



3D numerical modeling and experimental validation of diamagnetic levitating suspension in the static field

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ABSTRACT

Diamagnetic levitation principle opens to promising solutions for innovative powerless and low stiffness suspension applicable to many technological fields. The peculiarities of diamagnetic suspension make this design solution very attractive for some applications such as microdevices and energy harvesters. Low stiffness and powerless functioning are the most appreciable characteristics of this kind of suspension, despite their force–displacement curve is generally hard to predict and strongly nonlinear. The modeling complexity resides in the preliminary prediction of magnetic field distribution and in the calculation of diamagnetic forces as function of the levitation height. This work introduces a modeling approach for calculating the levitation height of a parameterized diamagnetic suspension composed of a ground of permanent magnets and a levitating mass made of pyrolytic graphite. The numerical discretization approach is used and the predicted values are compared with experiments providing good agreement between results.

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1. Introduction

Magnetic levitation has been investigated as valuable design approach for the suspension of mechanical systems in various dimensional scales in alternative to the traditional elastic linear and nonlinear springs. Basically, the most relevant benefits provided by levitated suspension to the system dynamic response are due to their intrinsic low stiffness; additionally, their simple structure assures high reliability and long lifetime. More specifically, diamagnetic levitated suspension can operate without external power supply with significant advantages for the energetic efficiency improvement. Active magnetic levitation is typically applied to maglev transports and is operated through electromagnets; this solution, based on magnetic fields induced by the electric power supply, has its main drawback in the significant energy consumption. The alternative to active levitation is represented by passive levitated suspension, which can be divided in two typologies: the first type is based on the repulsive force between magnets and, usually, is simply composed by one permanent magnet attached to the frame and another one working as oscillating proof mass owing to the repulsive force. The polarity orientation of magnets allows generating the repulsive force between the facing sides; Mann and Sims [1] provide an

example of this kind of levitated system. The second typology of levitated suspension, namely ‘diamagnetic suspension’, is based on the repulsive force generated inside diamagnetic materials. When surrounded by an external magnetic field, diamagnetic materials can generate a weak field that opposes the external one; if the configuration is properly studied, the magnetic repulsive force acting between the magnetic and the diamagnetic poles of the suspension may balance the gravity force and produce levitation [2,3]. Permanent magnets are generally used to generate the external magnetic field; they are organized to form arrays or matrices of magnets and their polarity is properly oriented to maximize the diamagnetic force. Alternative strategies have been explored, for instance by using high-temperature superconductors to increase the levitation force [4] or with compact high field force magnets [5].

Traditional mechanical suspension systems are characterized by deformable elements that are able to store elastic potential energy when bended and then return almost the same amount of energy, except for small dissipations, when restoring the original shape; generally, their force–displacement characteristics are linear only for small travels and exhibit strong nonlinearities for long travels. The benefits of diamagnetic suspension compared to mechanical suspension are very significant, especially considering some applications (such as energy harvesting, inertial sensing, micromanipulation, bioengineering, etc.): their stiffness is some orders of magnitude lower, the energetic efficiency is comparable (but extremely higher than that of active magnetic suspension),

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and their dimensions are sensitively smaller. The missing of deformable structural connections prevents some serious problems, such as the energy dissipation inside the material (e.g. thermoelastic damping), the energy dissipation with the surrounding fluid caused by viscous friction, and the mechanical fatigue effect, that reduces considerably the lifetime of mechanical parts when subjected to alternate loads [6].

Even though diamagnetism is a well-known physical property of materials and diamagnetic levitation has been deeply studied in the past [7–11], the application of this effect to practical devices and systems is still not mature. In the next years, the development of new fields such as micro- and nano-technology will offer the opportunity to exploit more in deep the properties of diamagnetic levitation and the benefits deriving from the integration of diamagnetic levitated components in real systems.

Several theoretical and empirical models of levitated systems have been described in the literature to explain and predict the static and dynamic behavior of the magnetic coupling associated to specific components with defined shape and dimensions. Simon et al. [12] discussed the equilibrium limits of a spinning rotor levitating on an annular magnet depending on its rotational velocity. The same authors in [13] found that the introduction of a diamagnetic material in some particular locations of magnet–magnet levitating systems allows stable equilibrium without external energy input, although this condition is generally prohibited by the Earnshaw theorem of levitation [7]. Cansiz and Hull [14] investigated the use of diamagnetic materials in magnetic bearings to study their characteristics in the static and in the dynamic behavior and their load-carrying capacity; in the paper is experimentally investigated a NdFeB disk-shaped rotor levitating over a ferrite magnet with a diamagnetic stabilizer in a vacuum chamber. The results show the rotational energy losses due to eddy currents and frequency of bearing rotation.

According to Earnshaw's theorem the equilibrium of forces acting on a ferromagnetic or paramagnetic body is not stable in a static magnetic field. A stable levitation can be achieved using a levitated body made of a magnetic material [15] having a relative permeability locally less than one; diamagnetic and superconducting materials can be used for this purpose. Diamagnetic materials present a value of magnetic permeability that differs only slightly from unity so with these materials the attained levitated load is very small compared to superconductors, which have practically zero permeability. Even though the levitation capacity is greater than that of the diamagnetic materials, the cooling cost, hysteresis and maintenance decrease the practical usefulness of superconductive bearings. This is the reason why the diamagnetic materials with no hysteresis can be used to create a stabilizer in the magnetic bearings if the application requires rather small loads.

Other studies investigated the dissipations occurring in diamagnetic suspension due to eddy currents [16]; this effect may have relevant influence on the suspension dynamics, in particular on its quality factor and on the response to impulsive excitations. Analytic compact models and numerical models based on the finite elements method (FEM) have been introduced to predict the static levitation height of the suspension starting from the magnetic field distribution and the discretization of the diamagnetic force induced in the levitating mass [18,19].

Also Chen et al. [17] investigated the eddy-current effect on the performance of diamagnetic bearings. Eddy current could be induced in the diamagnetic bearing with viscous forces opposing the relative motion between the rotor and the stator. Such damping mechanism was analyzed with a thin-sheet model and the image method and compared with that due to aerodynamic effects so as to give an idea of its significance at the microscale. The obtained results indicated that, due to its rotating nature,

eddy current has a destabilizing effect on the diamagnetic bearing which is operated in the supercritical range, whereas for operation in the subcritical region, it provides a simple and effective damping mechanism.

Some examples of devices and prototypes with embedded magnetic levitating components were effectively described. The acceleration sensor introduced by Barrot et al. in [20] is based on a force-feedback sensing concept that exploits the optical detection of a levitated inertial mass, providing high accuracy and sensitivity to the measurements. Instead, the accelerometer described by Garmire et al. in [21] is based on the micro electro-mechanical systems (MEMS) technology and includes a miniaturized proof mass made with a diamagnetic material that is suspended on a magnetic ground; the acceleration measurement is provided again by an optical detection of the mass motion. Sometimes, MEMS accelerometers include special finger-shaped features, namely 'comb drives', used to detect the mass motion via their capacitance variation; the electrostatic interactions between comb drives may induce the magnetic levitation of the structure, offering the opportunity to control its position in static and dynamic conditions thanks to this particular magnetic micro-suspension [22,23]. Li et al. [24] efficiently applied a magnetic levitated suspension system to an atomic force microscope for the calibration of the lateral force. A diamagnetic rotor suspension was developed in [25] and in [26] for optical devices positioning purposes.

Differently from the previous studies, this work does not focuses on a specific device but introduces a general modeling approach to predict the behavior of diamagnetically levitated suspension [27]. A very basic layout of the suspension is considered and the calculation predictions are supported by experimental validation tests. The behavioral prediction of simple structures and their characterization by experiments permit to setup the design parameters of more complicated solutions to suit every specific application. This statement led to consider the particular typology of samples used in this work, instead of more complicated specimens addressed to more specific fields of application. After the preliminary analysis of the theoretical background of magnetic levitation, the numerical discretization of the suspension is presented with the goal to predict its static properties, i.e. levitation height and stiffness. The diamagnetic force acting on the levitating part is calculated by means of the finite elements approach. The suspension is defined through the parameterization of its geometrical dimensions, according to the approach already used in the literature [19,28,29] in order to derive size-dependent properties of the suspension.

2. Theoretical background

This section reports the basic physical relations and interactions between the external magnetic field ($\vec{H}$) and diamagnetic materials. The magnetic behavior of diamagnetic materials depends on its orbital magnetization: when an external magnetic field influences a diamagnetic material, the electrons of its atoms react to the field by orbiting in such a way as to create an opposite magnetic field. The magnetization of an elementary volume ΔV of material is defined by the magnetic dipole per unit volume ($\vec{M}$) that is also called induced magnetization; for some materials such as permanent magnets, it persists even if the external magnetic field is removed.

In diamagnetic materials, $\vec{M}$ depends on the external magnetic field and on the magnetic susceptibility (χ) of the material. The magnetic susceptibility of anisotropic materials varies depending on the directions; for example, the pyrolytic graphite used in the

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