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Energy-aware 3D micro-machined inductive suspensions with polymer magnetic composite core

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Abstract. This paper addresses the issue of Joule heating in micromachined inductive suspensions (MIS) and reports a significant decrease of the operating temperature by using a polymer magnetic composite (PMC) core. The PMC material has a high resistivity, thus inhibiting the formation of eddy currents, and a high permeability, thus guiding the magnetic field more efficiently within the MIS structure. We experimentally study the distribution of the PMC material inside the MIS structure and evaluate the effect of the core from the dependence of the levitation height on the excitation current. The experiments carried on in ambient room temperature demonstrate that the temperature inside the micromachined inductive suspension is reduced to 58°C, which is a record-low temperature compared to other MIS structures reported before.

1. Introduction

Micromachined inductive suspensions operate by exciting a levitation coil with an alternative current, therefore creating an alternative magnetic field, which induces a current in a conductive proof mass, the proof mass being levitated on top of the MIS structure. However, the energy transfer between the excitation current of the coil and the current induced in the proof mass is rather inefficient, and this translates in relatively high excitation currents with respect to the achievable levitation height. The first MIS prototype used single turn coils obtained by planar lithography [1] and reported a temperature as high as 600°C. A significant reduction of the operating temperature down to 120°C has been achieved by replacing the planar coils with 3D wirebonded microcoils [2]. Following the trend of approaching room temperature operation of micromachined inductive suspensions, we have recently demonstrated further improvement by introducing a polymer magnetic composite core material [3].

In this work, we investigate the distribution of the PMC core material inside the MIS structure, focusing on the dependence between the levitation height and the excitation current. A further reduction of the operating temperature is demonstrated for operation in ambient room temperature, i.e., 58°C, which is a record-low value to date. At the same, time, this work suggests solutions for further improvement in terms of energy efficiency of micromachined inductive suspensions.

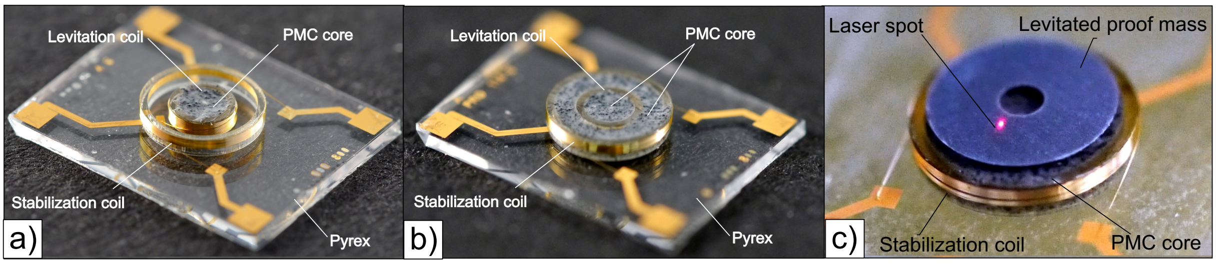

Figure 1. a) Design A: only the inner (levitation) coil is filled with PMC material; b) Design B: both the inner (levitation) and the outer (stabilization) coils are filled with PMC material; c) An Al proof mass is successfully levitated on a design B MIS structure.

2. Fabrication and operating principle

The MIS structures used in this work have been presented in detail in previous reports [2] and consists of two concentrical solenoidal wirebonded microcoils obtained by wirebonding. The role of the inner "levitation" coil (2 mm in diameter and 20 windings) is mainly to levitate the conductive proof mass, whereas the role of the outer "stabilization" coil (3.9 mm in diameter and 12 windings) is to achieve a stable levitation of the proof mass. The height of the coils is 650 μm. In order to investigate the influence of the PMC core material to the MIS performance, two different designs have been investigated experimentally: design A - only the levitation coil is filled with PMC material Figure 1a), and design B - the entire volume of both coils is filled with PMC material Figure 1b). The performance of these structures is compared to the performance of the structure without core. Figure 1c) shows a MIS prototype with an integrated PMC core successfully levitating an Al proof mass (3.2 mm in diameter and 13 µm in thickness). The PMC core [4] consists of a NiFeZn ferrite soft magnetic powder (CMD5005, National Magnetics Group, USA) dispersed in a mixture of two epoxies (AW4510 and HW4804, Huntsman Advanced Materials GmbH, Switzerland). My means of a dispenser (DX-250, OKI, USA), the MIS structure has been filled with the PMC mixture.

The research hypothesis of this work is that the PMC core focuses the magnetic field lines around the body of the two coils, thus minimizing their air-path and increasing the magnetic induction in the region of stable levitation. This translates in lower excitation currents required to achieve the same levitation height, therefore a lower operating temperature.

The field, B, generated by the coil without core can be found by solving the following set [3]

$$\begin{cases} B + \mu_0 H = \mu_0 \dfrac{(n_l - n_s)I}{l'_{air}}; \\ B = \mu_0 H, \end{cases} \quad (1)$$

where n_l and n_s are the number of windings for levitation and stabilization coils, respectively, H is the magnetic field, l'_{air} is an effective path of magnetic field passing through the air, and I is the current through the coil. Solving set (1), we obtain the magnetic field in the center of the levitation coil without core as follows

$$B_a = \mu_0 (n_l - n_s) I / (2 l'_{air}). \quad (2)$$

For coils with core the relationship between B and $\mu_0 H$ becomes as

$$H l_{core} + B l''_{air} / \mu_0 = (n_l - n_s) I, \quad (3)$$

where l''_{air} is the effective path of magnetic field passing through the air for coils with the magnetic core. Accounting for $l_{core} < l'_{air}$ and $l''_{air} \leq l'_{air}$, and the fact that μ_{core} is large [4], the magnetic induction generated by coils with core is

$$B_b \approx \mu_0(n_l - n_s)I/l''_{air}. \tag{4}$$

As a result, even if $l''_{air} \approx l'_{air}$ (due to the fact that the linear size of coils is one order of magnitude larger than their height), still the magnetic field generated by the coils with integrated core is larger than by coils without core.

3. Experimental Results

The experimental setup consists of a current amplifier (LCF A093R) delivering a square wave excitation current to the coils. A function generator (Arbstudio 1104D) was used to control the amplitude and the frequency of the excitation current, while a laser distance sensor (LK-G32) was measuring the levitation height. Finally, an IR (Infrared) camera PI-160 (Optris GmbH, Berlin, Germany) was used to measure the temperature of the MIS prototype.

The dependence between the levitation height and the excitation current in the coils at a frequency of 10 MHz has been measured experimentally and is being shown in Figure 2a) for the following MIS prototypes: design A, design B and, in order to enable direct comparison, a prototype without core. The position of the three curves in Figure 2a) indicate that, for the same excitation current, higher levitation heights are being achieved for a higher degree of filling the coil volume with PMC material. Conversely, for the same levitation height, e.g., 110 µm, the highest actuation current is obtained for the structure without core - 110 mA, and the smallest current value - 70 mA, is demonstrated for design B, i.e., for the prototype having the entire coil volume filled with PMC material.

In order to check the prediction of the equations above, we choose one specific operation point for the design B prototype of the suspension: for an excitation current of 60 mA, the levitation height of the proof mass is 110 µm. In order to achieve the same effect for the suspension without core, i.e., 110 µm, the excitation current must be 110 mA, which is a factor of 1.8 higher. Equations (2) and (4) above also predict that the magnetic induction doubles for a prototype with a magnetic core, therefore we can conclude a relatively good agreement between

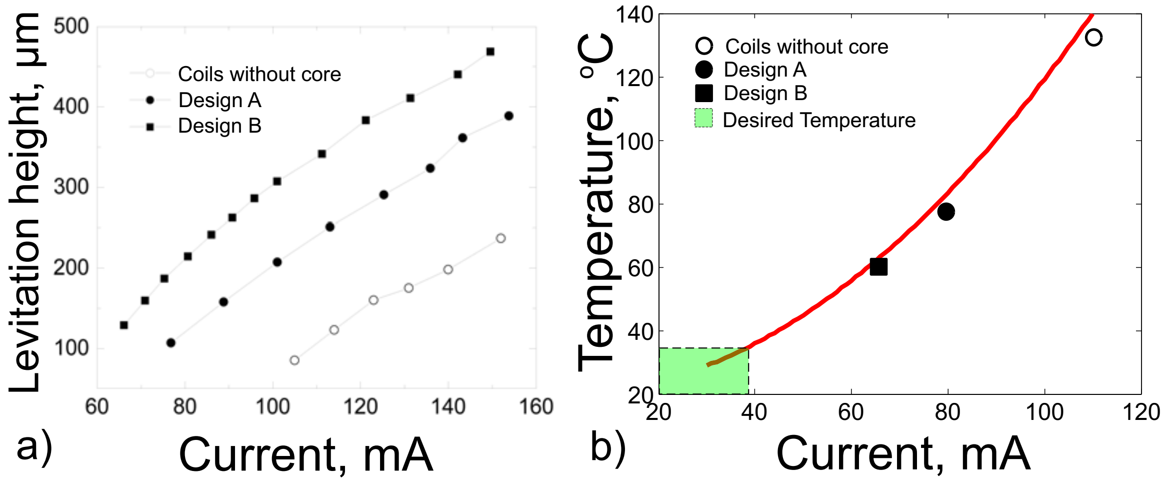

Figure 2. a) Dependence of the levitation height on the excitation current (at 10 MHz) as a function of the PMC distribution inside the MIS; b) Temperature vs. current dependence for a levitation height of 110 µm.

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the theoretical prediction and the experimental results. It means that managing the distribution of magnetic field within coils by designing magnetic core the required current for levitation can be reduced together with operating temperature. Figure 2b) sums up this fact by showing the dependence of operating temperature for considered coils design on the excitation current. Figure 2b) predicts that operating temperature can be comparable with ambient one, when the excitation current will be less than 40 mA. This can be reached for instance by adding a PMC backing plane to the MIS design, could decrease the operating temperature to around room temperature values. A significant reduction of the current leads to a significant reduction in the Joule heating within the MIS structure. This is indeed confirmed by the temperature map of the design B prototype shown in Figure 3, which demonstrates that the temperature on top of the structure is lowered to 58°C. Moreover, the temperature distribution is relatively uniform within a range of 10°C, whereas the prototype without core shows a large temperature gradient from the coil windings to the center of the structure [5, page 1482].

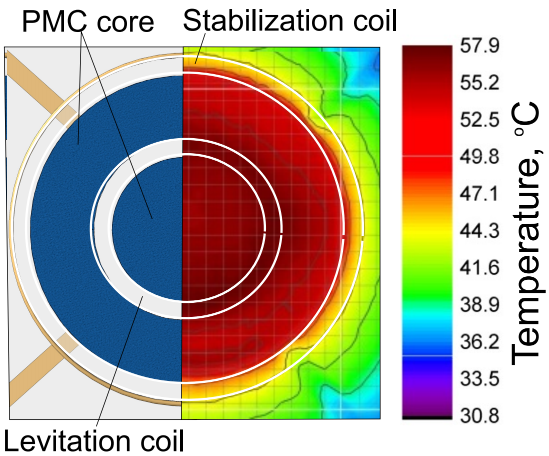

Figure 3. Temperature map for design B MIS prototype operating at 60 mA.

4. Conclusion

This work continues the efforts in our group in the field of MIS based on 3D microcoils obtained by automatic wirebonding, by further integrating a polymer magnetic composite material as a core to improve the MIS performance. Due to its high resistivity, the PMC core hinders the formation of eddy currents. Due to its high magnetic permeability, the PMC core increases the magnetic field in the region of stable levitation. Both properties lead to a more efficient energy transfer from the excitation, i.e., actuation current to the proof mass to be levitated. We expect that further improvements can be achieved by exploiting the flexibility of the dispensing method for the PMC core to cover the bottom and the outermost surface of the coils, i.e., embedding the entire MIS structure in the PMC material. However, the very top of the MIS structure must not be convered by the magnetic composite material in order to allow the lines of the magnetic field to "escape" the structure in order to induce eddy currents inside the conductive proof mass. Approaching room temperature in the operation of 3D micromachined inductive suspensions is a pragmatic step in the direction of integrating these elements into levitated micro-systems.

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