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Dedicated to the memory of Academician Andrei Ţugulea

ASSESSMENT OF TILT ANGLE MEASUREMENT BASED ON A DIAMAGNETICALLY STABILIZED ALL PERMANENT MAGNET LEVITATION STRUCTURE

IOSIF VASILE NEMOIANU, VERONICA MANESCU (PALTANEA),
GHEORGHE PALTANEA, RADU MIRCEA CIUCEANU

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A permanent magnet passive levitation structure is assessed for a possible use as tiltmeter. Two aligned lifting permanent magnets produce the magnetic field necessary to a small cylindrical permanent magnet to achieve suspension in gravitational field. Not to contradict Earnshaw's theorem, which prohibits the existence of all magnet levitation structures, two stabilizing diamagnetic pieces are used in the proximity of the levitated magnet. The magnetic charge equivalence used for modeling the lifting magnets allows a closed-form of the flux density formula, for further use in equilibrium point coordinates determination, as well as for stability functions and tiltmeter sensitivities. The magnetostatic problem is numerically solved for tilt angles ranging from horizontal to vertical positions. Metrological characteristics for the possible tiltmeter are derived, namely conversion characteristics and sensitivities. Finally, the obtained results are presented and critically discussed.

1. INTRODUCTION

Static levitation structure comprising permanent magnets (PMs) have recently become increasingly used in a series of technical applications. Their use takes advantage from the fact that no energy input is needed to generate the magnetic field in which levitation occurs, in contrast to the case when electromagnets are present.

Nowadays, there are numerous practical applications [1–4] taking benefit of these levitation structures, such as: contactless bearings, microelectromechanical systems (MEMS), micromotors, energy harvesting devices *etc*. Tiltmetres or inclination sensors constitute such an application, as presented in [5, 6], where a symmetrical structure with dc fed electromagnets was used as the magnetic field source in which levitation of a small cylindrical permanent magnet occurs.

Passive levitation in general mainly refers to the following two possibilities [7].

Firstly, one can mention the suspension of a diamagnetic small piece in static magnetic fields [8–10]. In this case, the force opposing and finally balancing the force of gravity is generated as a result of the inhomogeneity of the magnetic field. This type of levitation takes advantage of the physical property of diamagnetic materials to be repelled from the more intense magnetic field regions. Many materials exhibit diamagnetic characteristics at room temperature like water, copper, mercury, bismuth *etc*. The strongest diamagnetic response is that of pyrolytic graphite, a layer deposited material with anisotropic properties on two directions, along the layers and perpendicular to them, case corresponding to the most negative magnetic susceptibility.

Secondly, the inherently unstable suspension of small permanent magnet(s) can take place in both PM and dc fed electromagnets time invariant fields [11–15]. The governing principle of this type of levitation was first stated and proved by Earnshaw, postulating that no stable equilibrium is ever achievable within a set of mutually interacting bodies by forces inversely proportional to their squared separating distance. Since the theorem is valid for any kind of such forces (electric or magnetic), the need of some additional exterior action becomes imperative for stabilizing the equilibrium. In static magnetic field (passive levitation) a solution to this limitation may constitute the use of diamagnetic materials placed in the near proximity of the levitated magnet(s) [16]. Their role would be to provide the adaptive restoring forces bringing back the suspended PM to its initial equilibrium point position, whenever a small deviation from that point occurs.

The investigated levitation structure, pertaining to this latter category, was presented and partially characterized in [12]. In this work the physical feasibility of such a tilted structure was experimentally proven. Also, a computation methodology was proposed and validated by numerical simulations and also checked against measured results. Nonetheless, further characterization of the structure for tilt angle detection and measurement remained an open issue. The present work focuses on filling this gap by assessing the possible use of the levitator as tiltmeter, being structured as follows:

- Section 2 summarizes the setup description (geometry and used materials) and how equilibrium and stability are achieved.
- Section 3 presents the analytical method used to model the lifting permanent magnets, in order to further compute the lifting force acting on the levitated magnet.
- Section 4 contains simulation and results for three variants of the levitator, in what concerns its metrological capabilities as tiltmeter, *i.e.* conversion characteristics, stability functions and associated sensitivities.
- Section 5 highlights the main conclusions of the study in comparison to the previously obtained results if the structure uses dc fed electromagnets [6].

"Politehnica" University of Bucharest. Corresponding author Radu Mircea Ciuceanu, E-mail: radu.ciuceanu@upb.ro.

2. MAGNETOSTATIC PROBLEM STATEMENT

2.1. INCLINED SYMMETRICAL ALL PERMANENT MAGNET SUSPENSION SETUP USING DIAMAGNETIC STABILIZERS.

The levitation structure under scrutiny was first presented in [12], being shown in Fig. 1. Two identical cuboidal Nd-Fe-B permanent magnets (PM 1 and PM 2, respectively) are mounted on a nonmagnetic fixture (not shown in Fig. 1, for simplicity reasons) such that they share the same axis of symmetry (the *x*-axis). In between, a small cylindrical permanent magnet (PM) has achieved levitation state, being attracted to PM 1 and PM 2 that produce the magnetic field in which levitation occurs. The identical lifting magnets have the following geometrical dimensions: width *w*, height *h* and length *l*. All the magnets are supposed to be made of Nd-Fe-B. At the equilibrium point of coordinates (x_0, z_0) (belonging to the PM center of mass, where the balance of forces is considered), stabilization is ensured by two diamagnetic stabilizers (DS) placed perpendicular to the lifting magnets' common symmetry axis, according to Earnshaw's theorem. As a material of choice pyrolytic graphite may be considered for the stabilizing pieces, due to the exceptional diamagnetic properties at room temperature. It is supposed that the stabilizers can freely move providing thus with the needed stabilization for the PM for each possible equilibrium point.

The origin O of the Cartesian frame of reference is set at equal distance *D* between lifting magnets PM 1 and PM 2. North pole lifting magnets face centers C_1 and C_2 have the coordinates ($x_{C,1}$, $y_{C,1}$, $z_{C,1}$) and ($x_{C,2}$, $y_{C,2}$, $z_{C,2}$), respectively. The considered fixture allows setting a global tilt angle θ for the entire structure. In that respect if θ > 0, one has to notice that the equilibrium point is placed nearer to PM 1 (the higher lifting magnet) in order to provide the magnetic uphill directed force necessary to balance the *x*-component of the weight (of magnitude *W* sin θ), as shown in Fig. 1.

In more detail, Fig. 2 shows the two diamagnetic plates (DS) which stabilize the equilibrium of the PM of radius *r* and length λ. The equal separation between PM and DS plates is *s*. The stabilizing pieces are supposed to be parallel to the PM pole faces, namely parallel to *yz*-plane, approximation present in [11–15]. Vector ***m*** denotes the magnetic moment of the PM and $\boldsymbol{B}_x(x, y)$ the flux density *x*-vector component, the only component to generate lift in this configuration. Following the considered approximation it turns out that ***m*** is also directed along the *x*-axis. Variants of the levitator shown in Fig. 1 can be derived by removing either the left or the right diamagnetic stabilizing pieces. In such a case, PM will slightly find another equilibrium point by shifting toward the remaining stabilizing piece.

2.2. EQUILIBRIUM OF FORCES AND STABILITY

Levitation state is achieved when the magnetic force $\boldsymbol{F_m}$, provided by both the lifting magnets PM 1 and PM 2, equals the force of gravity ***W*** (the weight), as shown in Fig. 2. As mentioned in the previous Subsection 2.1., the equilibrium is intrinsically unstable in accordance to Earshaws's theorem. The response provided by the two stabilizing pieces (DS) to exterior small equilibrium perturbations, consists in two oppositely directed adaptive diamagnetic forces, which act as restoring forces. If an equal separation on each side of the levitated magnet is considered (*s*, as shown in Fig. 2), the two diamagnetic forces are equal in magnitude, and thus they cancel each other out. Consequently, they do not appear in the overall balance of forces $\boldsymbol{F}_{\text{resultant}} = \boldsymbol{F_m} + \boldsymbol{W} = 0$. Unlike this case, the presence of a single DS would determine an unbalance along the *x*-axis. The remaining diamagnetic force combined with the other two components, already existing along the *x*-axis, will slightly shift the equilibrium point. The effect is quite small due to the minute generated diamagnetic force magnitude even for a highly diamagnetic characteristic material as pyrolytic graphite.

Further ignoring the influence of the diamagnetic forces and aiming to derive the equilibrium of forced equations, one can consider the total potential energy of the PM in the gravitational field and being simultaneously embedded in the magnetic filed produced by PM 1 and PM 2 [12]:

$$U(x, y, z) = -\boldsymbol{m}\cdot\boldsymbol{B}(x, y, z) - W\,\Delta(x, z), \qquad (1)$$

where $\boldsymbol{B}(x, y, z)$ is the local (at PM center of mass) flux density vector and $\Delta(x,z) = z\cos\theta - x\sin\theta$ is the distance between the PM center of mass and the origin set for the gravitational potential energy. Additionally, the force of gravity $W = \rho V g$, ρ is the mass density of the Nd-Fe-B material, $V = \pi r^2 \lambda$ is its volume and $g \approx 9.81$ m·s^{-2} is the gravitational acceleration magnitude assumed in further calculations. In the *xz*-plane where by symmetry levitation is expected to occur, we get with (1)

$$U(x, 0, z) = -m\,B_x(x, 0, z) - W\,(z\cos\theta - x\sin\theta). \qquad (2)$$

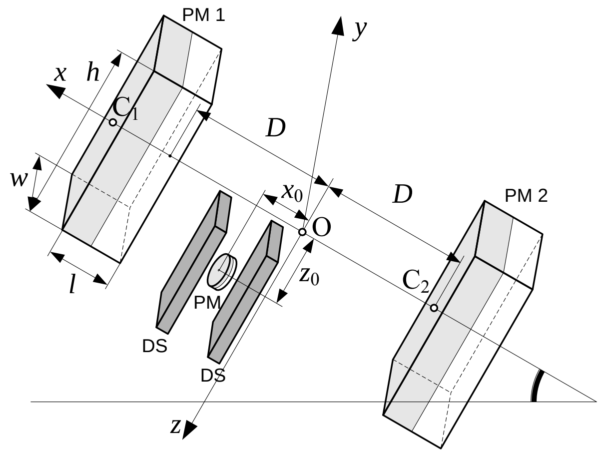

Fig. 1 – Investigated tilted magnetostatic levitation structure with permanent magnets and diamagnetic stabilization.

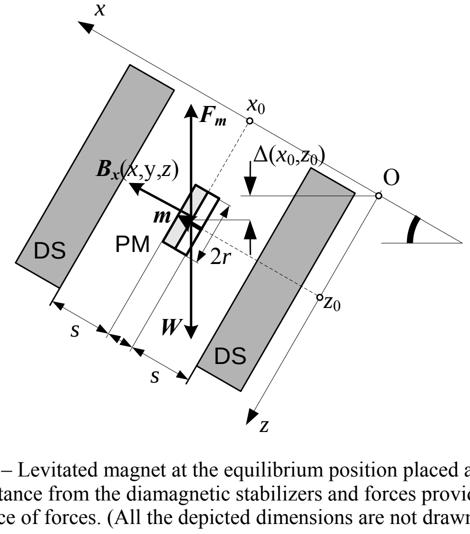

Fig. 2 – Levitated magnet at the equilibrium position placed at equal distance from the diamagnetic stabilizers and forces providing the balance of forces. (All the depicted dimensions are not drawn to scale.)

The resultant force acting on the levitated magnet is then $\boldsymbol{F}_{\text{resultant}} = -\,\text{grad}\,U$. By imposing a zero total force, one gets the following system of equations [12]:

$$\begin{cases} m\dfrac{\partial B_x}{\partial z}(x,0,z)+W\cos\theta=0 \\ m\dfrac{\partial B_x}{\partial x}(x,0,z)-W\sin\theta=0 \end{cases}. \tag{3}$$

Interestingly, only the B_x component of $\boldsymbol{B}$ appears in the magnetic force computation on both axes.

Once determined the equilibrium point coordinates x_0 and z_0, stability is assessed by defining the *stability functions* (*discriminants*), which must be *simultaneously positive* [11–15]:

$$D_x=\frac{\partial^2 U}{\partial x^2}(x_0,0,z_0),\; D_y=\frac{\partial^2 U}{\partial y^2}(x_0,0,z_0),$$
$$D_z=\frac{\partial^2 U}{\partial z^2}(x_0,0,z_0). \tag{4}$$

Finally, with (1), the *stability functions* (*discriminants*), evaluated at the equilibrium point, become [11–15]:

$$D_x=-m\frac{\partial^2 B_x}{\partial x^2}(x_0,0,z_0),\; D_y=-m\frac{\partial^2 B_x}{\partial y^2}(x_0,0,z_0),$$
$$D_z=-m\frac{\partial^2 B_x}{\partial z^2}(x_0,0,z_0). \tag{5}$$

A negative value, taken by the stability function at the equilibrium point along an axis, indicates the need of introducing at least one DS normal to the respective axis. If two DS are present, a supplementary quantity termed *diamagnetic influence factor* is to be added to the corresponding stability function evaluated at the equilibrium point coordinates (x_0, 0, z_0), namely [16]

$$C=\frac{6\mu_0|\chi|m^2}{\pi(2s+\lambda)^5}, \tag{6}$$

where $\mu_0 = 4\pi\cdot10^{-7}$ H/m is the vacuum permeability and $|\chi|$ is the absolute value of the magnetic susceptibility for the diamagnetic material. According with [16], relationship (6) was established using the method of images. Consequently, parameters s and λ must be correlated to the stabilizing pieces thickness so that the PM images should be entirely contained inside the diamagnetic material volume.

3. ANALYTICAL MODEL FOR LIFTING MAGNETS USED FOR FORCE, EQUILIBRIUM POINT COORDINATES AND STABILITY FUNCTIONS COMPUTATION

In order to determine the equilibrium point coordinates using (3) and to evaluate the achieved stability with (5) an analytical formula for the B_x flux density component would be necessary. Excepting the possibility of using numerical methods for calculating this quantity [17, 18], which would not provide a closed form, a very efficient approach is the one offered by the magnetic charge equivalence of the lifting magnets. In general, generating an analytical formula for the flux density associated to a permanent magnet is a challenging task. The used method consist of assimilating their pole faces with magnetic charge uniformly distributed on surface: positive on the two North pole faces and negative on the two South pole faces of PM 1 and PM 2. Obviously, ignoring the end effects, the uniform distribution hypothesis is an accepted approximation, allowing a Coulombian integral to be performed on each of the four pole faces. This approach finally provides the following 16 term closed form [12, 14, 15]

$$B_x(x,y,z)=\frac{B_{\text{i,L}}}{4\pi}\sum_{s=1}^{2}\sum_{i,j,k=0}^{1}(-1)^{i+j+k}\times$$
$$\times\arctan\frac{Y_{k,s}\cdot Z_{j,s}}{X_{i,s}\sqrt{X_{i,s}^2+Y_{k,s}^2+Z_{j,s}^2}}, \tag{7}$$

where $X_{i,s}=x-x_{\text{C},s}+i\cdot l$, $Y_{k,s}=y-y_{\text{C},s}+(-1)^{k+1}(w/2)$, $Z_{j,s}=z-z_{\text{C},s}+(-1)^{j+1}(h/2)$, $i,\ j,\ k\in\{0,1\}$, and $s\in\{1,\,2\}$. One can notice that, for the problem depicted in Fig. 1, $y_{\text{C},s}=0$ and $z_{\text{C},s}=0$.

Quantity $B_{\text{i,L}}$ represents the intrinsic flux density obtained in open loop for the lifting magnets. Even when permanent magnets are not included in some magnetic circuits, they exhibit self demagnetization. In such a case their operating point falls on the intrinsic demagnetization branch of the permanent magnet *B-H* characteristic. Although very stiff for Nd-Fe-B magnets, on this branch the actual operating point belongs to a slightly smaller value of the flux density than remanence B_r. Consequently, permanent magnets appear to be "weaker" than expected by their remanence. This phenomenon can be accounted by the actual shape of the magnet having a quantitative expression in the permeance coefficient P_c. In [12] it is shown that $P_c + 1$ represents the operating line slope whose intersection with the demagnetization branch provides the actual $B_{\text{i,L}}$ value for both PM 1 and PM 2. Most often ignored in the vast majority of technical calculations, where B_r value is more likely to be used, the above-mentioned phenomenon cannot be ignored in a very sensitive levitation problem.

Similarly, the magnetic moment of the levitated PM is given in [12, 14, 15] as

$$m=\mu_0^{-1}B_{\text{i,f}}V, \tag{8}$$

where $B_{\text{i,f}}$ is the intrinsic flux density specific to the actual operating point of the floating magnet.

The important advantage offered by the closed form (7) is that all the first and second order partial derivatives appearing in (3) and (5) can be further analytically obtained and implemented as such in a general-purpose math package.

4. SIMULATION RESULTS

Aiming to evaluate the possible use of the levitator depicted in Fig. 1 as a tiltmeter, three numerical simulations are performed. All the magnets used in the simulations are off-the-shelf products and therefore their exact characteristics had been available for the computation. As mentioned at the end of Section 3, equations (3), (5), (6) and (7) are implemented in a program, taking advantage of the closed-form taken by all the used quantities.

Data that are common to all the three simulation parameters are organized in Table 1.

Table 1

Common parameters used for all three simulations

Parameter	Value
Levitated PM radius, r [mm]	2.5
Levitated PM length, λ [mm]	1
Permeance coefficient for the operating point of PM, P_c	0.468
Intrinsic flux density value for the operating point of PM (grade N45), $B_{i,f}$ [T]	1.315
PM magnetic moment magnitude, m [A·m^2]	0.0205
PM mass [g]	0.15
Separation between PM and DS plates, s [mm]	2
Pyrolytic graphite normal direction magnetic susceptibility value, χ	$-45\cdot10^{-5}$
Diamagnetic influence factor C [J / m^2]	0.146

Specific data to each of the three performed simulations are presented in Table 2.

Table 2

Parameters used for the three performed simulations

Parameter	Simulation 1	Simulation 2	Simulation 3
Lifting magnets PM 1 and PM 2 width, w [mm]	50	90	70
Lifting magnets PM 1 and PM 2 height, h [mm]	50	90	140
Lifting magnets PM 1 and PM 2 length, l [mm]	25	30	25
Lifting magnets PM 1 and PM 2 grade	N48	N45	N45
Permeance coefficient for the operating point of PM 1 and PM 2, P_c	0.981	0.669	0.518
Intrinsic flux density value for the operating point of PM 1 and PM 2 $B_{i,L}$ [T]	1.37	1.32	1.3185
Half of the separating distance between PM 1 and PM 2 (Fig. 1), D [mm]	125	175	175

As shown in Table 2, three different pairs of identical Nd-Fe-B were considered for the simulations. First type of lifting magnets consist of half a cube, the second one third of a cube and the last has an elongated shape in vertical direction. Values $B_{i,L}$ and $B_{i,f}$ have been obtained on the average nominal demagnetizing curves at 20 ºC, specific to N45 and N48 grades magnets after the corresponding four permeance coefficients were determined [12].

In order to determine the equilibrium point coordinates by solving the system of equations (3), we first use the symbolic capabilities of the software package for calculating the derivatives and thereafter its numerical toolbox. This kind of determination is performed in steps of 5° starting from the horizontal position ($\theta = 0$) up to the vertical position ($\theta = 90$º). At each step, stability at the computed equilibrium point coordinates is assessed by implementing relationships (5) and symbolically computing the second order derivatives for the x-component of flux density. Due to the large amount of data to be presented, we choose to organize the results under the form of graphical plots. Obtained equilibrium point coordinates are shown in Fig. 3 for the three sets of data shown in Table 2, each determination being performed using the common data of Table 1.

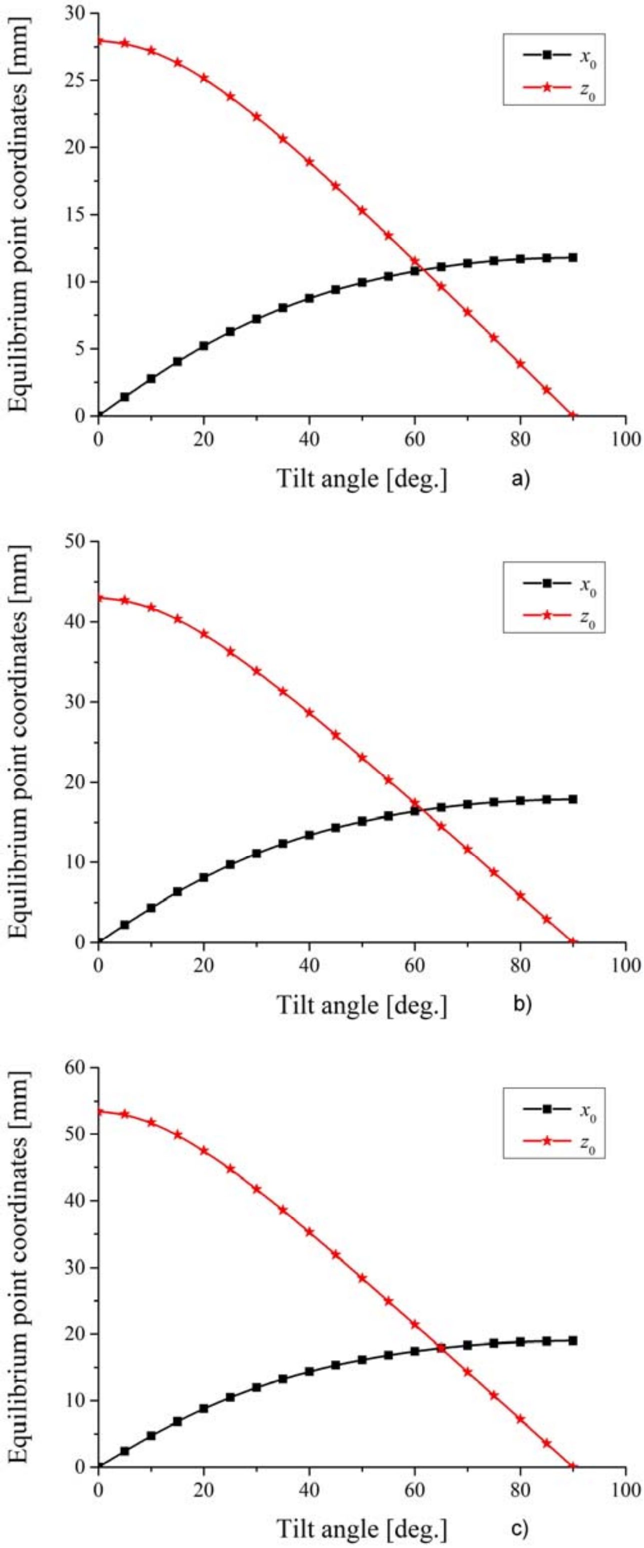

Fig. 3 – Conversion characteristics (equilibrium point coordinates *vs*. tilt angle: a) simulation 1; b) simulation 2; c) simulation 3.

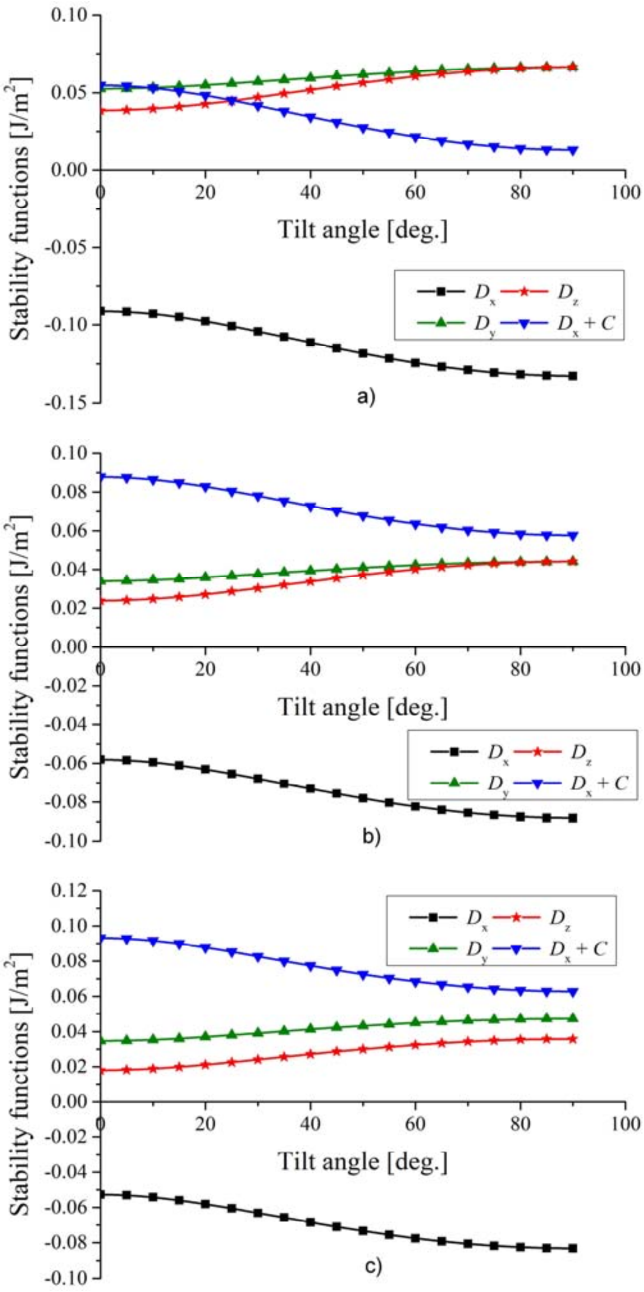

Fig. 4 – Stability functions (discriminants) at the equilibrium points *vs.* tilt angle: a) simulation 1; b) simulation 2; c) simulation 3.

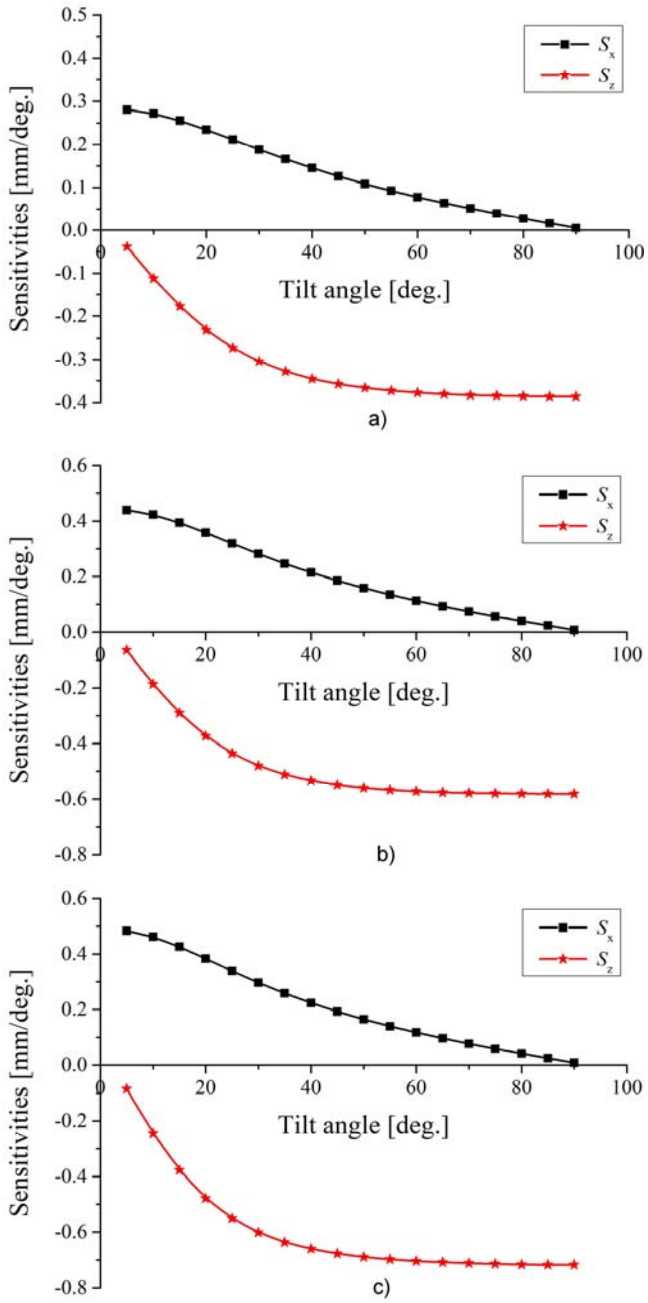

Fig. 5 – Sensitivities *vs.* tilt angle of a possible tiltmeter based on the presented levitator: a) simulation 1; b) simulation 2; c) simulation 3.

Validation of the obtained results can be performed by computing the stability function values (5) corresponding to the equilibrium points coordinates plotted in Fig. 3. The obtained results are shown in Fig. 4. As expected, the negative values of D_x, obtained for all the range of tilt angles shown in Fig. 4, prove the necessity of introducing at least one DS. Their effect resides in the addition of the diamagnetic influence factor (6) so that the new value $D_x + C$ becomes positive, proving that stable equilibrium has been achieved in all cases.

In order to get an insight of the possible use of the device as tiltmeter, we define the following sensitivities:

$$S_x = \frac{\mathrm{d}\, x_0(\theta)}{\mathrm{d}\,\theta} \text{ and } S_z = \frac{\mathrm{d}\, z_0(\theta)}{\mathrm{d}\,\theta}. \qquad (9)$$

Equations (9) consider the proposed structure as a device with a single input – tilt angle θ – and a double output – equilibrium point coordinates x_0 and z_0. The two sensitivities are plotted for each of the three cases in Fig. 5.

5. CONCLUSIONS

The possible use as tiltmeter of a levitation structure, comprising exclusively permanent magnets and stabilizing diamagnetic pieces, was investigated both theoretically and numerically through three sets of simulations. Its application is destined to non-magnetic working environments, in order to preserve the accuracy of the performed conversion: tilt angle – two linear displacements. This specificity reveals one fundamental property of a possible tiltmeter, namely redundancy, similarly to the case of the device whose functioning is based on dc electromagnets [6]. Thus, the tilt angle information may be extracted independently from two variation functions.

As expected, the conversion characteristics plotted in Fig. 3 for the three sets of data show that $x_0 = x_0(\theta)$ is a monotonically increasing function, in contrast to $z_0 = z_0(\theta)$, which is a monotonically decreasing one. A more elongated shape for the lifting magnets shape (third simulated variant) does not lead to a significant increase in measurement performances neither for conversion characteristics nor for the associated sensitivities. Contrary to the dc fed variant of the levitator case [6], here $z_0 = z_0(\theta)$, instead of $x_0 = x_0(\theta)$, is a more "linear" conversion characteristic. This aspect is consistent to the more "constant" sensitivity S_z (even though negative) for the interval 50º… 90º. Additionally, it can be noticed that S_z is almost zero when approaching the vertical position ($\theta = 90º$).

The feasibility of the use of this structure as tiltmeter is guaranteed by the positive values achieved for $D_x + C$, along with $D_y > 0$ and $D_z > 0$. Notice that for the two cases in which the lifting magnets have square pole faces, in vertical position ($\theta = 90º$), $D_y = D_z$, as a result of the symmetry presented by the structure with respect to the *y*- and *z*- axes.

Compared to the performances of the levitator presented in [6], the three variants assessed in this paper do not exhibit an almost "constant" sensitivity S_x and/or S_z over a large span of the input variable θ, as does the electromagnet levitator variant. Indeed, the latter presents a quite linear variation for $x_0 = x_0(\theta)$ and a corresponding almost constant sensitivity S_x in the interval 0º… 85º.

As a final conclusion, the choice of the type of levitator (with permanent magnets *vs*. dc electromagnets) is a trade-off between measurement accuracy and energy input consumption.

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