CURRENT RESEARCH ON THE VARIABLE STIFFNESS MAGNETIC SPRINGS

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This paper provides a synthesis of research on magnetic springs with variable stiffness that can be the basis for obtaining configurations of electromechanical systems whose operation requires fixed or real-time adjustable pre-established elastic forces, such as vibration damping or humanoid and medical recovery robots. The study and systematization of the research known up to this point highlights the basic concepts and specific characteristics for the two main categories of magnetic springs with variable stiffness, namely, passive magnetic springs with a predetermined stiffness at a desired value (ASMSs) and active magnetic springs with real-time adjustable stiffness (CSEMSs). The study highlights that CSEMSs that generate variable stiffness in a very wide range, from –9800 N/m to +9800 N/m, can be obtained, which makes them very useful in the design and construction of systems for controlling fast processes, such as vibration isolation systems with quasi-zero-stiffness (QZS).

1. INTRODUCTION

The emergence of high-performance permanent magnets based on NdFeB alloys has led to a significant increase in the performance of PM-based technical systems, such as high-power synchronous electric machines [1,2] and high-force actuators [3]. The magnetic spring, which is a magnetic actuator that generates a magnetic force or torque, represents a highly efficient substitute for a mechanical spring. Magnetic springs based on Nd-Fe-B magnets use interactions between permanent magnets (PMs) and can substitute conventional metallic springs in many technical applications, *e.g.*, energy harvesters from vibration [4-7], vibration damping and isolation [8-12], vibration and oscillatory actuators [13-16], robotic joints and grippers [17-20]. In all these applications, the magnetic springs can limit or even eliminate some of the shortcomings of metallic springs regarding friction, compactness, material fatigue, and failure.

The principles of elastic actuation were introduced by Alexander et al. [21]. Pratt and Williamson [22] developed an actuator that included a series elastic element that gives the actuator a compliant nature, being considered the first to introduce the term compliant actuators for this new category of actuation devices [23]. In the following years, numerous studies on such elastic actuators appeared, whether series elastic actuators (SEAs) [24] or parallel elastic actuators (PEAs) [25].

Elastic actuators have been consistently proven to improve actuator performance in service robotics. These systems rely on high torque and force density of mechanical springs to reduce peak power requirements and improve the actuator's energy efficiency. For example, in the work by Mettin et al. [26], energy consumption is reduced by 55%.

All these benefits have led in recent years to the intensification and expansion of research on the magnetic springs to obtain new and high-performance technical systems with controllable dynamics. An example is quasi-zero stiffness systems (QZS). In Fig. 1, the three main mechanisms for obtaining passive and active magnetic springs with negative rigidity are presented as various negative stiffness mechanisms to achieve quasi-zero stiffness characteristics systems (QZS) [27-29]. It should be noted that the same schemes with the reversal of the magnetic polarity of the central mobile magnets are used to obtain positive stiffness in most technical applications based on passive magnetic springs.

In what follows, the basic concepts used in *ASMSs* and *CSEMSs* are described and analyzed with reference to their applications and performances.
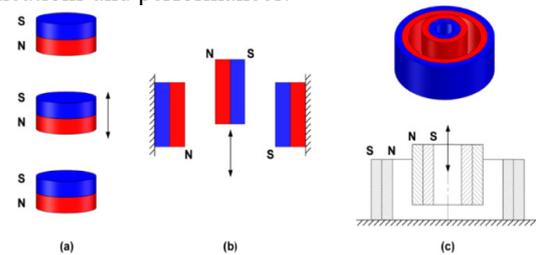

Fig. 1 – Schematic diagram of various negative-stiffness magnetic springs. (a) Attractive configuration; (b) Repulsive configuration; (c) Parallel configuration [27].

2. CONCEPTS OF VARIABLE STIFFNESS SPRINGS

To increase the elastic forces and the possibilities of adjusting the forces and stiffness of magnetic springs to expand their applicability, coils with electric currents are used, in which case we speak of active or electromagnetic magnetic springs. Both passive and active magnetic springs can provide stiffness variation either by pre-establishing stiffness before operation, which is kept constant, or by controlled variation of the stiffness during operation. The magnetic springs with variable stiffness can be classified into two categories:

a. *Adjustable-stiffness magnetic springs* (ASMSs) are passive magnetic springs that allow stiffness changes by modifying some structural configuration parameters and/or magnetic field, without being able to intervene during their operation.

b. *Controllable stiffness electromagnetic springs* (CSEMS) are active magnetic springs or electromagnetic springs that allow continuous and real-time control of forces and stiffness through the magnetic fields generated by coils traversed by command currents.

2.1. ADJUSTABLE STIFFNESS MAGNETIC SPRINGS (ASMS)

It is the category of variable stiffness magnetic springs that is best developed in the internationally visible scientific literature, if we consider the number of scientific papers elaborated.

The first magnetic spring with adjustable stiffness was proposed by Hyun et al. in 2007 [17]. This *ASMS,* like others proposed later, is a torsion magnetic spring that can adjust the stiffness by axially displacing the magnetic rotor and locking the axial position in place. Figure 2(a) shows

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the conceptual basis in realizing *ASMS* with torsion torque, and Fig. 2(b) illustrates the torque characteristics. Figure 2(c) shows the design layout, selected five design variables (inner and outer stator width, rotor width, height, and angle for angular direction magnetization), and the magnetization direction of the PM-type ASMS using the Halbach array with three magnetic rings. The stiffness of ASMSs can be varied by moving the rotor in the axial direction to change the cross-section between the rotor and the stator by an additional mechanism.
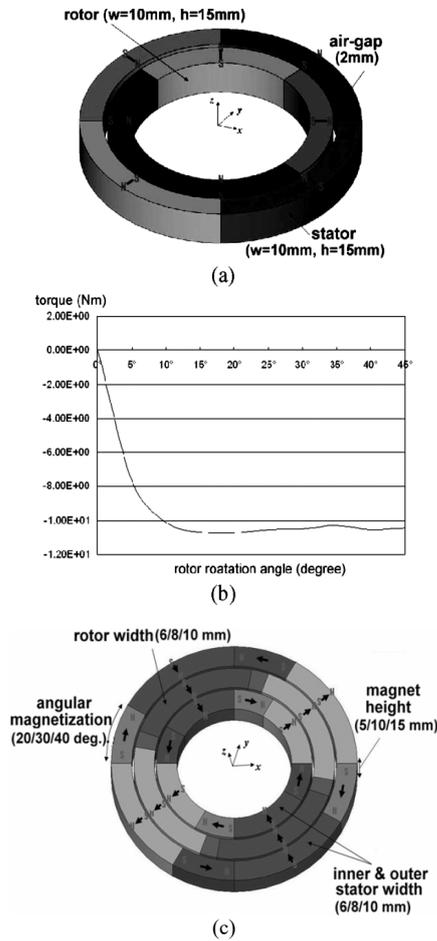

(a)

(b)

(c)

Fig. 2 – Layout of ASMSs. (a) 2-rings PM-type. (b) Torque characteristics. (c) 3-Rings PM-type [17].

Junho Choi et al. used a torsion magnetic spring with adjustable stiffness to design a robot joint with variable stiffness [18]. The *ASMS* has two concentric rings with different radii sharing a common rotational axis. Each ring is composed of four arc-shaped magnets and four arc-shaped spacers. Each magnet is magnetized in the radial direction. The spacers are not magnetized. The magnets are arranged so that the direction of magnetization alternates, see Fig. 3. Two concentric magnetic rings are composed of magnets. Two adjacent magnets are magnetized in the opposite direction (radial magnetization). Gray parts between the magnets are spacers, which are not magnetized. Δq is the displacement from the neutral position. τ is the torque generated by the magnets. The inner ring is the rotor, and the outer ring is the stator. The magnetic spring is in neutral position when each magnet of the rotor faces a magnet with the opposite pole of the stator. When an external torque is applied, the rotor rotates away from the neutral position. The stiffness is changed by a displacement in the axial direction
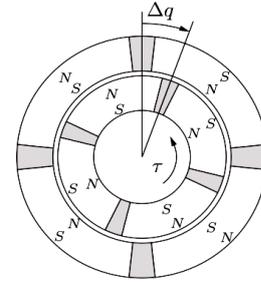

Fig. 3 – Torsion ASMS principle for designing a robot joint with variable stiffness [18].

In recent years, new types of *ASMS* were studied that have the ability for the stiffness to be adjusted via the rotation of a central magnet of an axially stroke magnetic springs [7, 30], or by axially translating the magnetic outer rotor of a torsion magnetic spring [31].

A new concept of axial magnetic spring with an adjustable stiffness capability is illustrated in Fig. 4, being adapted to investigate an ASMS that could enable an ocean generator to continuously operate [7]. The configuration of the adjustable magnetic spring having a linear stroke consists of four Nd-Fe permanent magnets. The two rectangular cubical side magnets are mechanically allowed to move only translationally along the *z*-axis, and they are magnetized in opposite directions along the *z*-axis as shown. The two cylindrical tube magnets are magnetized diametrically and allowed to rotate only around the *z*-axis. The force relationship for the 100mm stroke length is shown in Fig 5, θ_k is the rotor angle position.
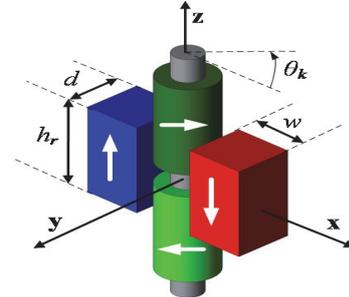

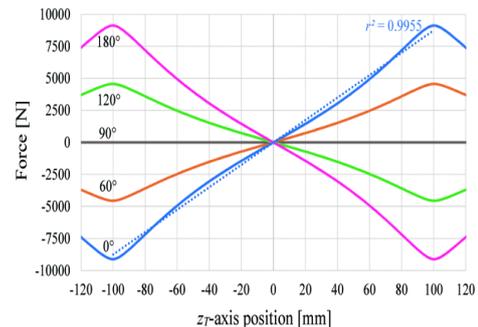Fig. 4 – Perspective view of the adjustable axial magnetic spring [7].

Fig. 5 – Force as a function of stroke length and angular position, θ_k, for a maximum stroke length of $z_m = 100$ mm. [7].

From the above it follows that the most promising technical solutions proposed and researched for magnetic springs with adjustable stiffness are based on the use of a fixed magnetic structure (stator) and a movable one (rotor) consisting of arc-shaped magnets with radial magnetization that generate rotational elastic torques or of rectangular magnets (stator) and cylindrical or rectangular magnets (rotor) that generate linear elastic forces. The stiffness

adjustment can be done by means of a servomotor to actuate the rotor of the device, but the system of which the magnetic arc is part has high relative time constants, which prevents real time adjustment, so that only applications with limited control of the process dynamics, such as some robotic manipulations, can be addressed.

2.2. CONTROLLABLE STIFFNESS ELECTROMAGNETIC SPRINGS (CSEMS)

Under the constructive-functional aspect, two categories of CSEMSs can be highlighted, having the basic configurations, coil+permanent magnet and coil+ permanent magnet+ magnetic core, respectively.

2.2.1. COIL-PERMANENT MAGNET CSEMS

CSEMSs using coil-permanent magnet combinations allow real-time control of forces and stiffness by varying the coil current magnitude and polarity. And here, much research has been carried out by integrating such electromagnetic springs into specific applications, such as the nonlinear vibration isolation systems with quasi-zero-stiffness (QZS). A first example of such an isolator is the "three-spring" configuration proposed by Yuan et al. [28], which can realize the negative stiffness and high-static-zero-stiffness by combining a linear electromagnetic spring (LES) in parallel with a conventional linear isolation system, as shown in Fig. 6.
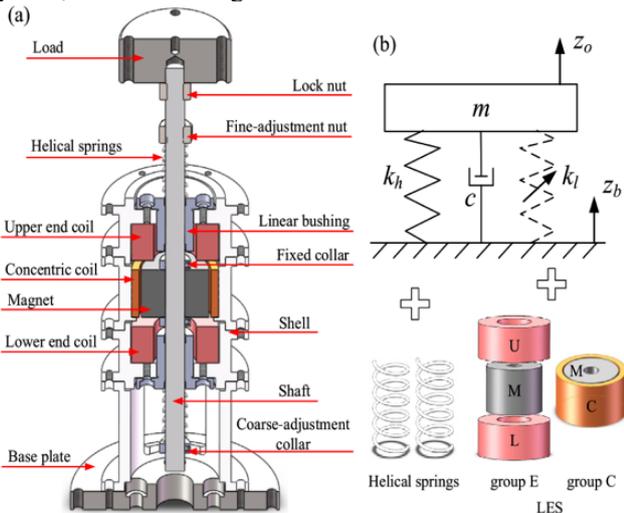

Fig. 6 – Concept of the QZS isolator using *CSEMS*: (a) structure of the isolator with the LES in the equilibrium position, (b) equivalent model of the isolator [28].
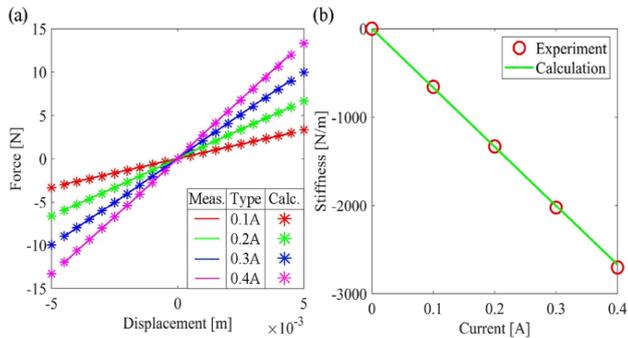

Fig. 7 – Linearity analysis of the designed LES: (a) generated electromagnetic force vs. displacement. (b) axial stiffness vs. current [28].

The electromagnetic spring contains three toroidal coils arranged coaxially with a ring magnet. By controlling the

current in the coils, the electromagnetic spring could generate a linear negative stiffness that balances the positive stiffness of the conventional system, thereby achieving a quasi-zero stiffness over the long stroke.

Figure 7 shows the force and stiffness characteristics of the designed LES. The LES has a linearity of 1% over the whole stroke (±5 mm) and can be tuned online in a very wide domain of $±2400 Nm^{-1}$.

A novel compact multi-layer electromagnetic spring (MES) with tunable negative stiffness for semi-active vibration isolation is proposed by Huayan Pu et al. [32]. The MES comprises multiple identical layers axially stacked, with each layer containing a permanent magnet ring and a coaxially arranged annular coil. To obtain negative stiffness characteristics near the equilibrium point, the direction of the control current in each coil is determined from the magnetization direction of the magnet in the same layer. Figure 8 shows the MES unit in two configurations for negative stiffness. The clockwise current direction and the upward magnetization direction are considered positive. Thus, a unit with an upward magnetizing magnet can be represented by P, and that with a downward magnetizing magnet by N. By properly controlling the current in each coil, the force acting on the magnets is zero at the equilibrium point where the magnets coincide with the coils (the displacement *D* of the magnets relative to the coils is zero). Moreover, the direction of the electromagnetic force is the same as that of the relative displacement within a small region around the equilibrium point. This implies that a negative stiffness spring acts on the moving magnet.

By combining multiple layers of MES units of type MES-P and MES–N, see Fig. 9, multiple MES configurations for the negative stiffness generation can be obtained, which provides great flexibility and efficiency in the design of QZS isolators and compliant systems that require stiffness control. Figure 10 shows the variation of the elastic electromagnetic forces with the displacement of the MES unit, for 4 values of the control current. For a control current varied from -1.2 A to 1.2 A, the proposed 6-layer MES can generate a variable stiffness ranging from –9800 N/m to +9800 N/m.
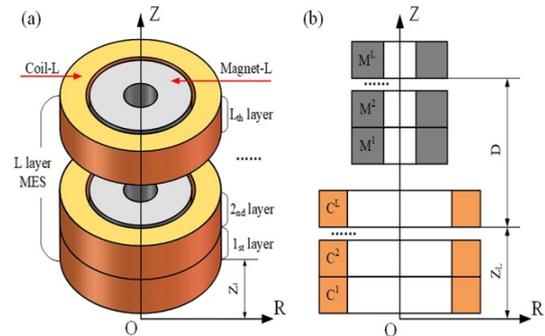

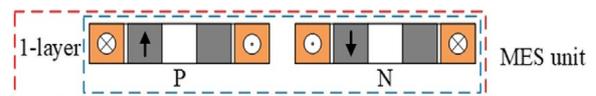Fig. 8 – Concept of the MES: (a) MES at the equilibrium point; (b) MES with a displacement of *D* [32].

Fig. 9 – Two MES unit configurations for negative stiffness generation [32].
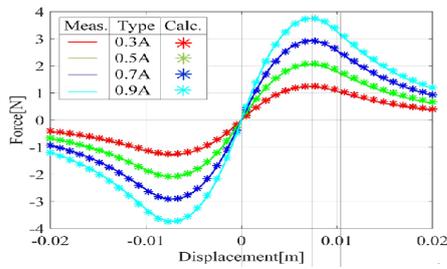
Fig. 10 - Calculated and measured electromagnetic forces of the MES unit [32].

2.2.2. COIL-PERMANENT MAGNET-MAGNETIC CORE ELECTROMAGNETIC SPRINGS

Until now, very few papers from the scientific literature have addressed research on CSEMSs, considered separately or incorporated/integrated in applications of technical systems. We could thus mention only three articles in chronological order of appearance [9, 33, 35].

The simplest example of CSEMS is the one proposed in [33], Fig. 11. The electromagnetic spring mainly includes an electromagnet and two repulsively arranged magnets. Fig. 12 illustrates the variations in the electromagnetic spring force with the air gap size for 4 values of the coil supply voltage. It is found that with increasing voltage, both the electromagnetic spring force and the slope of the force curves increase. However, it is clearly observed that the range of variation of the elastic properties of the proposed electromagnetic spring is very low.
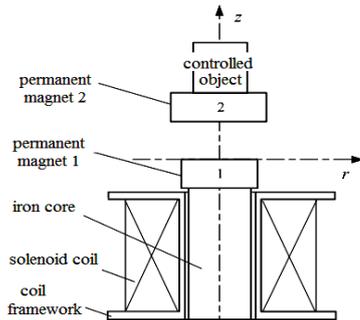

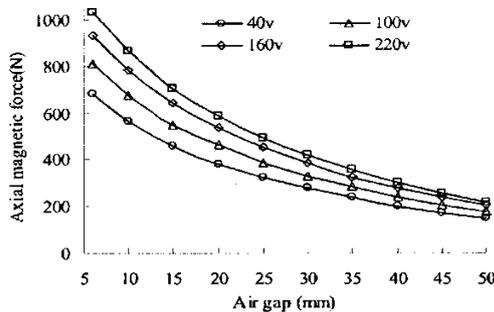Fig. 11 – Structural diagram of the electromagnetic spring [33].

Fig. 12 – Force curves as a function of air gap for 4 values of coil supply voltage: 40, 100, 160, and 220 V [33].

A controlled electromagnetic spring that can be applied in a vibration reduction system for a machine operator's seat is proposed by Snamina et. al. [16]. The electromagnetic spring is mainly composed of magnets, magnetic cores, coils, and a shaft, Fig. 15(a). Two mobile Ne-Fe-B magnets (1) are fixed at the end of a shaft (7), and two other magnets (2) are fixed to the lower magnetic core (5). The magnetic circuit consists of 4 magnetic cores on the sides (3), an

upper magnetic core (4), and a lower magnetic core (5). 4 coils (6) are installed on the four lateral magnetic cores (3). The linear movement of the shaft is achieved by a linear bushing (8). The proper position of all elements is ensured by an upper (9) and a lower (10) cover. The currents through the coils (6) have an influence on the magnetic field in the space between the magnets (1, 2) and at the same time on the magnetic arc force. It should be noted that the magnetic cores and coils are in orthogonal sections.

The relationship between the force and the displacement of the moving part of the spring for different sequences of switching the current supply to the coils is shown in Fig. 15(b). In Fig. 15(b), the origin of the axes has been placed at the end position of the axis when the distance between the magnets is at maximum. The force curves in the figure can be modified between certain limits by passing a current of 7A through one, two or four coils in one direction, which leads to an increase in the magnetic force and in the other direction, which leads to a decrease in the force, in relation to the situation of the passive magnetic spring, coils not covered by current.
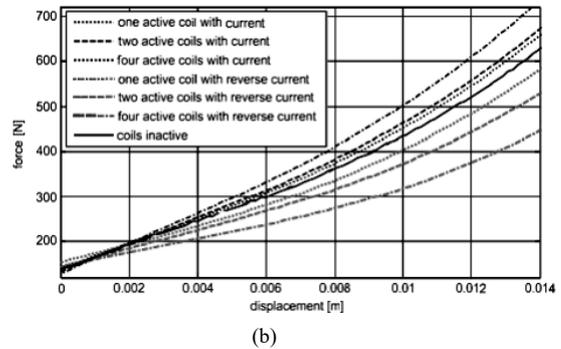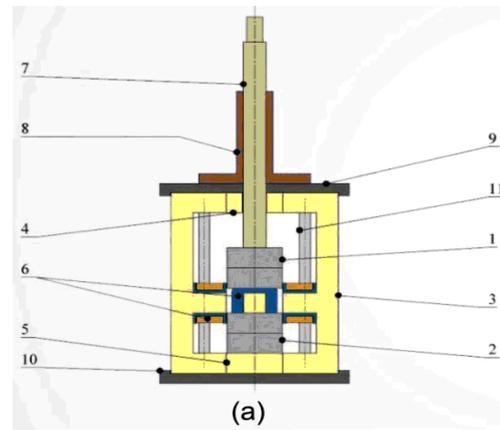

Fig. 13 – Electromagnetic spring, (a) description, (b) displacement/force characteristic [9].

Olaru et al described the concept [34], and in [35], a theoretical and experimental study of an innovative electromagnetic spring (CSEMS) was presented, whose force and elasticity change depending on the value and direction of the electric current passing through coils. The experimental prototype is composed by two magnets in repulsive disposition, two coils and a particular magnetic structure, see Fig. 14. The variation of the force with displacement when compressing the electromagnetic spring, for three values of the electric current, I=0, -2A and +2A, respectively, is illustrated in Fig. 15. For the variation of the current between -2A and +2A the variation of stiffness generated by the prototype was 3600 N/m, for a compression position of the

spring at a distance z=8mm between the two components with magnets, mobile and fixed.

The main advantage of the proposed CSEMS is the ability to vary the stiffness and force of the magnetic spring in the simplest, most direct way, which ensures high speed and dynamic control of CSEMS-based systems. Figure 16 exemplifies the principles of using CSEMSs in variable stiffness actuators (VSA), and Fig. 17 shows the force vs. compression curves for two antagonistic CSEMSs with the spring preload at 8 mm for the VSA configuration in Fig. 16 [35].
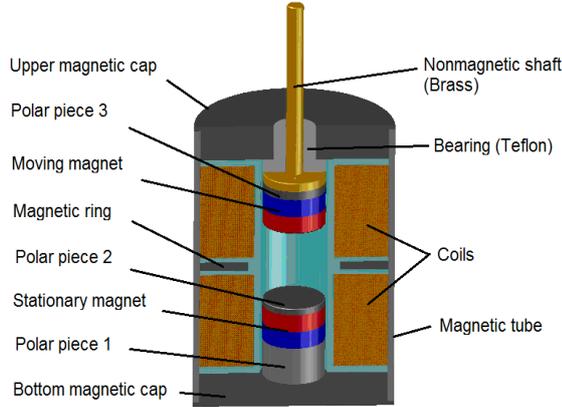

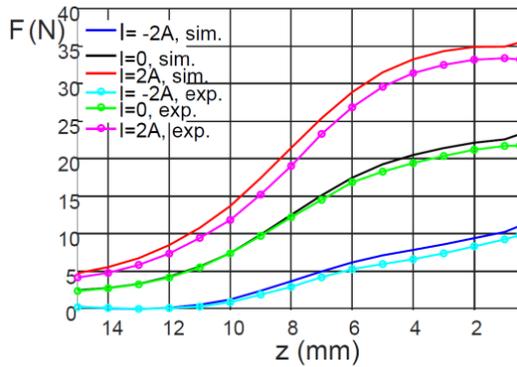Fig. 14 – CSEMS prototype with preload force [35].

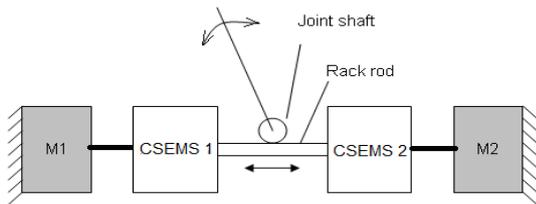Fig. 15 – Force vs. compression curves for CSEMS prototype [35].

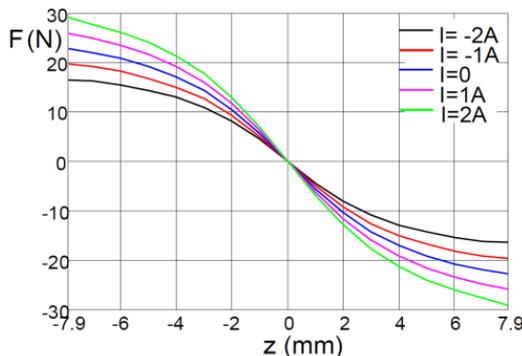Fig. 16 – Two antagonistic motors with two antagonistic CSEMSs arranged in line [35].

Fig. 17 – Force vs. compression curves for two antagonistic CSEMSs with spring preload at 8 mm [35].

It is found from the above that the most efficient *CSEMSs* studied so far, in terms of speed and capacity to control forces and stiffness, are those designed in the coil-permanent magnet configuration and usable in QFS, which can ensure the variation of negative and positive stiffness within very large limits, up to ±9800 N/m. Their disadvantage is that conditions must be ensured to avoid the use of ferromagnetic materials in their vicinity that influence the distribution of magnetic fields that affect the variation mode and values of elastic forces and stiffness. In this regard, *CSEMSs* in coil-permanent magnet-magnetic core configuration due to the fact that they are provided with magnetic circuits that counteract the magnetic flux in the air gap to generate electrically controlled variable magnetic forces and stiffness, have a much narrower control range, maximum 3600N/m of positive stiffness, as reported by the only work that provides such a result for a Coil-permanent magnet-magnetic core configuration [35]. These controllable electromagnetic spring configurations have the advantages of giving the highest controllable elastic forces. They can be designed to function integrated into systems or as an individual product/component, which can be added to a system, being functionally provided with magnetic circuits that implicitly ensure magnetic compatibility, without influencing the external environment and not being influenced by it in terms of magnetic fields.

3. CONCLUSIONS

Magnetic springs with variable stiffness are becoming a real alternative to traditional mechanical springs in devices and systems that use elastic actuation, offering new opportunities for developing high-performance technical systems that can be preset-adjusted or controlled in real time, such as robots, damping systems, and suspension systems. Scientific research into the design and application of ASMSs, especially CSEMSs*,* in the previously mentioned fields and beyond has continued to evolve in recent years. Most of the concepts of variable stiffness magnetic springs have been described and analyzed based on research into the use of these devices in specific applications proposed by the authors, in which magnetic springs have an essential functional role. Of the two categories of magnetic springs with variable stiffness, the passive *ASMSs* and the active *CSEMSs*, respectively, the first and most studied to date are *ASMSs*. The greatest potential for future development, however, is with active electromagnetic springs, *CSEMSs*, which can successfully face the technological challenges of the future to obtain increasingly better performing systems in terms of speed, precision, and economic efficiency.

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