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Analytical Modeling of Permanent Magnets on a Soft Magnetic Support for a Suspension System

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Abstract—The ever increasing quest for smaller details on computer chips requires increasingly accurate lithographic machinery. This paper discusses part of the design of a permanent magnet based vibration isolation system to be used within such machinery. In such system, the passive permanent magnets provide the gravity compensation and active electromagnets the accurate positioning. Flux-focusing materials may be incorporated for structural support, flux focussing and magnetic shielding. This paper investigates the feasibility of analytical surface charge modeling combined with the method of images for accurate force prediction in a suspension system with soft magnetic materials. More specifically, it is researched to what extent finite support lengths reduce the analytical model accuracy.

I. INTRODUCTION

In an advanced micro-lithography machine, schematically shown in Fig. 1, a stable platform in 6 degrees of freedom (DoF) is required to support and isolate the machine’s complex lens system from vibrations. To date, micro-vibration problems within these machines could often be solved by means of adequate isolation of the equipment from the floor, i.e. the main plate is resiliently isolated from the floor, both passively and actively, by means of three airmounts (special air bearings with additional linear actuators).

For future applications, devices using magnetic forces could provide a possible alternative for such airmounts, where the support and vibration isolation can be achieved by passive gravity compensation using permanent magnets (PMs) and accurate positioning and stabilization using active electromagnets. [1], [2], [3] describe similar vibration isolation systems, however, these are designed for applications having smaller forces and similar or larger positioning inaccuracies compared to the lithographic application.

For example, in the lithographic application, the payload, suspended on three points, is in the order of thousands of kilograms, hence forces in the order of ten thousands of Newton’s. These force levels give that the mechanical stress is these devices is considerable, even taken the nearly balanced forces in the equilibrium position into account.

It has been shown in [4] that considerable force levels and densities can be achieved using arrays of solely PMs, such as illustrated in Fig. 2. However, these structures are likely to be insufficiently rigid to withstand the mechanical stresses and to achieve the necessary accuracies, e.g. the strength of these devices is mainly determined by the glue between the PMs. Further, the complete lens structure and frame need to be mounted on the electromagnetic vibration isolation device, hence additional material is necessary to provide a robust support of the PMs. [4] investigated various topologies in terms of force density, with a 10mm thick nonmagnetic steel as support material.

In general, soft magnetic materials are extensively used to provide a significant increase in force density in electromagnetic devices such as rotating or translating PM machines due to their flux focusing properties [5], [6]. Therefore, inclusion of such materials is considered, which simultaneously provide structural support, magnetic shielding towards surrounding components and an increase in force density. Albeit that supplementary effects, e.g. eddy-currents, hysteresis, noise, etc, will be included by the use of soft magnetic material that have to be minimized.

In this paper, Section II discusses the model restrictions and Section III how to include the soft magnetic support materials in the analytical PMs modeling tools. In particular, two situations are distinguished, viz. a PM above and between a soft magnetic material. Subsequently in Section IV, the analytical tools are verified using FEM and experimental results and Section V investigates the influence of finite material dimensions, followed by the conclusions in Section VI.
II. Model restrictions

To suspend the platform in 6 DoF with the high accuracy requirement of the lithographic suspension application makes accurate 3D modeling essential. As such, the force level in this application is high with respect to the required position accuracy, i.e. 10kN and 10µm respectively. This combined with a required spring stiffness of 10kN/m gives that a nominal force variation (or inaccuracy) of 1% already requires at least 100N of active compensation. The necessary position accuracy can only be achieved with accurate passive/active magnetic forces with a resolution of approximately 0.1N. Further, in the envisaged vacuum conditions this active compensation also needs to be minimized, hence an even better modeling accuracy has to be achieved for the passive gravity compensation, e.g. of 1‰.

These force accuracies are very challenging for analytical and/or finite element techniques, since numerous parameters influence this force characteristic, e.g. saturation, hysteresis, magnetization misalignment, eddy-currents, material inhomogeneity, temperature, measurement noise, etc. Indeed also in the final practical set-up, this will be a challenge and only a first attempt is undertaken in this paper to achieve very accurate force predictions by analytical means although that a lot of future research is necessary to further enhance the force prediction.

For initial verification purposes, the numerical 3D finite element (FE) method is used, which requires a large number of mesh elements, especially since arrays of multiple PMs are necessary to achieve the necessary force level and density [4]. However, care must be taken when using the finite element method, since its ability to predict forces in a particular device under given conditions is reliant on the imposition of the correct boundary conditions, material characteristic, inclusion of hysteresis, etc. Whereas the FE solution accuracy will inevitably increase as the mesh discretization is increased, the computational requirements of models with very high levels of discretization may become overwhelming and in the limit numerical truncation errors may occur [7]. Further, in the used FE package, the virtual work method is used to compute the force as the derivative of the energy versus the displacement of the movable part. More specifically, the very small allowable force deviation relative to the force level gives that the energy derivative becomes very small compared to the total energy, hence reduces the the force prediction from the FE analysis.

For this reason, a purely analytical model based on surface charges is considered for the system, which provides fast-solving expressions for interaction force between PMs, although is unsuitable for modeling soft magnetic materials. In this paper, a first attempt to include soft magnetic material is undertaken by using the method of images to provide a field expression. This, of course, does not include the non-linearity, saturation, environmental influences, etc. but is used as an initial step towards the very accurate force prediction in this non-periodical, finite length, high force, high positioning accuracy, etc. device.

III. Analytical modeling tools

The lithographic suspension device is based on the interaction forces between PMs to provide the necessary gravity compensation. A method which is very suitable to provide an exact 3D expression for the interaction force between PMs in free space is based on the charge model [8], [9]. Here, PMs are modeled by a hypothetical distribution of surface magnetic charges, which provide exact field and force expressions. In this paper only PMs which are magnetized along z are considered. The analytically obtained interaction force between two equally sized PMs placed above each other is then given by

\[ F_z = \frac{B_r B_z}{4\pi \mu_0} \sum_{i=0}^{1} \sum_{j=0}^{1} \sum_{k=0}^{1} \sum_{l=0}^{1} \sum_{p=0}^{1} \sum_{q=0}^{1} \psi_z, \]

where

\[ \psi_z = (-1)^{i+j+k+l+p+q} \left[ -uw \ln(r-u) -uv \ln(r-v) + uv \arctan\left(\frac{uv}{rw}\right) - rw \right]. \]

Here is

\[ u = \left( (1)^i - (1)^j \right) \frac{l_{mag}}{2}, \]

\[ v = \left( (1)^k - (1)^l \right) \frac{w_{mag}}{2}, \]

\[ w = \left( (1)^p - (1)^q \right) \frac{h_{mag}}{2} + \gamma, \]

\[ r = \sqrt{u^2 + v^2 + w^2}, \]

where, \( l_{mag}, w_{mag} \) and \( h_{mag} \) are the dimensions of the PMs, as defined in Fig. 3. The distance between the geometrical centers of both volumes is given by \( \gamma \), and remanent flux density by \( B_r \) (the sign of \( B_r \) indicates magnetization along positive or negative z).

This charge model provides a force expression for PMs in free space. However, in this paper inclusion of soft magnetic materials is considered, and therefore the analytical surface charge model requires modification. A commonly used method to model the contribution of soft magnetic materials to the magnetic field is the method of images [10], [11], which models the field of a charged particle placed above an infinitely permeable half space by putting an oppositely charged
image particle equidistant below the air-metal interface, as is schematically illustrated in Fig. 4. This method is mathematically only valid for charges above or between infinitely large half spaces of infinitely permeable material.

The finite dimensions of the soft magnetic materials in the suspension application imply that the method of images is no longer mathematically exact to provide a field expression in the air. Therefore, investigation is required to verify that this method provides sufficiently accurate results when material dimensions are finite, i.e. end effects are negligible, which is presented below. In this paper, the following assumptions apply:

- infinite permeability of the back iron,
- linear PM BH-characteristic ($B_r$ and $\mu_r = 1$),
- temperature effects are negligible,
- uniform and homogeneous magnetization.

A. Permanent magnet above a soft magnetic body

A common and easy to understand example of the imaging method is found by calculating the field of a PM above an infinitely permeable half space (Fig. 4). Only a single image is required to obtain the analytical expression for the field above the soft magnetic surface. This assumption is verified in Section IV.A using non-linear Al1010 steel. However, when considering the interaction forces of PMs between a support finite structure a modification of the imaging method is necessary as will be discussed below.

B. Permanent magnets between soft magnetic bodies

It was shown in [11], that for 2D structures the magnetic field of a charge between infinitely permeable half spaces is described by an infinite array of images of that charge, generated by means of reflection in the iron-air interfaces. By representing the PMs as charge distributions, the field of PMs between infinitely permeable half spaces is obtained similarly in [12], as Fig. 5 schematically shows. In this paper, imaging is performed in a 3D domain and the number of images is limited in order to reduce computation time. The PMs and their respective images are divided into two groups, illustrated by Frame A and Frame B in Fig. 5, which are in effect separated by the airgap. The interaction force, $F_z$, is obtained by

$$F_z = \sum_{n=0}^{K} \sum_{m=0}^{K} F_{nm},$$

where $F_{nm}$ is the interaction force exerted on the $n^{th}$ image in Frame A by the $m^{th}$ image in Frame B, indicated in Fig. 5 and $K$ is the total number of considered consecutive images.

### Table I

<table>
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<tr>
<td>$B_r$</td>
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</tbody>
</table>

### IV. Validation of the analytical modeling tools

#### A. Permanent magnet above a soft magnetic body

The analytical model is verified by means of FE and experiments, for the dimensions of Fig. 6 and Table I. The PM material is Vacodym 655HR, i.e. $B_r$ equals 1.23T, where the soft magnetic material is nonlinear Al1010 mild steel. Fig. 7 shows a picture of the experimental setup with the various components highlighted. The software package used to obtain the numerical FE results is Flux 3D [13] using nonlinear steel. Fig. 8 presents the interaction force results obtained by the three methods described above as a function of the displacement $x_{mag}$, as defined in Fig. 6, whilst $y_{mag} = \frac{1}{2} w_{steel}$. At a displacement of $x_{mag} = 10$mm, the magnet edge is separated 2mm from the edge of the soft magnetic material, as can be deducted from Fig. 6 and Table I, hence, end effects occur.

The influence of these end effects are clearly visible in the FE and measurements for small and large horizontal displacements (parabolic function). This function is only observed at large airgap lengths, where at small lengths the measurements are inaccurate, since the results should be mirrored about the...
40mm displacement (alignment between the magnets and the center of the back-iron). Further, it is observed that the analytical force (single computation) is similar to the FE solution, where it is interesting to note that a constant offset of approximately 1N is apparent. It is concluded that the discrepancy observed between analytical/FE and measured results is mainly caused by measurement inaccuracies, e.g. test setup tolerances, non-uniform or slightly non-perpendicular magnetization of the PMs, sensor accuracy, magnet filleting, etc. However, for most applications the presented analysis would represent a model accuracy between the theoretically predicted and measured results, i.e. the error between measured and analytical results at $x = 40$mm is below 7% for all airgap lengths. However, the lithographic suspension system requires a higher degree of model accuracy, and therefore further research into the accurate modeling remains required, together with more accurate experimental verification.

The dimensions used in the verification process of the analytical method combined with the image technique are based on findings from [4] as illustrated by Fig. 9 and Table II. [4] reported that both repulsive and attractive force (Fig. 9a and b) or combinations could be applicable for the lithographic suspension device, e.g. in a halbach array. The used analytical surface charge modeling is unsuitable for modeling an infinite number of PMs, therefore to minimize the computational effort the number of images should be restricted although that this introduces an error in the field and force computation. Fig. 10 shows the analytically obtained interaction force versus the number of consecutive images, where the force is normalized to the force value obtained for $K = 500$, with $K$ defined in (7). The PM with its first image is indexed as 0 and each subsequent image as 1, 2, 3, etc, as illustrated in Fig. 5. Figure 10 demonstrates that the interaction force obtained for the attraction topology monotonically increases towards its end value, e.g. reaching 99% accuracy for $K \geq 9$. The repulsion topology oscillates towards its end value, where 3 consecutive images are required to reach 99% accuracy. It is observed that for $K = 50$ both topologies exhibit less than 0.04% deviation, which is well below the discussed 1‰ accuracy. Therefore, this value of $K$ is used in the analytical calculations below.

To validate this direct method, a comparison of the results is made with forces obtained by linear 3D FE calculations. In this analysis, the magnet height, $h_{mag}$, is varied, where the other parameters are defined in Table II. The results, shown in Fig. 11, demonstrate that the analytically obtained force results correspond well with the numerical simulation, i.e. less than 2% and 0.8% respectively for attraction and repulsion magnetization. Further, it is observed that the configuration having attracting PMs exhibits a larger interaction force, which is caused by the attractive force exerted between each PM and the soft magnetic material.

**Table II**

<table>
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</tr>
<tr>
<td>$g$</td>
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</table>

Fig. 7. Experimental setup.

Fig. 8. Interaction force between a permanent magnet and a solid steel plate for various airgap lengths, obtained analytically (solid line), numerically (circles) and experimentally (crosses).

Fig. 9. Definition of the variables used for verification of the interaction force between PMs having back-iron with (a) the attraction topology and (b) the repulsion topology.

**Table II**

<table>
<thead>
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<td>$h_{steel}$</td>
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<tr>
<td>$B_r$</td>
<td>T</td>
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<tr>
<td>$g$</td>
<td>mm</td>
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</tbody>
</table>
Fig. 10. Analytically obtained interaction force, normalized to its end value, as a function of the number of consecutive images, $K$.

Fig. 11. Interaction force obtained analytically and by means of FEM.

Fig. 12. Vertical interaction force obtained in FEM normalized to the analytically obtained force versus the horizontal size.

Fig. 13. Equipotential contours on a cross section of (a) the repulsion topology and (b) the attraction topology.

V. INFLUENCE OF FINITE MATERIAL DIMENSIONS ON INTERACTION FORCE

In this section, the influence of finite steel dimensions on the interaction force between PMs attached to this steel, which was illustrated in Fig. 5, is investigated using 3D FE analysis.

A. Soft magnetic material sizing

General dimensions were defined in Table II. The length and width of the soft magnetic material are simultaneously varied, hence, $w_{\text{steel}} = l_{\text{steel}}$ and $y_{\text{mag}} = x_{\text{mag}} = \frac{w_{\text{steel}}}{2}$. Results are normalized to the force obtained by analytical means ($K = 50$), i.e. 154.3N and 69.2N respectively for the attraction and repulsion topology.

The results, shown in Fig. 12, demonstrate that the FEM interaction force for the repulsion topology remains within 1.1% of the analytically obtained value even for small dimensions of the back iron, whilst the force obtained for the attraction topology decreases exponentially when horizontal size is reduced. The reason for this is illustrated in Fig. 13(a) and (b), which displays the equipotential contours in an $xz$-cross section through the center of the PMs for both topologies. It demonstrates that the magnetic flux is confined to a small volume in the repulsion topology, hence, the soft magnetic material dimensions can be significantly reduced without impairing the interaction force. In the attraction topology, shown in Fig. 13(b), magnetic flux is distributed horizontally and returns through the air volume between the soft magnetic materials. As a result this topology is more sensitive to reduced dimensions, since these directly influence the flux path.

A reduction of the horizontal equipotential contour distribution in the attraction topology is provided by the modified attraction topology shown in Fig. 14. Here, dimensions are maintained equal to those used above, where the PMs have been divided into two antiparallel magnetized parts. Fig. 15, in which $l_{\text{steel}}$ and $w_{\text{steel}}$ are simultaneously varied, demonstrates that the influence of reducing the soft magnetic material dimensions on the interaction force is very small, i.e. less than 1% deviation for $w_{\text{steel}} = 22$mm. Although applicable for most application, this error is still too large for the lithographic suspension application. A possible cause is saturation of the steel, where Fig. 16 shows the magnetic flux density. Although that the peak flux density in the linear steel is very high, i.e. more than 2T, the bulk flux density is well below 1T, which only slightly influences the force level. Therefore, the error in the force prediction is not solely caused by saturation and further research will be undertaken.
which additional characteristics have to be included to further improve the force accuracy by means of analytical, FE and measurements.

VI. CONCLUSION

This paper has investigated the suitability of the method of images combined with analytical surface charge modeling for a permanent magnet based suspension system, specifically, for incorporating soft magnetic material. Analytical tools, based on a combination of the surface charge model and the method of images, have been described and validated using finite element modeling and experiments. Although relatively high correspondence is observed, it is shown that the lithographic suspension requires an accuracy in the order of 1‰, which requires further investigation into accurate modeling tools.

For the topology with PMs between soft magnetic material, the influence of the number of consecutive magnetic images on the interaction force has been researched. 3D finite element modeling is further utilized to investigate the influence of finite steel dimensions on such topology. It is shown that a topology having two parallel magnetized permanent magnets, i.e. an attraction topology, exhibits a significantly reduced interaction force when the back iron size is decreased. This effect is significantly smaller for a topology having antiparallel magnetized permanent magnets, i.e. a repulsion topology, and it is shown that it is due to the horizontal flux distribution in the attraction topology. By modifying this topology, flux is focused in a limited horizontal space, hence, the influence of limited back iron size on the interaction force is reduced to almost zero.

From the work presented in this paper, it is concluded that analytical surface charge modeling combined with the method of images provides accurate results for modeling permanent magnets on a soft magnetic support structure. However, for the lithographic suspension, the modeling accuracy needs to be even further increased. This is the focus of future research by investigating end effects, saturation, hysteresis, eddy currents, measurement noise, etc.

REFERENCES