CHARACTERIZATION OF LOW-STIFFNESS SUSPENSIONS BASED ON DIAMAGNETIC LEVITATION FOR MEMS ENERGY HARVESTERS

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Abstract: This work reports the static and dynamic characterization of a magnetic suspension for energy harvesting applications. A macrodimensional prototype was built with NdFeB permanent magnets and pyrolytic graphite as levitating proof mass. The benefits related to the magnetic suspensions are discussed; particularly, the low stiffness and the powerless functioning appear as the most attractive properties and candidate this type of suspension to be a promising solution for the replacement of traditional mechanical connections.

Keywords: magnetic levitation, pyrolytic graphite, NdFeB, harvesting, MEMS, dynamic response

INTRODUCTION

The possibility to generate electric power by converting other forms of energy available in the environment is at the basis of the diffusion of energy harvesters. Small devices like sensors may be supplied more easily than the others, leading to push the design of micro energy harvesters, based on the micro electro-mechanical systems (MEMS) technology [1]. Many applications of MEMS energy harvesters are addressed to low frequency vibrating environments, like human body, vehicles, buildings, etc. The very small sizes characterizing the proof masses of these harvesters increase sensitively the resonance frequency of the generator; as a consequence it is usually hard to tune the resonance of the harvester to the frequency of the excitation force, which is typically one or two orders of magnitude lower in the mentioned applications [2]. This problem is quite common, and interests all the fundamental conversion principles (piezoelectric, magnetic inductive and capacitive).

The resonance frequency of the harvester may be reduced by the replacement of traditional mechanical suspensions with other low-stiffness suspensions; the diamagnetic levitation principle is suitable to design and build a promising new generation of suspensions for MEMS energy harvesters [3-6]. This strategy is based on the evidence that almost all the typologies of MEMS energy harvesters present a proof mass connected to elastic elements or suspensions. Furthermore, the powerless nature of magnetic suspensions does not reduce the efficiency of the harvester. Other advantages are given by the removal of mechanical bended elements, which are responsible to several energy dissipations sources: thermoelastic damping in the material, air damping under the suspensions, etc. Bended elements also may affect the device reliability, for instance because of the mechanical fatigue damaging.

Some theoretical studies were conducted about the modeling of magnetic suspensions [7, 8], where the magneto-structural coupling was considered. Also, it was shown [9] that eddy currents may be used to increase the damping of the levitating mass and to reduce its undesired vibrations. Instead, the experimental measurements of static and dynamic behavior of magnetic suspensions suitable for energy harvesting applications are not very diffused in the literature [10, 11].

The goal of this work is to characterize the static behavior and the dynamic response of a magnetic suspension; few simple relations useful for the designer will be also introduced. The effects of the geometry of permanent magnets and diamagnetic proof mass on the levitation height and dynamic response are documented. Another parametric characterization was reported by Alqadi [12] in the analytic formulation only. The prototype of the suspension considered is in the macroscale, due to the easiness of fabrication and assembling; additionally, the microfabrication techniques for building micro permanent magnets are not so well established at present, even if some promising samples are leaving the laboratories [13].

EXPERIMENTAL SETUP

The magnetic suspension prototype is composed of four square permanent magnets, oriented in the so-called ‘opposite’ configuration [8] and forming a planar layer (Fig. 1). The number of layers (N) of magnets is varied to increase the intensity of the magnetic field during the characterization. The permanent magnets are made by NdFeB and coated with Ni-Cu-Ni on the surface. A square proof mass with diamagnetic properties and variable dimensions made by pyrolytic graphite is used as the levitating part of the suspension. The dimensions of magnets and graphite proof mass are reported in Table 1.

The magnetic suspension is subjected to a driving force generated by a mechanical shaker (Tira TV51120), which simulates the vibrations of the environment. The shaker is controlled by a sinus function generator and a power amplifier. The excitation system is controlled in open-loop by an acceleration sensor. The motion of the levitating graphite was measured by an optical laser sensor (Keyence LK-G82) with 50kHz maximum sampling frequency and 0.2μm±0.05% accuracy. The complete testing setup is represented in Fig. 2.

Table 1: Magnetic suspension properties.

Description	Symbol	Value	Unit
NdFeB magnets side	*w*	20	mm
NdFeB magnets thickness	*t'*	3	mm
NdFeB magnets layers	*N*	1-2-3	-
pyrolytic graphite side	*l*	9-10-11-12-13-14	mm
pyrolytic graphite thickness	*t*	0.3-0.5-0.7-0.9-1-1.1	mm
pyrolytic graphite density	*ρ*	2200	kg/m^3

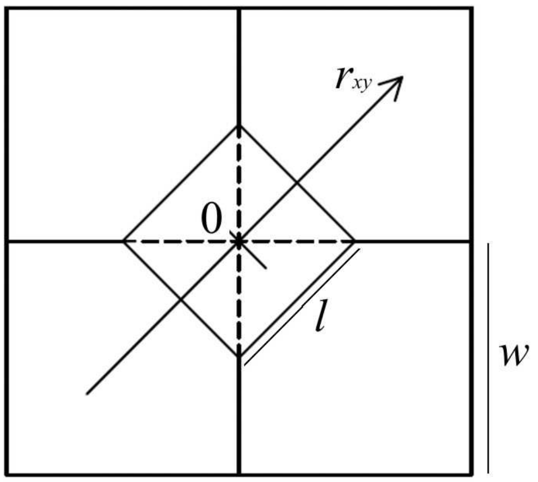

Fig. 1: Schematics of the magnetic suspension prototype with parameterized geometry.

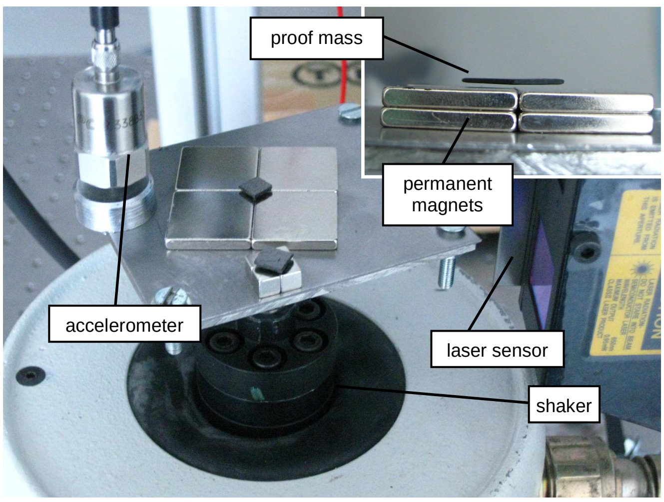

Fig. 2: Experimental setup.

EXPERIMENTAL RESULTS

Static Properties of the Suspension

The static behavior of the suspension was investigated for different dimensions of its components, which were considered as variable parameters. The configuration of the oriented NdFeB permanent magnets was obtained by four square pieces (side *w*=20mm, thickness *t'*=3mm); the number of layers of magnets was changed (1≤*N*≤3) to vary the magnetic field. The static levitation height of a square proof mass (side *l*=10mm) in pyrolytic graphite was measured by the laser sensor; the relation between the graphite thickness (*t*) and the levitation height (*z*) is shown in Fig. 3. A similar characterization was conducted for fixed thickness (*t*=1mm) by varying the graphite side: the results are represented in Fig. 4. All the levitation heights reported in this section were directly provided by the laser sensor and are referred to the upper surface of the proof mass.

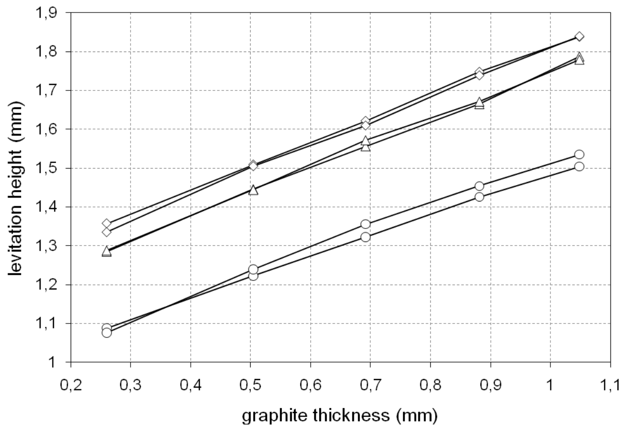

Fig. 3: Levitation height of graphite with variable thicknesses with one (○), two (△) or three (◇) layers of NdFeB permanent magnets.

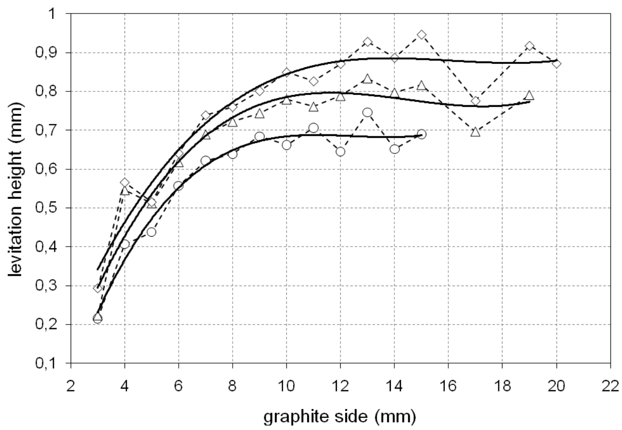

Fig. 4: Levitation height of graphite with variable side lengths with one (○), two (△) or three (◇) layers of NdFeB permanent magnets.

Dynamic Characterization

The dynamic response of the suspension was measured for different dimensions of its components by focusing the laser to the center of the graphite and storing the oscillation amplitude. The vibration amplitude was kept in smaller scale to avoid irregular motions of the proof mass; it was noticed that the motion becomes more stable with larger graphite pieces. The acceleration imposed with the shaker was fixed to a constant value in order to provide a consistent comparison throughout the measurements. The dynamic results are shown in Fig. 5 for increasing graphite side (*l*=9, 10, 11mm) and number of layers of NdFeB magnets (*N*=1, 2, 3). The dynamic response was then used to determine the resonance frequency of the system and to calculate its equivalent stiffness.

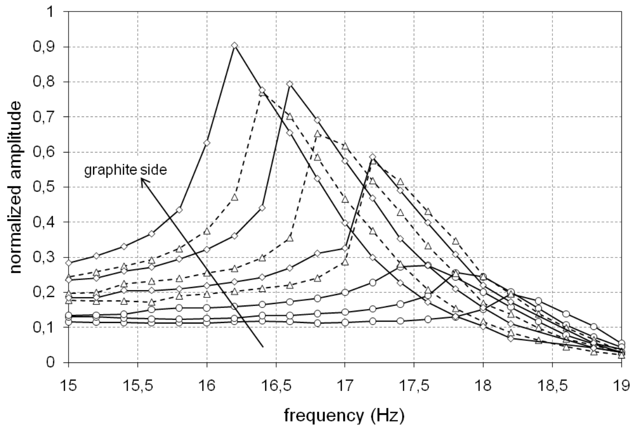

Fig. 5: Dynamic response of the suspension for 9, 10 and 11mm graphite side with one (○), two (△) or three (◇) layers of NdFeB permanent magnets.

DISCUSSIONS

The equilibrium condition of the proof mass is the result of the opposite effects of the gravity force (F_g) and the magnetic force (F_m). The linear relation between t and z shown in Fig. 3 reveals that the increasing of material quantity (in direct proportionality with the thicknesses) introduces additional contributions on both forces, that are $\Delta F_m > \Delta F_g$. The diamagnetic graphite in fact generates a magnetic field that is opposed in direction to that one of permanent magnets; the entity of the induced field is proportional to the material of the proof mass. The same effect is exhibited by increasing the side dimensions of the graphite (Fig. 4); however in this case, after the first region (l>10mm), the gravity force increasing due to the additional mass equals the higher magnetic force, i.e. $\Delta F_m \approx \Delta F_g$.

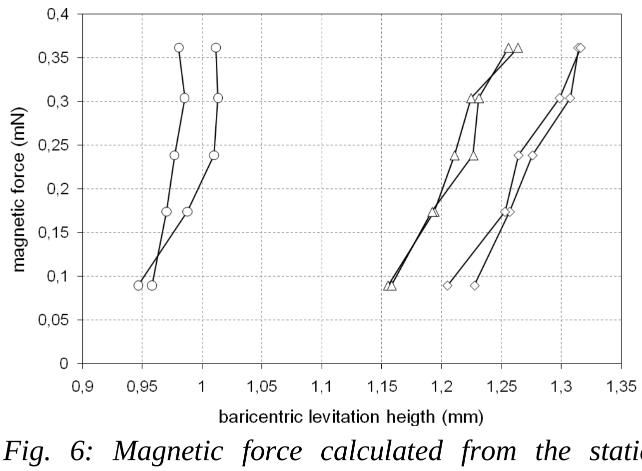

Fig. 6: Magnetic force calculated from the static equilibrium of proof masses with different thicknesses and one (○), two (△) or three (◇) layers of NdFeB permanent magnets.

The diamagnetic force per unit volume (f_m=F_m/V) acting on the levitating proof mass can be calculated as

$$f_{\mathrm{m}} \approx \frac{1}{2\mu_0}\chi_{\mathrm{m}} \cdot \mathrm{grad}(\vec{B}^2) \qquad (1)$$

and the overall magnetic force as

$$F_{\mathrm{m}} \approx \int \frac{1}{2\mu_0}\chi_{\mathrm{m}} \cdot \mathrm{grad}(\vec{B}^2)dV\,, \qquad (2)$$

where μ_0 is the magnetic permeability, χ_m is the magnetic susceptibility and $\vec{B}$ is the magnetic flux density. However, by considering that the magnetic force equals the gravity force in each equilibrium position, i.e. F_m=F_g=ρVg (where g is the acceleration of gravity), it results

$$\int \frac{1}{2\mu_0}\chi_{\mathrm{m}} \cdot \mathrm{grad}(\vec{B}^2)dV = \rho V g \qquad (3)$$

when the proof mass is steadily levitating. By considering the graphite density reported in Table 1, the magnetic force calculated for the stable levitating positions considered in the static characterization is represented in Fig. 6.

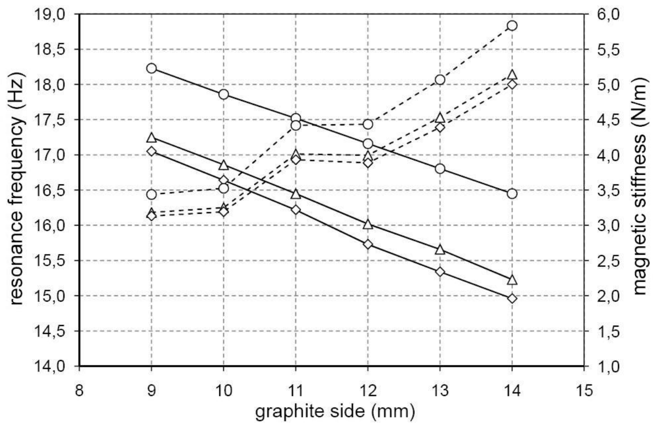

Fig. 7: Resonance frequency (continuous) and dynamic magnetic stiffness (dashed) of the suspension with one (○), two (△) or three (◇) layers of NdFeB permanent magnets.

Table 2: Experimental results of resonance frequency and magnetic stiffness with one, two and three layers of magnets.

Graphite side w (mm)	Resonance frequency f (Hz)			Magnetic stiffness k_m (N/m)		
	N=1	N=2	N=3	N=1	N=2	N=3
9	18.23	17.25	17.05	2.44	2.18	2.13
10	17.86	16.86	16.64	2.53	2.25	2.19
11	17.52	16.45	16.22	3.42	3.01	2.93
12	17.16	16.02	15.73	3.43	2.99	2.89
13	16.81	15.66	15.34	4.07	3.53	3.39
14	16.45	15.23	14.96	4.84	4.15	4.00

If the suspension is modeled as a single d.o.f. system and the air damping is neglected, the simple equation

$$k_{\mathrm{m}} = \omega^2 m \qquad (4)$$

can be assumed to calculate the magnetic stiffness, where ω is the angular frequency. In static conditions, k_m is proportional to the ratio $F_m(z)/z$; this parameter is nonlinear with respect to the vertical position z, as the magnetic flux density $\vec{B}$ nonlinearly depends to z. The dynamic characterization performed involves small oscillations of the mass; this allows considering the overall magnetic stiffness as linear in the z direction around the levitating position. As a consequence, the

Eq. (4) can be used to calculate k_m in this small interval; the results are reported in Fig. 7, where the resonance frequency variation of the suspension is also plotted. The same results are reported in Table 2. The experimental results show that the magnetic force can be used as tuning parameter for the resonance frequency of the suspension, as well as the proof mass size (Fig. 5).

CONCLUSIONS

The static and dynamic characterizations presented in this paper are referred to a macrodimensional prototype of magnetic suspension; the results derived from experiments can be used for the dimensioning of micro-scaled suspensions with similar topologies. The replacement of mechanical connections with magnetic suspensions is very promising for several applications, such as energy harvesters and inertial sensors. In both cases the levitated proof mass should host the electro-mechanical transducer (e.g. comb drive electrodes) to convert the vibrations in, respectively, electric power or capacitance variation. The information provided by the tests can also be used to tune the resonance of the system to the excitation frequency of the environment for power generators.

REFERENCES

[1] Yeatman E M 2007 Applications of MEMS in power sources and circuits *J. Micromech. Microeng.* **17** S184-S188

[2] Wei M. De Pasquale G. Wang J. Somà A 2009 Capacitively-transduced mechanically-coupled bandpass filter in electroplated nickel for harvesting energy from ambient vibrations *Proc. Power MEMS* (Washington DC. USA) 213-216

[3] Tang W C. Lim M G. Howe R T 1992 Electrostatic comb drive levitation and control method *J. Microelectromech. S.* **1** 170-178

[4] Chyuan S W. Liao Y S 2005 Computational study of the effect of finger width and aspect ratios for the electrostatic levitating force of MEMS combdrive *J. Microelectromech. S.* **14** 305-312

[5] Krishnamoorthy U. Olsson R H. Bogart G R. Baker M S. Carr D W. Swiler T P. Clews P J 2008 In-plane MEMS-based nano-g accelerometer with sub-wavelength optical resonant sensor *Sensor. Actuat. A Phys.* **145-146** 283-290

[6] Mann B P. Sims N D 2009 Energy harvesting from the nonlinear oscillations of magnetic levitation *J. Sound Vib.* **319** 515-530

[7] Chetouani H. Delinchant B. Reyne G 2007 Efficient modelling approach for optimization of a system based on passive diamagnetic levitation as a platform for bio-medical applications *Compel* **26** 345-355

[8] Barrot F 2008 Acceleration and inclination sensors based on magnetic levitation. Application in the particular case of structural health monitoring in civil engineering *PhD thesis* EPFL (Lausanne. Switzerland)

[9] Elbuken C. Khamesee M B. Yavuz M 2006 Eddy current damping for magnetic levitation: downscaling from macro- to micro-levitation *J. Phys. D: Appl. Phys.* **39** 3932-3938

[10] Garmire D. Choo H. Kant R. Govindjee S. Séquin C H. Muller R S. Demmel J 2007 Diamagnetically levitated MEMS accelerometers *Proc. of Transducers and Eurosensors* (Lyon. France) 1203-1206

[11] De Pasquale G. Siyambalapitiya C. Somà A. Wang J 2009 Performances improvement of MEMS sensors and energy scavengers by diamagnetic levitation *Proc. ICEAA* (Torino. Italy) 465-468

[12] Alqadi M K. Al-Khateeb H M. Alzoubi F Y. Ayoub N Y 2007 Effects of magnet size and geometry on magnetic levitation force *Chin. Phys. Lett.* **24** 2664

[13] Chetouani H. Haguet V. Jeandey C. Pigot C. Walther A. Dempsey N M. Chatelain F. Delinchant B. Reyne G 2007 Diamagnetic levitation of beads and cells above permanent magnets *Proc. of Transducers and Eurosensors* (Lyon. France) 715-718