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## LINEAR OSCILLATING DRIVES WITH ELECTROMAGNETIC VIBRATORY ACTUATORS USING MAGNETIC SPRINGS

BY

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**Abstract.** Linear electromagnetic vibratory actuators are commonly used for to drive oscillating or reciprocating systems, such as vibratory conveying and compressors. In this paper is investigated the use of two original electromagnetic actuators, provided with magneto-elastic suspension for the mobile assembly, in low power oscillatory systems, referencing linear pumps, vibratory conveyers and the control of valves to thermal motors. Magnetic spring-assisted actuators allow the energy consumption of a system to be reduced and the system's reliability increases.

**Key words:** oscillating drive; electromagnetic vibratory actuators; magnetic spring.

### 1. Introduction

Oscillating drives with linear electromagnetic vibratory actuators are used in many industrial applications, such as: vibratory feeders (Misljen *et al.*, 2016; Despotović *et al.*, 2013; Ribic *et al.*, 2010), linear pumps (Lee. *et al.*, 2010; Jiao *et al.*, 2016), and compressors (Poltschak *et al.*, 2016; Abdalla *et al.*, 2013). A linear electromagnetic vibratory actuator (LEVA) is usually represented as an electromagnetic actuator that can achieve short-stroke

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reciprocating movement directly without auxiliary transmission mechanism. Conventional mechanic springs impose some limitations on the system regarding mainly compactness, friction, material fatigue and failure (Poltschak *et al.*, 2016). Magnetic springs, based on repulsive or attractive permanent magnets, show the potential to overcome these issues especially for medium-long strokes and frequent operation.

Two models of linear electromagnetic vibratory actuator (LEVA), one based on active magnetic spring and the other with passive magnetic spring, for oscillating (reciprocating) drive systems of low power are described and proposed in the following. Examples of how to implement them in linear pumps with diaphragm or plunger and an electromechanical valve for a piston air compressor are discussed and analysed.

## 2. LEVA with Magnetic Springs

### 2.1. LEVA 1 Based on Active Magnetic Spring

LEVA 1 is exclusively based on a magnetoelastic system electrically activated to generate sinusoidal vibration movement, Fig. 1 (Olaru *et al.*, 2017). The actuator has a movable part consisting of a ring magnet with axial magnetization rigidly fixed on a non-magnetic shaft (brass).

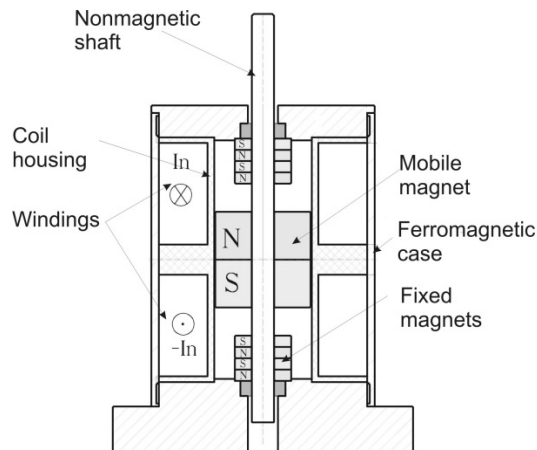


Fig. 1– Cross section of structural design of LEVA 1.

The stationary part contains two groups of magnets disposed repulsively relative to the mobile magnet, a coil with two windings fed in phase opposition and a ferromagnetic case which in this case fulfills a triple role: mechanical protection, magnetic circuit closure and magnetic shield. The magnets assembly can be assimilated to a differentially magnetic spring constituted from two simple magnetic springs, which is electrically activated

when a current passes through coils. The electromagnetic force exerted on the mobile magnet is Laplace type and is described by the equation:

$$F = B \times I \times l, \quad (1)$$

where:  $B$  is magnetic induction,  $I$  – the current passing through the coil,  $l$  – the length of the conductor traversed by the magnetic field lines generated by the mobile magnet.

LEVA 1 prototype using active magnetic spring is illustrated in Fig. 2a.

It consists of a mobile magnet with an outer diameter of 25.4 mm, an inner diameter of 6 mm, a height of 25.4 mm and a residual induction  $B_r = 1.25$  T and two pairs of stationary magnets with an outer diameter of 15 mm, an inner diameter of 6 mm, height 6mm and residual induction  $B_r = 1.25$  T.

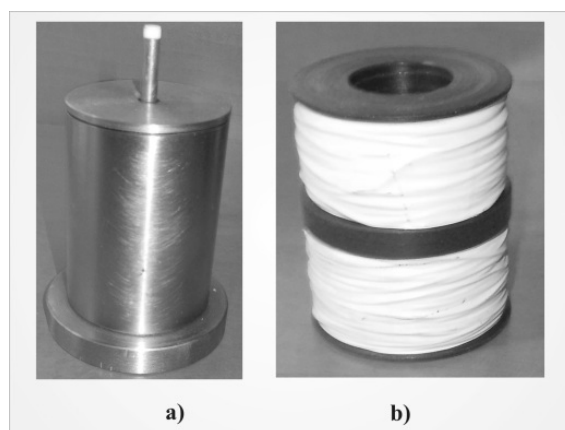


Fig. 2 – Prototype of LEVA 1 with active magnetic spring: *a* – ensemble; *b* – coil.

The stiffness coefficient of the magnetic spring is,  $K_{me} = 5,490$  N/m. The dependence of the electromagnetic force versus current, with the moving magnet blocked in equilibrium position, is proportional, Fig. 3, resulting a force of 34.9 N for a current  $I = 1.5$  A.

It is noted that experimental values of force are very close to those obtained by numerical simulation. Due to the linearity of the characteristic, an actuator constant can be defined as:

$$\alpha_p = \frac{F}{I} = 23.28 \text{ N/A}, \quad (2)$$

The device was also tested dynamically. In this sense, the coils were fed with a sinusoidal current with value  $I_{rms} = 70.7$  mA constant and the amplitude versus frequency characteristic was plotted, for an frequency range from 0 to 80 Hz (Fig. 4). Following the tests, a resonance frequency  $f_{rz} = 37.4$  Hz was obtained which corresponds to a maximum amplitude of oscillations  $Z_{max} = 4.1$  mm.

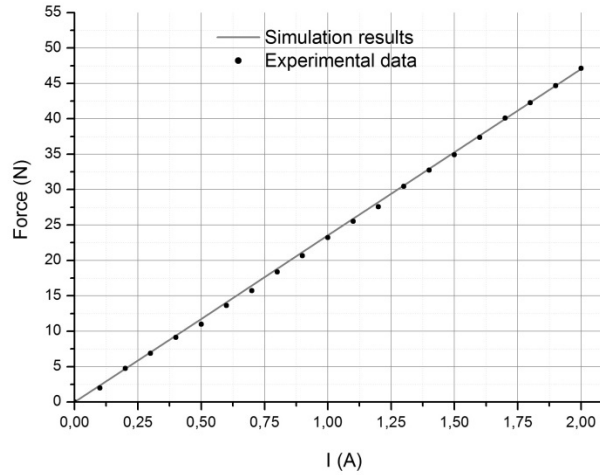


Fig. 3 – Electromagnetic force versus current in the equilibrium position.

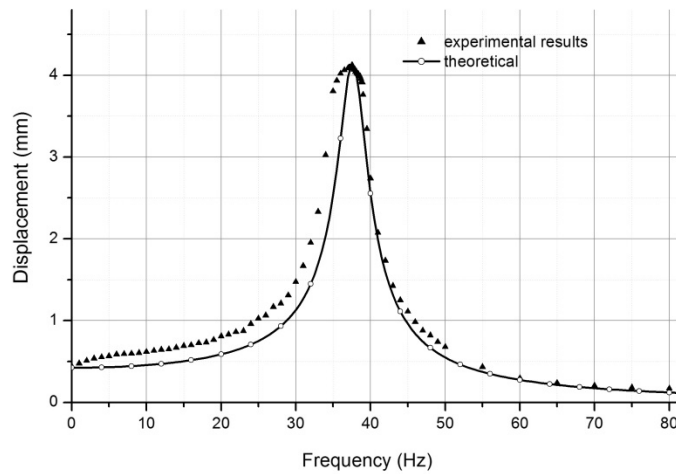


Fig. 4 – Displacement amplitude for the moving assembly vs. frequency.

The natural oscillation frequency has the value  $f_n = 37.73$  Hz and was determined by calculation based on the expression:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{K_{me}}{m}}, \quad (3)$$

where:  $K_{me}$  was previously determined, and  $m = 0.098$  kg, is the mass of the mobile part of the device. The fact that the resonance frequency is lower than the natural frequency is explained by the fact that the oscillation movement takes place in the presence of a damping.

## 2.2. LEVA 2 with Passive Magnetic Spring

A LEVA double-electromagnet device with a ferromagnetic drive disk in which the suspension is made with a passive magnetic spring is shown in Fig. 5 (Gîrtan *et al.*, 2017).

The stator of the device is made up of a superior electromagnet, a lower one and the fixed magnets of the passive suspension spring. These elements are mounted in a ferromagnetic case. The mobile part of the device is made up of a non-magnetic shaft (brass), on which is mounted a ferromagnetic disk and the mobile magnet of the magnetic spring.

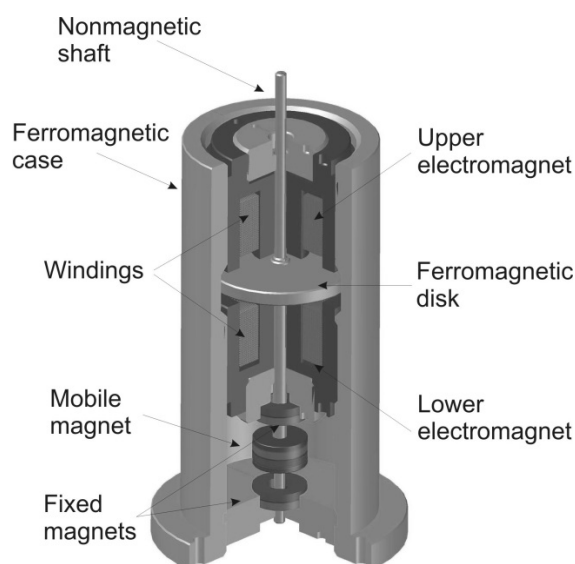


Fig. 5 – LEVA 2 with passive magnetic spring.

The oscillatory movement of the shaft is obtained with an excitation current passing successively through the two windings.

The role of the magnetic spring is to achieve the suspension of the mobile part, but also to bring the disk back to its equilibrium position when the coils are no longer fed. The prototype, illustrated in Fig. 6, has two electromagnets with 900 turns and the ferromagnetic disk with a diameter of 52 mm and a thickness of 5 mm. The magnetic spring is made with three ring shape neodymium magnets, with axial magnetization, two fixed and one mobile, and they are disposed in a repulsive configuration of differential type. The magnets have an outer diameter of 19.1 mm, an inner diameter of 9.5 mm, a height of 6.4 mm and they have a residual induction  $B_r = 1.28$  T. The

distances between the disk and the electromagnets, but also the distances between the mobile and the fixed magnets, can be adjusted to perform various tests in static and dynamic regime.

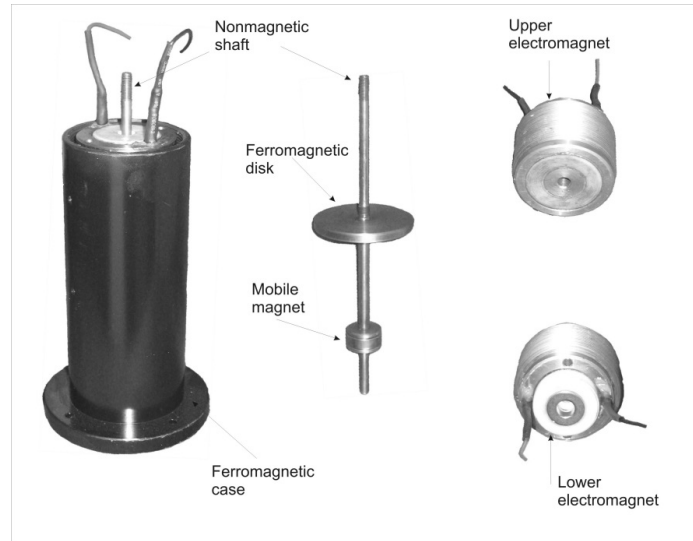


Fig. 6 – Prototype of LEVA 2 with passive magnetic spring.

Fig. 7 shows the dependence of electromagnetic force versus the distance between the electromagnet and the mobile disk. The curves were obtained by numerical simulations for different values of the DC supply.

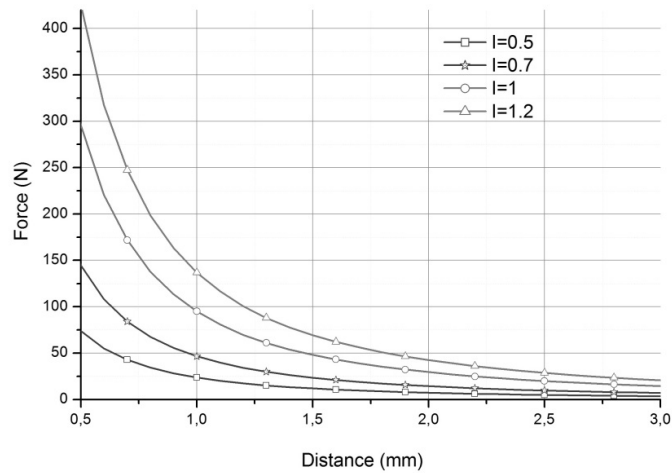


Fig. 7 – Dependence of electromagnetic force versus the distance between the electromagnet and the mobile disk.

It is noted that the electromagnetic force has a non-linear character, with small values at great distances and with very high values when the disk is near the electromagnet. Due to these features, the device can be used in applications such as closing valves where high forces are required to keep the valve in the closed or open position, or can be used to generate vibrations in various applications where the linearity of electromagnetic force is not important.

The device was also tested in permanent sinusoidal regime with an exciting current  $I_{rms} = 0.25$  A. An electronic circuit with two diodes was used to alternately supply the two electromagnets.

Under these conditions a maximum amplitude  $Z_{max} = 2.1$  mm was obtained at the resonance frequency  $f_r = 52.4$  Hz.

### 3. Possible Applications of LEVAs with Magnetic Springs in Oscillatory Systems

There are many technical applications where linear oscillatory movements are required and in which LEVAs are used. The most common applications are: diaphragm pumps, piston pumps and vibration-based conveyors. Below are some ways to use the two LEVA devices, described above, in oscillating (reciprocating) systems.

#### 3.1. Linear Pumps with Diaphragm and Piston

LEVA 1 can be used to equip membrane dispensing pumps, thanks to its linear motion, reversibility, and ease of control. The dispensing pumps have many applications in the food, pharmaceutical, textile, cosmetic, chemical and electrochemical industries, water treatment and precise dosing of liquids.

In the case of a single membrane pump, the operation is provided by a diaphragm mounted on a shaft, which is actuated by an rotary motor with eccentric, or an actuator, which can be pneumatic, electromagnetic or piezoelectric.

Nitto-Kohki Company, Japan, produces dual diaphragm pumps with permanent magnets on the mobile shaft and electromagnets on the stator. Linear motion is obtained by alternating feeds of electromagnets followed by the attraction forces between the opposite electromagnetic poles and the magnets from the mobile shaft.

The proposed diaphragm pump based on LEVA 1, Fig. 8, has the advantage that the Laplace electromagnetic forces do not vary much with the position of the mobile magnet, but also that the force versus current characteristic is linear.

The pump can be fed with positive rectangular signals Fig. 9 *a*, in which case the shaft moves only half the stroke, and the pump will discharge only the quantity of liquid  $V_1$  in a cycle, or it can be fed with positive and negative rectangular signals, Fig. 9 *b*, in which case the pump will discharge the  $V_1 + V_2$  quantity at each operating cycle.

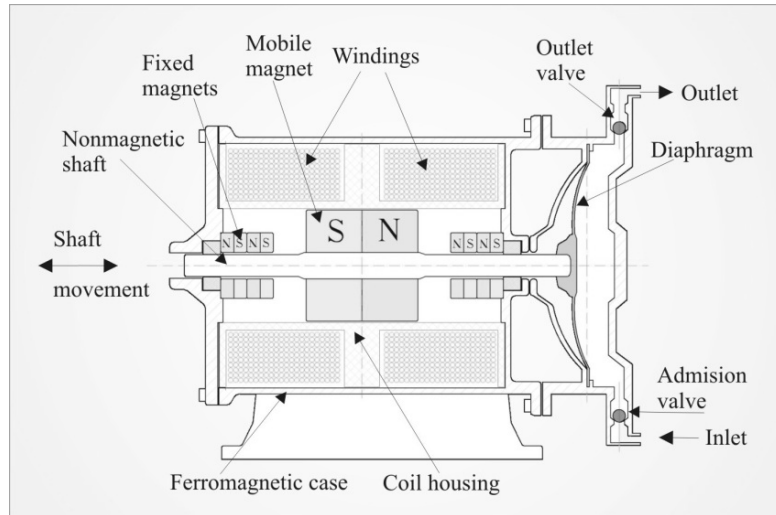


Fig. 8 – Diaphragm pump based on LEVA 1.

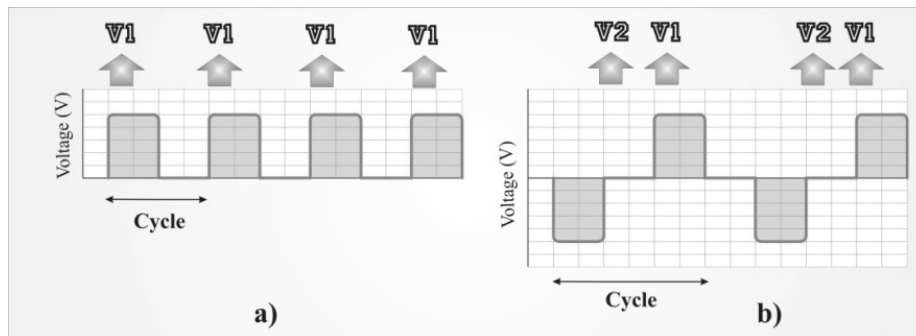


Fig. 9 – Control options of the LEVA1 diaphragm pump.

In the first case, when the positive voltage is supplied to the coil, the actuator shaft moves to the right in the direction of discharge, the membrane draining the liquid volume  $V_1$  from the pump body. When the supply signal is canceled, under the action of the magnetic spring, the shaft will move to the left, the pump body being filled again with the volume  $V_1$ . In the second case, fig. 9b, initially a negative signal is applied, the shaft moves to the left and the pump is charged with the volume  $V_2$  of the liquid. When the negative signal is canceled, the shaft will move to the right, the pump will discharge the volume  $V_2$ , then the  $V_1$  will be discharge at the positive signal feed. When the positive signal is canceled, the pump is recharged with volume  $V_1$  and the cycle is resumed.

The first feeding system can be used when small amounts of liquid are to be dispensed, and the second when larger quantities are to be dispensed.



Using the same principles of operation, the dual diaphragm pump model (Fig. 10), has been designed to be used for higher flow rates.

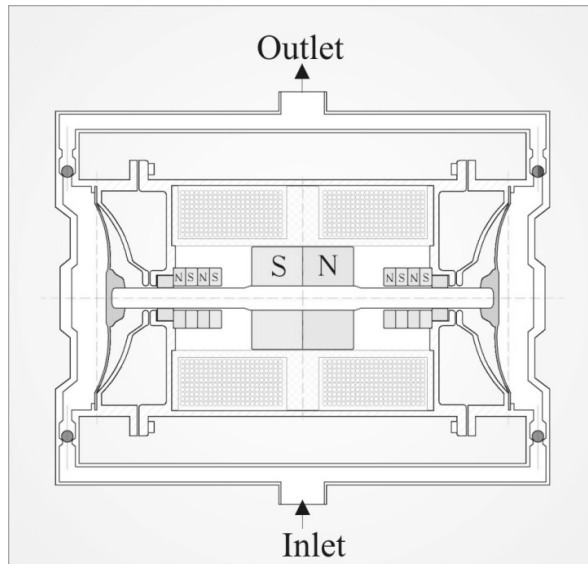


Fig. 10 – Dual diaphragm pump based on LEVA1.

A piston pump can also be built with a LEVA 1 actuator (Fig. 11), a pump of this type is described in (Poltschak *et al.*, 2016), but with another type of LEVA, intended for higher powers.

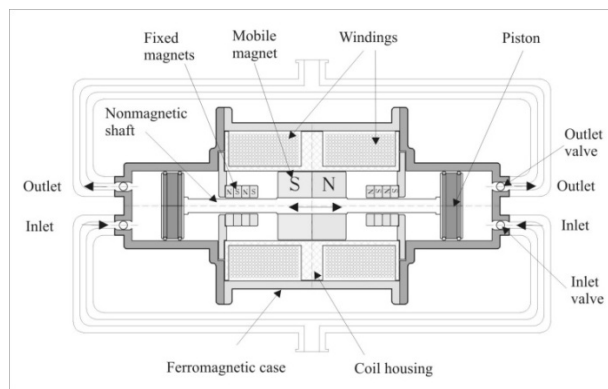


Fig. 11– Linear piston pump with LEVA 1.

### 3.2. Vibration-Based Conveyor

This device is commonly used in small-size or granular material transport applications in the pharmaceutical, electronics and metallurgical industries. There are numerous articles in the scientific literature describing the

operation of these devices and a series of studies on the kinematics of component elements and on the possibilities for optimization of operation (Despotović *et al.*, 2015).

Fig. 12 shows a low power vibration feeder that is equipped with a LEVA 2 that uses a passive magnetic spring. This system could be used to move light and small materials, such as tablet or pills drugs.

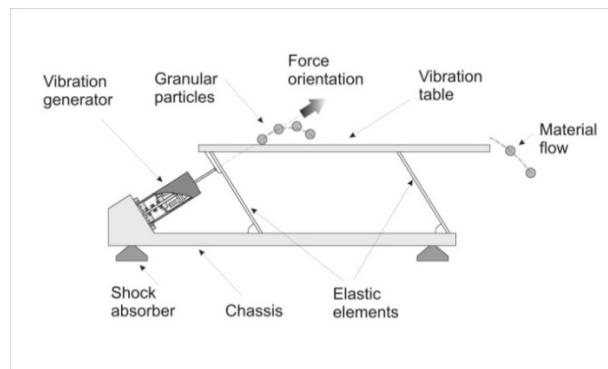


Fig.12 – Conveyor based on LEVA 2.

The device is made up of a chassis that is attached to the workbench with shock absorbers to prevent the vibrations being transmitted to it. The material to be transported is placed on a vibratory table, which is fixed to the chassis by means of elastic elements which are inclined in the opposite direction to the displacement. The vibration actuator sends an oscillatory motion to the table. Due to the fact that the elastic elements perform an angular oscillatory motion, the table will exert on the particles forces that will detach them from it and will impose a trajectory forward. After the fall on the table the particles will be hit again, and will advance until they leave the table.

### 3.3. Control of Valve Opening Using Electromagnetic Actuators

Electromagnetic actuators with double electromagnet and ferromagnetic drive disk can be used in valve opening or closing control mechanisms due to their ability to develop very large forces at the stroke ends, with low power consumption.

At present, there are similar devices, but based on classic steel helical springs, which are used to control the opening of valves to thermal motors (Mohamed, 2012), or to valve opening control of piston compressors (Schiavone, 2018). The Italian company Cozanni produces the Flux to Flow electromagnetic actuator based on the patent (Schiavone, 2018). In this case, the actuator is used to optimize the power consumption of high-capacity piston compressors.

A similar device can be achieved by using the LEVA 2 described in

section 2.2. Fig. 13 shows a LEVA 2 with passive magnetic spring in a system used to control the opening of the intake valves of a compressor. The advantage of using this device is that it has low energy consumption, and by using the magnetic spring the device's reliability increases.

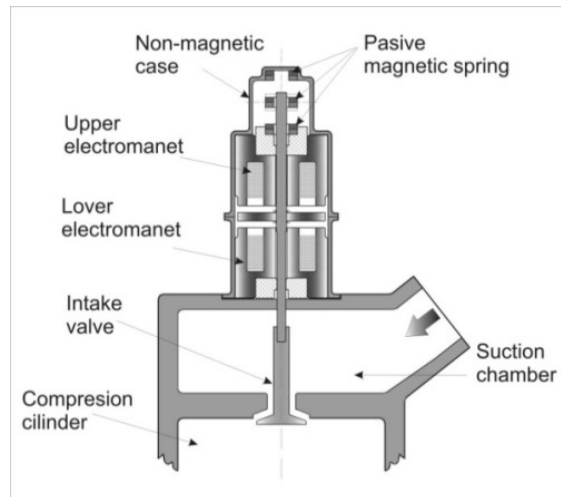


Fig. 13 – Electromagnetic valve based on LEVA 2.

#### 4. Conclusions

In this paper, two original electromagnetic actuators provided with magneto-elastic suspension of the mobile assembly and their possible applications in oscillating or reciprocating systems were investigated. The first device, LEVA 1, is exclusively based on a magnetoelastic system that is electrically activated to generate vibration movement when an excitation current passes through the coil. The magnetoelastic system can be assimilated to a linearized magnetic spring that is the key of linear working of the LEVA 1. The linear working, low cost and a simple design recommend LEVA 1 in applications with precise control, such as dispensing pumps in the food, pharmaceutical, textile, cosmetic, chemical industries, water treatment and precise dosing of liquids.

LEVA 2 device, constituted from a drive double electromagnet and a passive magnetic spring, is suitable for applications requiring strong forces at the end of stroke of the drive shaft, such as vibratory conveyors and the control of valves to thermal motors.

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## ACȚIONĂRI OSCILANTE LINIARE CU ACTUATORI DE VIBRAȚII ELECTROMAGNETICI CU ARCURI MAGNETICE

(Rezumat)

Actuatorii electromagnetici de vibrații liniari sunt utilizați în mod obișnuit pentru a acționa sisteme oscilante sau alternative, cum ar fi transportoare vibratoare și compresoare. În această lucrare este investigată utilizarea a doi actuatori electromagnetici originali, prevăzuti cu suspensie magneto-elastică pentru ansamblul mobil, în sisteme de oscilație cu putere redusă, cu referire la pompe liniare, transportoare vibratoare și controlul supapelor la motoare termice. Actuatorii prevăzuti cu arcuri magnetice conduc la reducerea consumului de energie al sistemului și creșterea fiabilității acestuia.