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Bearing Lifetime of Linear PM Machines

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Abstract -- With the ever advancement and increased force density of slotted brushless linear permanent magnet (PM) actuators the attraction forces become more dominating. In the early years this attraction force was advantageous, although that it now becomes a problem due to the reduced bearing lifetime. This lifetime is influenced by the lubrication, rolling contact fatigue, time of operation, metal selection and pre-loading. As such, the attraction force of slotted linear permanent magnet machines has to be compensated to extend the maintenance free operating time of contactless Pick-and-Place robots. This has been achieved by counteracting the attraction force with passive permanent magnets placed underneath a soft-magnetic plate. Various ways to calculate the attraction force will be explained in this paper, where it will be shown that 2D finite element analysis suffices and that implementing this passive attraction force compensation considerably extends the bearing life.

Index Terms — Bearings, magnetic levitation, linear motors, linear synchronous motors, electromagnetic analysis, actuators, brushless machines and electrical machines.

I. INTRODUCTION

The increasing prevalent industrial use of permanent magnet (PM) linear motors in various precision metrology, semiconductor processes and miniature system assembly are self-evident testimonies of the effectiveness of these linear synchronous motors in addressing the high requirements associated with these application areas. As such, today’s brushless PM linear machines are evermore implemented, since they incorporate a high power and torque density and provide the most efficient motor technology available to the industry [1, 2]. Various linear machines topologies exhibit ever-increasing force densities, especially due to the ever-improvement of versatile design capabilities [3, 4, 5]. Further, high accuracies at fast movements can be achieved, which results in consistent and repeatable performances, e.g in manufacturing automation [6]. Here robot manipulators for the pick-and-place (P&P) and assembly tasks require both accurate positioning and high speed motion [7].

Pick-and-place robots are used to automate electronic components mounting or placements on print circuit boards (PCB). An example of such a machine is the AX-501 component mounter (Fig. 1) with a maximum of 20 individual parallel P&P robots. This machine is capable of placing up to 165,000 components per hour (cph); around 8,000 cph per robot with an accuracy of 40 µm at 3 sigma.

Fig. 1. AX-501 component mounter (Philips-Assembléon).

Each robot is equipped with a single nozzle placement head [9, 10] and is able to pick components from a limited number of feeders located at the front side of the machine (Figs. 1 and 2). After picking, each robot will move the component to the correct placement location above the PCB. During travel, the component will be aligned by a laser align sensor. In this case, alignment will not add time to the P&P cycle and thus high cph outputs are possible. The main advantages of this modular machine concept are output and component-type flexibility, parallel P&P actions, in-situ feeder replacements and static PCBs. However, the number of feeders is directly related to the number of accommodated placement robots on the machine and the output can be sensitive for component clusters on PCBs.

Currently, various technologies are investigated to increase the throughput of these P&P robots [11], where in order to achieve elevated accelerations and speeds at an ever-
improving accuracy, a long-stroke direct-drive brushless linear PM motor in cooperation with contactless energy and data transfer is preferably used (Section II). However, even this contactless P&P robot still has frictional contact that results in bearing failures (Section III). The particularities of the moving coil linear motor will be explained in Section IV, where Section V will illustrate the bearing lifetime and how using attraction forces this can be prolonged. Numerous ways to calculate these passive attraction forces are discussed in Sections VI and VII, where Section VIII shows attraction force measurements and Section IX discusses an additional practical implementation. Finally, Section X presents the conclusions.

II. CONTACTLESS ROBOT

In many high precision applications (Fig. 1), the moving-coil linear PM actuator is applied due to its commercial maturity and relative simple sensor technology. The aim of the contactless robot demonstrator was to develop enabling technologies to operate a high performance P&P robot to increase reliability, lower overall cost and improve output and accuracy. Ideally, the contactless energy transfer (CET) should be integrated within the linear actuator, however currently this is still within the research phase and not commercially available [12, 13]. Also a linear motor that works either as transformer or motor has previously been presented, however it cannot operate in both modes simultaneously [14]. For slotted machines CET can be obtained via high frequency sliding transformers mounted separately along the mover of the PMLSM [15], which has also been implemented in the contactless robot of Fig. 3.

Of course, a truly contactless high-performance P&P robot has no moving cables, “Intelligent head” distributed control, integrated contactless energy and data transfer, increased output, direct-drive motor and no frictional contact (hence magnetic or air bearings) [16]. However, due to cost considerations some contact still exist, namely the air tube for component clamping, shield to provide an earth to the moving parts and linear friction bearings. These bearing are subject of investigation in this paper, where they are prone to failures which are discussed in the next Section.

III. BEARING FAILURES

To enable the linear motion most often rolling elements [7] or pressurized bearings are used [17, 18]. For performance considerations iron-core motors are often used, but they can cause excessive loading and premature failure of rolling elements (Fig. 4). As such, linear bearings typically have to deal with two kinds of loading, vertical and horizontal, although that also torque could be exerted on the bearings. Depending on were the bearing is used, it may see all gravity (vertical) force, all thrust (horizontal) force or a combination [19].

Typically, bearing life is compromised by:
1. lubrication (back-and-forth rolling causes many stops, or zero rolling velocity, which will cause the lubrication to be thin or squeezed out),
2. rolling contact fatigue (characteristic of advanced rolling contact fatigue by means of pitting causes large amounts of metallic wear debris),
3. time of operation (bearing catalog life is determined by the occurrence of contact fatigue under ideal conditions),
4. metals used (e.g., 440 C stainless steel has a life factor of 0.6 compared to the carbon steel 52100 of 3.0), and
5. pre-loading (the most common cause of premature contact fatigue is overload because it increases stress and thins oil films).

By carefully selecting the commercial linear bearings 1-4 can be optimized [20], especially after rigorous bearing failure investigations [21]. However, especially for horizontally placed linear bearings 5 can only be optimized by reducing the gravitational force that is exerted on the linear bearings. A very elegant way to reduce this force is to use integrated passive attraction force compensation as addition to the moving coil linear motor.

IV. MOVING COIL LINEAR ACTUATOR

The moving-coil linear PM actuator has the disadvantage
that attraction force is apparent in both moving-magnet and moving-coil linear PM machines. In these direct-drive iron cored brushless permanent magnet (PM) linear actuators, silicon laminations are used to maximize the thrust forces. However, these iron cores also introduce both cogging and attraction forces between the iron mover and the PM’s. Most commercial brushless PM linear machines are designed to minimize these forces to allow them to be used in high precision constant velocity applications. However, in this respect the attraction force is, in general, less considered in the design of PM actuators although that [22] reports a double sided moving magnet linear actuator that has a reduced attraction force. In most linear applications having some attraction force can be advantageous, e.g. to preload the air of mechanical bearings. However, if large attraction forces are apparent, this will impede on the bearing lifetime. Therefore, some passive attraction force compensation components can be used to counteract these forces (Fig. 5).

V. BEARING LIFETIME

The linear bearings in this moving-coil linear actuator system (Fig. 5) should be taken very large, however this would occupy a large proportion of the available space, hence it would be beneficial to minimize the linear bearing by providing a passive attraction force that counteracts the gravitational and attraction force. This lighter linear bearing system enables more rapid movements and the costs are considerably lower, whilst its lifespan will be longer [23]. For example, the selected smaller linear bearings for the P&P demonstrator robot are a commercial rail guide assembly (Speedi-Roll size 25), where the robot is assumed to have a length of travel of 1500mm with a stroke frequency of 5Hz. This linear guide system provides rigidity and torque resistance and consists of a guide rail and a carriage with three rollers. The rail is composed of a drawn and anodized aluminum body with hardened steel angle raceways fitted on each side. The aluminum base plate of the carriage, which is also anodized, houses the factory-fitted rollers. The load, centrally applied on these linear bearings, is assumed to be constant in magnitude and direction (see Fig. 5). The static load rating of this bearing system is 1400 N and is expected to be moved smoothly without any shocks, where the life of the linear table, in km and hours of operation, as well as the static safety factor of the system has to be known. As such, the lifetime in modified nominal working hours, \(L_{life}\), is calculated by [6]:

\[
L_{life} = \frac{50000 \left( \frac{C f_i}{P f_d} \right)^3}{s f_L n f} \sqrt{\frac{3}{60}}
\]

where \(s\) is the stroke in m, \(n_f\) is the frequency of the stroke in minutes, \(C\) is a linear bearing constant, \(f_i = 0.8\) (for only normal force) and \(f_d = 1.0\) (for smooth load conditions). For a commercial linear PM actuator the attraction force combined with an additional pay-load mass of 7.5 kg leads to a total attraction force by the moving coils of approximately 975 N (TL6 www.tecnotion.com).

A. Passive pre-load reduction

Numerous active or passive solutions can be investigated to reduce this attraction force, where compensating passive components have the positive peculiarity that they are cheap, require negligible energy consumption and can be used with an unlimited track length. One possible solution for such a passive magnetic levitation system is to use passive attraction compensation (Fig. 5). This passive attraction compensation has the advantage that only little PM material is required, however has the disadvantage that a construction is needed to enable the PM to be placed so that the compensating attraction can be utilized, although that in e.g. a pick-and-place application this construction could be used to mount the placement actuators (dashed area at the bottom of Fig. 5).

Another possible solution for the magnetic levitation system is passive repulsive compensation on top of the linear actuator, which is based on two magnetic guides, with PMs. These magnetic guides provide the lifting force by employing the repulsive force generated by the interaction between a long magnet, mounted along the way and short permanent magnet mounted on the moving coil assembly. This configuration has the advantage that it does not require a separate construction, however it does increase the width of the pick-and-place robot which is not desirable in a P&P machine that employs multiple robots [8].

B. Linear bearing lifetime

Assuming the use of 3 linear bearing units, the dynamic load per bearing is 325 N, which results in a bearing lifetime of 1.5 year. This, for example, requires an attraction force compensation of 575 N for a sought after bearing lifetime of approximately 10 years. The next section presents passive magnetic solutions to provide for this, mainly, vertical force compensation.
VI. ATTRACTION FORCE: ANALYTICAL CALCULATION

A. 2D Attraction force calculation

The passive attraction force of a PM to iron can be calculated using the Maxwell stress tensor. This tensor has to be integrated over a closed surface in air around the magnet array to calculate the total attraction force on the permanent magnets. The force on the magnets is obtained by:

\[
F_{\text{att}} = \int \frac{1}{\mu_0} \begin{bmatrix}
\frac{1}{2} \left( B_x^2 - B_y^2 - B_z^2 \right) & B_x B_y & B_x B_z \\
B_x B_y & \frac{1}{2} \left( B_x^2 - B_y^2 - B_z^2 \right) & B_y B_z \\
B_x B_z & B_y B_z & \frac{1}{2} \left( B_x^2 - B_y^2 - B_z^2 \right)
\end{bmatrix} \cdot n \, dS
\]

where \( B_x, B_y \), and \( B_z \) are the flux densities, \( n \) is the unity vector perpendicular to the surface element \( dS \). In this analysis the \( B_x \) and \( B_y \) are considered to be zero, since, neglecting fringing, all the flux flow along the z-axis (Fig. 3). The \( B_z \) component can also be considered as the flux density within the middle of the airgap, \( B_g \), which simplifies (3) to:

\[
F_{\text{att}} = \frac{B_z^2 A_m}{2 \mu_0}
\]

(3)

where \( A_m \) is the total area of both permanent magnets, \( u_0 \) is the relative permeability of air and \( B_g \) is the flux density can be expressed by neglecting saturation or leakage effects by:

\[
B_g = \frac{B_y}{1 + \mu_s \frac{l_g A_m}{l_m A_g}}
\]

(3)

In this \( l_g \) and \( l_m \) are the airgap and magnet length, \( A_g \) and \( A_m \) are the airgap and magnet area. Using a high grade NdFeB magnet the remanent flux density, \( B_r \), is 1.23 T and the recoil permeability, \( \mu_r \), of 1.05.

B. 3D Attraction force calculation

Considering the topology of two permanent magnets between iron bodies, normally the Finite Element Method (FEM) would be used to calculate the attraction force between the bodies, however, this method is rather time consuming. Therefore, an analytical approach is considered.

The 3D analytical surface charge method [24], provides fast solving analytical expressions of the interaction force between permanent magnets in free space. More specifically, these analytical solutions are not mesh based, and therefore exhibit their high accuracy especially at large magnetic field gradients (e.g. the magnet edges) [25]. This makes them especially suitable for applications having small air gaps.

In [26] it is shown that the 2D field of a charged particle placed between two infinitely large and infinitely permeable half planes is equal to the field of an infinite array of images placed equidistant below the surface (Fig. 7).

In the analytical charge model, it is assumed that there are no materials present that influence the magnetic field, where the pre-load compensator incorporates significant volumes of flux-focusing material. In the analytical mode, these high-permeable surfaces are dealt with using the charge imaging method. This method is based on that the field due to a magnetically charged particle placed above an infinitely permeable half space equals the field as if an oppositely charged particle would be placed equidistant below the surface (Fig. 7).

In [26] it is shown that the 2D field of a charged particle placed between two infinitely large and infinitely permeable half planes is equal to the field of an infinite array of images

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TABLE I
INITIAL GEOMETRY DIMENSIONS

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationary core length     ( l_{sc} )</td>
<td>5.0 mm</td>
<td></td>
</tr>
<tr>
<td>Airgap length ( l_g )</td>
<td>0.3 mm</td>
<td></td>
</tr>
<tr>
<td>Magnet length ( l_m )</td>
<td>4.0 mm</td>
<td></td>
</tr>
<tr>
<td>Moving core length ( l_{mc} )</td>
<td>5.0 mm</td>
<td></td>
</tr>
<tr>
<td>Extra width ( dL )</td>
<td>1.0 mm</td>
<td></td>
</tr>
<tr>
<td>Magnet pitch ( t_m )</td>
<td>8.0 mm</td>
<td></td>
</tr>
<tr>
<td>Between magnet pitch ( t_{bas} )</td>
<td>0.1 mm</td>
<td></td>
</tr>
</tbody>
</table>
of this particle, mirrored in the surfaces of the half planes. Since the charge model expresses the permanent magnets as charges, the imaging technique is applied to model permanent magnets between iron volumes, although in 3D instead of the 2D described in [26]. Here, it is assumed that the iron volumes are infinitely permeable and infinitely large [27]. The result of such imaging is schematically shown in Fig. 8. Although the number of images should be infinitely high for exact results, it has been found that applying 5 consecutive images in each half plane are sufficient to obtain accurate values for the attraction force. In total this gives 11 permanent magnet images of each PM along the vertical axis, all having the same dimensions as the original magnet. The sign change occurring for each image causes the magnetization pattern shown in Fig. 8b.

![Fig. 8 Schematic representation (a) 2 PMs between infinitely permeable half spaces and (b) the equivalent array of images in air.](image)

Applying the dimensions of Table I, the 3D analytical interaction attraction force obtained from the analytical model is 487N, which is well below the attraction force obtained from the 2D analytical model. Hence, a longer axial length is selected to be 83 mm, which provides a force of 578 N. This is only caused by fringing, which is not incorporated in the 2D analytical model. Further, the analytical model does not consider saturation, hence a further numerical analysis is necessary to determine the back-iron thicknesses.

**VII. ATTRACTION FORCE: FINITE ELEMENT ANALYSIS**

**A. 2D Attraction force calculation**

A 2D finite element analysis is used to incorporate the saturation effect, since it is more time efficient than the 3D analysis. In this analysis the materials used are the same as mentioned before, however additionally a non-linear mild-stell BH characteristic is implemented for the back-irons. Applying the dimensions of Table I with a large back-iron, $l_{sc}$ and $l_{mc}$, of 10 mm to the geometry of Fig. 6, results in an attraction force of 7000 N/m, hence using an axial length of 82 mm provides attraction force of 575 N respectively.

![Fig. 9 Equipotential contours and flux density for the passive attraction force with the initial dimensions of Table 1.](image)

However, this back-iron length is not realistic and therefore the dimensions of Table I are used (Fig. 9), which decreases the attraction force to 6900 N/m, hence an axial length of 83 mm is required to attain the 573 N attraction force, which is equivalent to the axial length from the 3D analytical model.

To improve the model of Fig. 6, the influence of the magnet length, $l_{mc}$, on the attraction force is investigated (Fig. 10). This Figure shows that increasing the magnet length enhances the attraction force albeit at a diminishing rate. For example, a magnet length of 1.5 mm instead of 4.0 mm (62.5% reduction), only reduces the attraction force by 88 N (i.e. 578 N to 490 N or 15%). The corresponding total moving mass reduction is respectively 27.0 gr (or 31%), i.e. a 1.5 and 4.0 mm magnet length have a mass of respectively 60.5 and 87.5 gr (magnet and steel density respectively 7500 kg/m³ and 7600 kg/m³).

![Fig. 10 Variation of magnet length versus attraction force for the dimensions of Table 1.](image)

It seems likely that some force improvement could be obtained when increasing the space in between magnet pitch, $\tau_{bm}$, since it will reduce the magnet flux leakage. This was investigated, and however increasing this to 1.0 mm increases
the force by only 1% (for $l_m = 1.5$ mm). Additionally, the back-iron thickness is varied to investigate its influence on the force, where a back-iron thickness of 5.0 mm is a good compromise to maximize the force from an extended back-iron thickness. Indeed a clear dependency of the back-iron thickness and the width of the magnet is apparent, hence a more comprehensive analysis was undertaken (Fig. 11) to illustrate the influence of both the back-iron thickness and magnet width on the attraction force. Clearly a very non-linear behavior becomes apparent when the back-iron saturates, which reduces the attraction force. This also influences the maximum achievable force for various magnet pitches, which shows the same linear characteristic as would be determined by the analytical method as discussed in the previous sections.

![Fig. 11. Variation of magnet pitch versus attraction force for various back-iron thicknesses.](image)

Finally, it is also interesting to investigate the relationship between the mass and the magnet length, hence an analysis is undertaken to investigate this dependency. In this analysis all the remaining dimension are fixed to the values summarized in Table 1. Fig. 12 shows the magnet length versus axial length and the magnet length versus the magnet mass to achieve an attraction force of 575 N. This excludes the back-iron, which would only slightly amplify the values within this figure. Further, the magnet mass is arguably the most important characteristic, since it directly translates into costs of the compensator.

![Fig. 12. Variation of magnet length versus axial length and magnet length versus mass for an attraction force of 575 N.](image)

TABLE II

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stationary core length</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>Airgap length</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Magnet length</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>Moving core length</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>Extra width</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Magnet pitch</td>
<td>8.0 mm</td>
</tr>
<tr>
<td>Between magnet pitch</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Axial length</td>
<td>93 mm</td>
</tr>
</tbody>
</table>

B. 3D attraction force calculation

The objective of this finite element study is to determine the force of the passive attraction and gravity permanent magnet compensator. The 2D model has been useful for determining the various influences of the variables in the 2D environment, where the effects of steel grade selection and 2D fringe effects are accounted. To complete the study also the 3D (axial) fringe effects are accounted for by a three-dimensional (3-D) finite element model (Fig. 13), i.e. the 2D and 3D analysis provided an attraction force of 565 N and 559 N respectively.

![Fig. 13. 3D finite element mesh (2800000 elements) for the dimensions of Table 2.](image)

VIII. FORCE MEASUREMENTS

In the previous sections analytical and finite element tools to model interaction force between PMs with soft magnetic materials were discussed. Verification of the assumptions is performed in this section.

The analytical model is verified by means of FEM and
experiments, for a magnet length, \( l_m \), of 5 mm, magnet and steel axial length of 20 mm and 90 mm, magnet pitch, \( \tau_m \), of 20 mm, stationary core length, \( l_{sc} \), of 10 mm and an airgap of 1.0 mm and 2.0 mm, respectively. The PM material used is Vacodym 655HR with a \( B_r \) of 1.23 T, where the soft magnetic material is standard A11010 mild steel. Fig. 14 shows the experimental setup with the various components highlighted. For several airgap sizes, the PM is moved horizontally with respect to the soft magnetic volume along \( x \), where \( x = 40 \) indicates the middle position where centers of both objects are aligned. The software package used to obtain the numerical FEM result is Flux 3D [28].

Fig. 14. Experimental set-up to measure the attraction force of a single PM with soft-magnetic iron.

Fig. 15 presents the comparison of the results obtained by the three methods. The analytical results are obtained by a single computation, and show high correspondence with the FEM and measured results. Further, the FEM and measured curves demonstrate that the constant behavior of the attraction force, hence, the analytical model provides a good approximation of the interaction force for any position above the soft magnetic material.

Fig. 15. Interaction force between permanent magnet and soft magnetic plate for two airgap lengths, obtained analytically (squares), numerically (circles) and experimentally (solid line).

IX. COMMERCIAL P&P ROBOT IMPLEMENTATION

Besides the concept application presented in the introduction and the verification of the analytical tools in the previous Section, also these attraction and gravity force compensators [29] are commercially used in the P&P machine AX-201 that uses an H-bridge linear motor configuration (Fig. 16b where the passive compensator is encircled) [6]. As such, Fig. 17 shows the zoomed picture of the single DoF passive gravity compensator implemented in this P&P robot. The same approach was used to calculate the force as was presented in this paper, where a very good agreement was apparent between the 3D analytical calculations, measurements and finite element analysis.

Fig. 16. (a) AX-201 component mounter, with (b) H-bridge pick-and-place machine topology and encircled passive attraction compensator.

Fig. 17. Practically applied passive attraction and gravity force compensator.

X. CONCLUSIONS

In order to extend the bearing lifetime a passive attraction and gravity permanent magnet compensator is selected. This configuration incorporates high strength rare earth PMs and a low cost commercial soft-magnetic material. The influence of this device on the bearing lifetime has been investigated and various techniques for calculating the permanent magnet attraction force have been presented.

The relative dimensions have been optimized both by applying analytical equations as by implementing finite element models. The influences of the main variables have been presented, where a topology having a small magnet volume has been found and verified using 3D FEM and with force measurements on a separate test set-up. Further, a commercial P&P machine has been introduced that uses the passive gravity compensator to maximize the bearing lifetime.

To conclude, when a moving permanent magnet passes solid soft magnetic material at considerable speeds, eddy-
currents could appear that result in a damping force. These losses have been identified using transient FEM, however are completely negligible for the stroke frequency and length of 5 Hz and 1.5m, respectively.

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