two disk-like end magnetic conductors. In this version, the energy of the system is close to the energy $(BH)_{max}$ of a permanent magnet material with the same volume.

The aim of this work is to study and compare the power characteristics of the basic magnetic spring model ("two permanent magnets") and the magnetic spring model with a magnetic conductor instead of the external permanent magnet. The modification was made in order to reduce the cost of the magnetic spring and change the shape of its power characteristic. For this purpose, a number of model experiments were done, and a comparison of experimental data with theoretical assumptions and estimates will be performed.

2. Research Material and Technique

Two variants of magnetic springs are studied.

1. The basic model of the magnetic spring, "two permanent magnets", consisted of two permanent magnets made of the hard magnetic neodymium-iron-boron material (grade N40). The diameter of the outer magnet was 40 mm, and the diameter of the inner one was 25 mm; the lengths of both magnets were 40 mm. The displacement of permanent magnets with respect to each other coincided with the magnetization direction.

2. The modified version of the basic model consisted of a magnetic spring with the same inner permanent magnet. At the same time, the outer permanent magnet was replaced by a ring made of electrotechnical steel 10895 (GOST 3836-83). The shape and size of the ring were identical to those of the outer permanent magnet in the basic model of the magnetic spring.

The study of the force characteristics of two variants of magnetic springs was carried out on an experimental installation for mechanical tests (on the basis of the R-5 tearing machine). The displacement velocity of the spring core was equal to 1 mm/min.

3. Experimental Results and Their Discussion

When using a magnetic spring 40 mm in diameter and 40 mm in length, the volume of the magnetic material equals $V = 5 \times 10^{-5}$ m^3. The energy product of the hard magnetic material used in the basic model of the magnetic springs was $(BH)_{max} = 320$ kJ/m^3. Then the theoretically possible amount of the energy that can be stored in this volume equals $E = 16$ J.

For the N55 hard magnetic material with the current maximum $(BH)_{max} = 440$ kJ/m^3, we have

$E = 22$ J, i.e., the theoretical limit of the potential energy capabilities of hard magnetic materials in really used volumes (5×10^{-5} m^3) is about 20 J. Thus, in really good magnetic springs, we can store about 10 J of energy and fulfill the same amount of work. This is a rather large value for possible specific applications of magnetic springs.

Let us consider the replacement of the hard magnetic material with the soft magnetic one. The energy product of soft magnetic materials is three to four orders of magnitude lower (due to a low coercive force) than that of hard magnetic materials, which was illustrated in detail in work [5]. So, there is no point in trying to store energy in them. Nevertheless, they can be successfully used to enhance the efficiency of hard magnetic materials included in a magnetic system.

The latter statement can be explained as follows (see Fig. 2). To detach a permanent magnet with its pole lying on the ferromagnetic plane, the force F is required (Fig. 2, *a*). If the magnet is covered with a magnetic conductor made of a soft magnetic material, which makes it possible to use the second, partially engaged pole of the magnet at length (Fig. 2, *b*), then the pullat force F increases 3–5 times [5].

Thus, the application of magnetic conductor

• changes the demagnetization factor of the permanent magnet, i.e., the stored energy of the permanent magnet increases, because the second pole of the magnet begins to be used in full;

• allows the magnetic induction value to be transformed owing to the continuity of the magnetic induction flux.

In a lot of soft magnetic materials, the saturation induction exceeds a value of 2 T [5], whereas the residual induction of hard magnetic materials hardly reaches a value of 1.4 T. Since the pullat force is proportional to the squared induction, the pullat force becomes two times larger at once, if the magnetic conductor is applied.

From the cost viewpoint, soft magnetic materials are an order of magnitude cheaper than hard magnetic materials. For example, a kilogram of medium-sized neodymium magnets (100–200 g) costs about US $70, and the cost of electrical steel or armco-iron is US $6–8 per kilogram. Therefore, the use of soft magnetic materials in magnetic springs is fully justified. This makes the product cheaper and contributes to a more complete usage of the potential of hard magnetic materials.

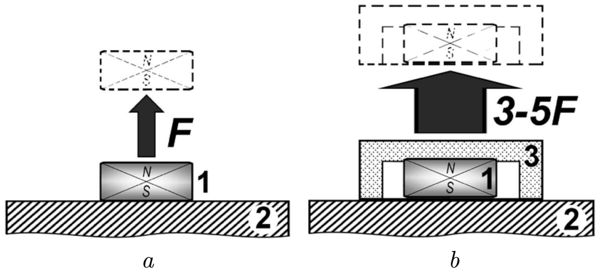

Fig. 2. Schematic diagram of using a magnetic conductor to shift the operating point of the permanent magnet along the demagnetization curve: the permanent magnet is on a ferromagnetic plane (*a*); the same permanent magnet is additionally covered with a magnetic conductor (*b*): permanent magnet (*1*), ferromagnetic plane (*2*), magnetic conductor (*3*)

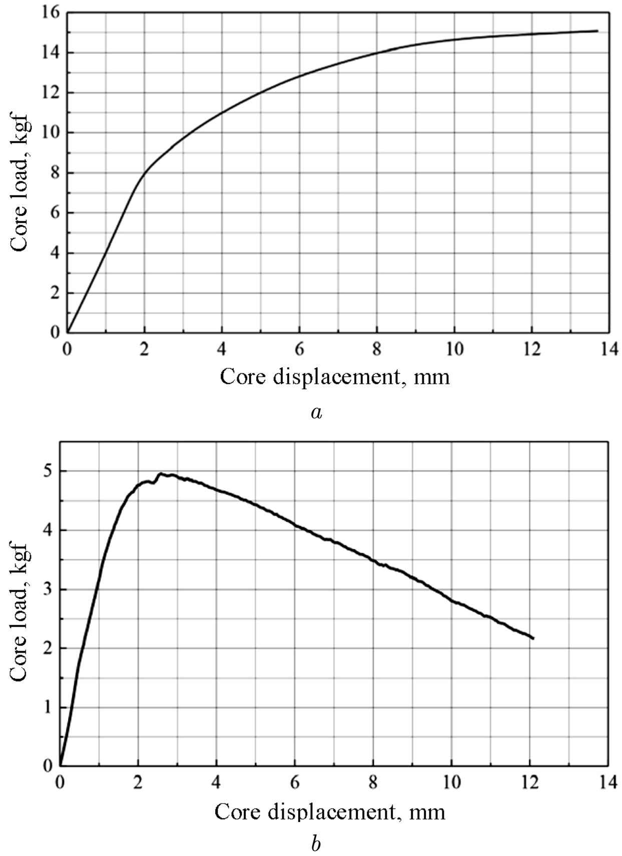

Fig. 3. Force characteristics of magnetic springs: basic model (*a*) and spring with the magnetic conductor instead of the outer permanent magnet (*b*)

The results of the study of the power characteristics of the basic model of the magnetic spring and the spring with a magnetic conductor instead of the outer permanent magnet are shown in Fig. 3. The power characteristics in the main part of the stroke are very different for two springs. In the basic model, the force increases smoothly and reaches a plateau. For the spring with the magnetic conductor, the force characteristic also increases at first and reaches a maximum; afterwards, the retraction force decreases.

The work fulfilled by both springs can be calculated as the area under the plot of force characteristic. The energy stored in the magnetic spring with the inner magnetic conductor equals 0.43 J, which is approximately three times lower than its counterpart in the basic spring model (1.25 J). This result experimentally confirms our theoretical assumption that it is impractical to store mechanical energy in soft magnetic materials.

At the same time, the magnetic spring with the outer magnetic conductor has its own advantages:

• for some applications, a sloping force characteristic may be necessary and useful (for example, for door closers to prevent a strong impact at closing);

• a spring with an outer magnetic conductor provides good screening (closure) of the magnetic field of the permanent inner magnet.

The Swiss brand MagSpring® fabricates similar magnetic springs with an outer magnetic conductor [6]. However, in that design, the poles of the permanent magnet slide along the magnetic core, which requires the precise alignment of the permanent magnet in the magnetic core cavity. Otherwise, the magnet will stick to the magnetic core, and the arising large friction force will prohibit the magnet from moving. The force of such a spring in the interval of force characteristic is constant, but it is two times less than that in our basic model of the same diameter. Moreover, due to the absence of end magnetic conductors, industrial magnetic springs cannot change the shape of force characteristic. Unlike the industrial magnetic spring, our spring with the outer ring magnet has no problem with the friction force. In our design, the latter is very small because the side surface of the permanent magnet is not attracted by the magnetic conductor (the poles of the magnet are at its ends).

4. Conclusions

The examined design of the magnetic spring, where the outer permanent magnet is replaced with a magnetic conductor, may be promising due to the special shape of its power characteristic. The obvious advantage of such a spring is the lower cost of the included materials. Furthermore, owing to the application of an outer magnetic ring, almost complete screening of the permanent magnet can be achieved, and the magnetic field is almost absent outside the structure. The design does not require precise alignment, because there is no unwanted frictional force between the moving parts of the magnetic spring.

1. M.A. Woodward, M. Sitti. Universal custom complex magnetic spring design methodology. *IEEE Trans. Magn.* **54**, 1 (2017).
2. R. Zhou, Zh. Huang, H. Chen, J. Wu, J. Che, X. Chen, W. Jiang. Inverse design method of magnetic springs with customized force–displacement relationship over a wide range. *IEEE Trans. Ind. Electron.* **71**, 9394 (2024).
3. V.Yu. Tsivilitsin, Yu.V. Milman, V.A. Goncharuk, I.B. Bondar. Magnetic spring based on two permanent magnets. *Dopov. Nats. Akad. Nauk Ukr.* **1**, 81 (2011) (in Russian).
4. V.Yu. Tsivilitsin. *Magnetic spring.* UA Patent 83233, Aug. 27, 2013, F16F6/00.
5. L.R. Moskowitz. *Permanent Magnet Design and Application Handbook* (Krieger Publishing Company, 1995) [ISBN-10: 0894647687].
6. *LinMot®. MagSpring.* https://linmot.com/products/magspring/.

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ВПЛИВ ЗМІНИ КОНСТРУКЦІЇ МАГНІТНОЇ ПРУЖИНИ НА ЇЇ СИЛОВІ ХАРАКТЕРИСТИКИ

Проведено оцінку потенційних енергетичних можливостей магнітних пружин. Розраховано теоретичну границю магнітостатичної енергії, накопиченої в пружині, яку можна перетворити на механічну. Проведено порівняльний аналіз силових характеристик двох моделей магнітних пружин (базової моделі магнітної пружини "два постійні магніти" та магнітної пружини з магнітопроводом замість зовнішнього постійного магніту). Показано перспективність використання конструкції магнітної пружини з магнітопроводом.

Ключові слова: магнітна пружина, теоретична границя магнітостатичної енергії, співвідношення сила–переміщення.