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A novel vibration actuator based on active magnetic spring

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ABSTRACT

The paper presents a theoretical study and experimental results regarding an original, low cost actuator, with a simple design, that uses an active magnetic spring in order to generate vibration. The analysis performed in the paper shows that the differential magnetic spring is the best solution for replacing the classical elastic suspensions in vibration generators. Mathematical modeling enables the determination of the parameters that characterize the actuator operation in the frequency domain. The experimental results show that the vibrator has, practically, a linear characteristic for oscillations of the order ±3 mm in amplitude and has a resonance frequency of approximately 36.5 Hz. The proposed model can generate dynamic forces of up to 15 N for an input sinusoidal current of 0.1 A (peak). The maximum force supported by the magnetic spring is 42 N.

1. Introduction

Magnetic springs began to develop after the appearance of high performance magnets based on Nd-Fe-B alloys, with the main advantage of having a high energy product (B·H). Two such repulsive magnets positioned face to face constitute the simplest "magnetic spring"; the terminology and technical device being already well-known in literature. LinMot (USA) manufactures passive magnetic springs (MagSpring) that generate a constant force over their entire working range, for many technical applications where mechanical springs are replaced. The mode of operation is based on the attractive force of permanent magnets. Magnetic springs have been studied and used in harvesting energy from vibration since 2008 [1–4]. Gas springs that use high-pressure gases can be replaced with magnetic springs [5]. A magnetic spring can also be used as a magnetic bearing, if one magnetic ring is fixed and the other one rotates, as described in [6]. A magnetic spring train and magnetic bearing kilowatt-hour meter are given as an example of application. A novel multipole array of passive magnetic springs, which has an application as a vibration isolation table, is presented in [7].

Many technical devices and systems are designed to work in passive and/or active mode, according to performance requirements. Devices such as passive/active dampers, suspensions and vibration isolators are known. For the magnetic spring, there is the concept "passive magnetic spring" and, rarely, "controlled magnetic spring", when an interaction between a current and magnet is applied to influence the magnet behavior. We will use in this paper the concept of active magnetic spring (AMS) and we will promote this new term, instead of controlled magnetic spring.

We found only two articles in literature, by the same first author, who studies an AMS with positive stiffness for use in vibratory technology. The author uses the terminology "controlled magnetic spring" in case of active vibroisolation system [8,9]. The parts of the controlled magnetic spring are: two pairs of magnets, magnetic core, four coils and a shaft. Current switching in one, two or four coils allow a force variation between 444 and 733 N. These papers do not give constructive details about the magnets and coils used (magnetic characteristics, size and number of turns of the coil, etc.). Moreover, Snamina's device uses a simple spring, consisting of two pairs of magnets with strong nonlinear operation, while in the present paper differential magnetic springs with a linear characteristic around the position of equilibrium are used, perfectly adaptable to applications of vibration technology.

There are no references in literature concerning actuators with active or passive magnetic springs for generating vibration. Currently, the most commonly used vibrator systems are those with mobile coil, voice-coil type [10–12], and, rarely, with mobile magnet [13] and with mobile magnetic core [14], all using classical elastic systems.

Due to the development of the neodymium magnets, for many applications the technologies based on activated magnetic suspension are of great interest. From the perspective of using systems of vibration, an actuator with magnetic springs removes the elastic elements, such as mechanical springs, subject to wear and fault because of the numerous and lengthy operating cycles. AMS's offer

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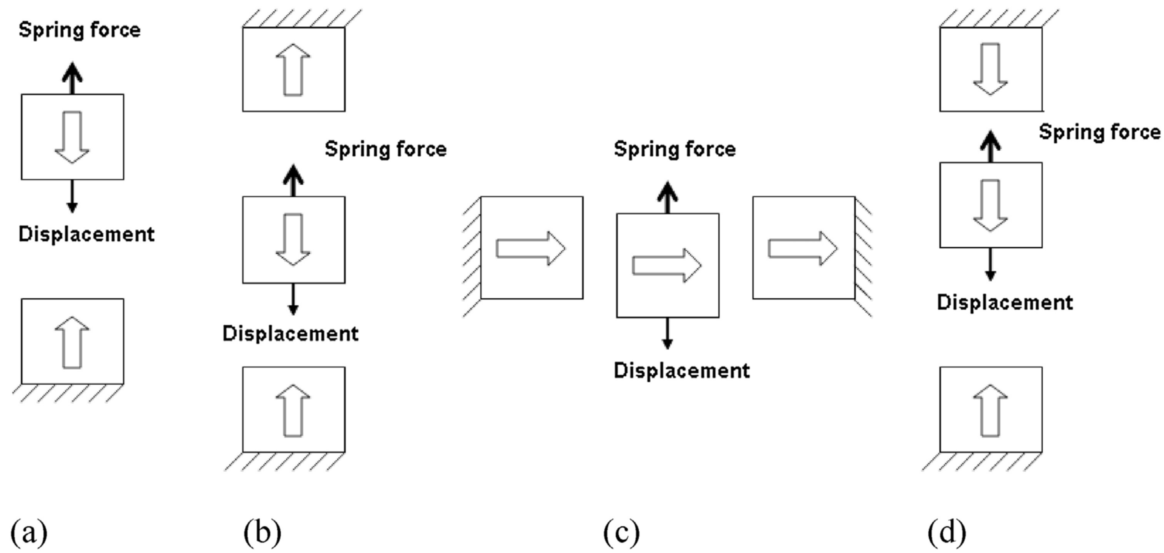

Fig. 1. Schematic of magnetic springs with: positive stiffness, in vertical arrangement with two repulsive magnets (a), in vertical arrangement with three repulsive magnets (b), in horizontal arrangement with attractive magnets (c), and quasi-zero stiffness with repulsive and attractive magnets (d).

possibilities to control the stiffness coefficient and the force and frequency characteristics of the system. Such systems based on the AMS vibratory technology become more efficient and more easily controllable.

In the following, a demonstration model of vibration actuator based on active magnetic springs is developed. Although the model can be used both for generation and damping of vibrations, in this paper only the vibration generator is studied.

2. Magnetic spring analysis

2.1. Configurations of magnetic springs

Fig. 1 illustrates four of the most common arrangements of magnetic springs with positive stiffness (Fig. 1(a)–(c)) and with quasi-zero stiffness, Fig. 1(d), respectively.

The magnetic spring in Fig. 1(b) consists of two simple magnetic springs of the type represented in Fig. 1(a), differentially coupled. The first three configurations are passive magnetic springs, while the last one represents an active magnetic spring with quasi-zero stiffness, QZS, Fig. 1(d). The last configuration consists of an arrangement of three magnets, one mobile and two fixed, the mobile magnet being repelled by the lower magnet and attracted by the upper magnet [15]. This arrangement is equivalent to two magnetic springs, one with positive stiffness and the other, upper one, with controlled negative stiffness, so that zero-siffness can be obtained for the entire magneto-elastic arrangement. The drawback is that a pair of attractive magnets is much more difficult to control than a pair of repulsive magnets. In general, a QZS vibration isolation system is designed as a fully passive system such as those demonstrated in [16–21].

2.2. Passive magnetic spring (PMS)

A simple magnetic spring, as is presented in Fig. 1(a), can be obtained using two magnets, NdFeB discs with a remanence Br = 1.3 T, a diameter of 15 mm and 8 mm in height. The characteristic repelling force vs. displacement z of the moving magnet, $F(z)$, obtained through a numerical simulation in COMSOL Multiphysics, Fig. 2, indicates a high nonlinearity.

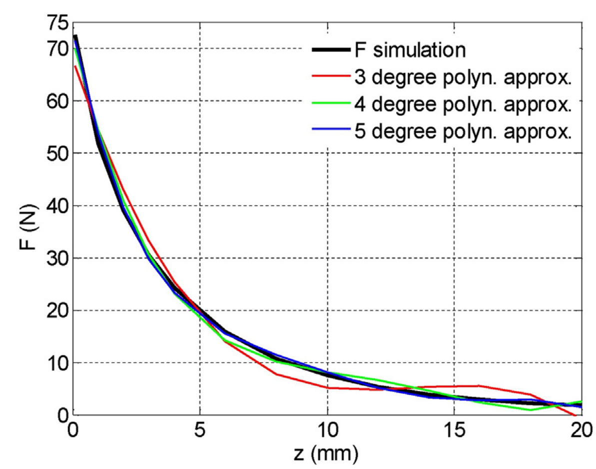

Fig. 2. The force-displacement curve and its polynomial approximations for the simple magnetic spring.

The characteristic $F(z)$ may be approximated as a polynomial function having the general form:

$$F(z) = \sum_{n=0}^{m} \alpha_n z^n \tag{1}$$

Relations (2)–(5) give the polynomial approximation for $F(z)$ when m = 3, 4 and 5, respectively.

$$F_3(z) = -0.0265z^3 + 1.08z^2 - 14.45z + 68.2 \tag{2}$$

$$F_4(z) = 0.0025z^4 - 0.128z^3 + 2.364z^2 - 19.75z + 71.865 \tag{3}$$

$$F_5(z) = -0.0003z^5 - 0.0157z^4 - 0.36z^3 + 4.04z^2 - 24.0545z + 73.78 \tag{4}$$

The plots obtained using these approximations are also represented in Fig. 2. As may be seen the most accurate approximation is obtained for n = 5, but the fourth order approximation may be also considered satisfactory.

In the case of two magnetic springs with differential coupling, Fig. 1(b), the total restoring force is given by the sum of the repulsive