Position controlled diamagnetic linear conveyor

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***Abstract*— In micro-factories mini-conveyors will be used to convey small parts and components between storage, production and assembly units. Since a clean environment as well as a low power consumption are some of the prerequisites for a micro-factory, it is essential that mini-conveyors used in such an application respect these requirements. In the present article the authors propose a new kind of position controlled conveyor that meets these conditions.**

***Index Terms*— diamagnetic levitation, conveyor, micro-factory, contact-less, contact-free.**

I. Introduction

Magnetic levitation is an interesting concept in applications where friction and wear-particle contamination should be avoided. In this respect, a former study [1] has shown that diamagnetic levitation, in conjunction with an electrodynamic impulse drive, is a promising solution for the design of a linear conveyor to be used in a micro-factory. In the present article the authors present a contact-free position controlled diamagnetic linear drive based on the conclusions of [1] and improved with regards to the power consumption and the load carrying capacity.

II. Diamagnetic Levitation

For most materials it is theoretically impossible to achieve a stable levitation using any combination of magnetostatic or electrostatic fields [2]; however, thanks to their negative magnetic susceptibility (Table I) it is possible to levitate diamagnetic materials (Fig.1), over carefully optimised arrangements of permanent magnets [3].

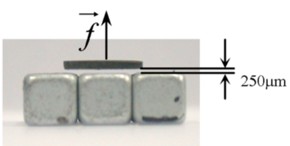

Fig. 1. Room temperature levitation of graphite

$$\vec{f} \prec \frac{1}{2\mu_0}\chi_m.\overrightarrow{grad}(B^2) \qquad (1)$$

The main idea is to mix the magnetic flux lines, for instance by arranging the magnets in a Halbach structure (Fig.2) or by alternating the polarity of neighboring magnets, so as to create a magnetic potential hole in which the levitated diamagnetic element is trapped.

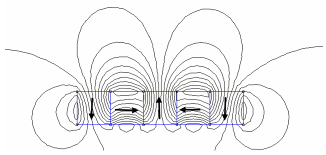

Fig. 2. Flux created by an Halbach arrangement of permanent magnets

One has to note that the diamagnetic force $\vec{f}$ (1) is weak due to the low value of the diamagnetic susceptibility (Table I) but it is the only passive levitation stable at room temperature.

TABLE I
Magnetic susceptibility of some diamagnetic materials

Material	$\chi_m(\times 10^{-6})$
Water	-9
Bismuth	-150
Graphite	-160
Pyrolitic Graphite	-450
Super Conductor	-10^6

III. Position controlled diamagnetic linear conveyor

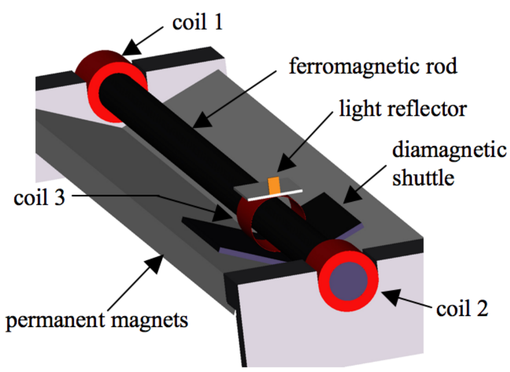

Fig. 3. Positioned controlled contact-free conveyor

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A. Mini-conveyor based on diamagnetic levitation

The main idea consists in using the diamagnetic force to levitate a shuttle made of pyrolitic graphite and to move it by means of non-contact electromagnetic forces. A small payload can then be carried in addition to the weight of the shuttle. Thanks to the limited number of mechanical components and the absence of contact between moving parts, such a conveyor is simple and is characterized by the absence of friction and mechanical wear.

A former study [1] showed that, to avoid generating large forces normal to the displacement of the conveyor, it is necessary to adopt a driving principle that relies on repulsive electromagnetic forces: electrodynamic impulse drives such as reluctance or induction coilguns meet this requirement. A prototype based on the Thompson jumping ring device (induction coilgun) has hence been implemented in conjunction with diamagnetic levitation (Fig.3).

B. Practical implementation

A “V-shaped” diamagnetic shuttle, (the flotor), which carries a light copper coil shorted on itself (Fig.3: coils 3), floats over a “V-shaped” rail, made of permanent magnets. Such a passive levitation arrangement results in both a vertical and lateral stable equilibrium of the conveyor.

The passively levitated shuttle is linearly set in motion by a driving force based on the principle of the Thompson jumping ring device [4]: two coils (Fig.3: coils 1 & 2), mounted at each end of a plain cylindrical magnetically conductive rod, induce variable magnetic fields through a coil shorted on itself (Fig.3: coil 3) which is fixed to the diamagnetic shuttle and concentric to the rod. When the current is switched in one of the fixed coils, the resulting magnetic field, guided by the magnetically conductive rod, flows through the conveyor coil where it induces currents. These induced currents are flowing in a direction opposite to the driving current of the fixed coil and thus are generating a magnetic field that opposes the net magnetic field flowing in the rod. The resulting magnetic force therefore repels the coil fixed to the levitated shuttle and the shuttle moves away from the coil fixed at the end of the rail. Although this driving principle delivers pulsed forces, a 5 grams conveyor is propelled smoothly without any ripple using a square-shaped current switching at 400Hz.

C. Position control

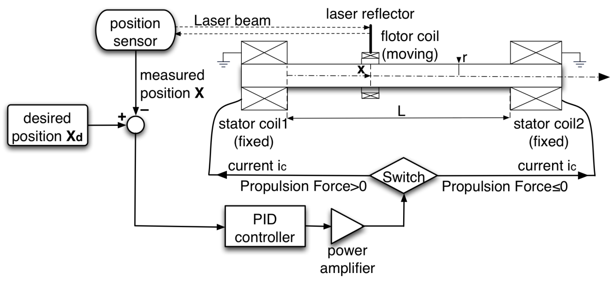

Fig. 4. Drive and position control of the diamagnetic conveyor

For a precise position control of the diamagnetic shuttle along its whole displacement range, a contact-less position sensor has been selected and included in a feedback loop comprising a PID controller (Fig.4).

In order to meet the requirements of a contact-less precise positioning (10s of μm) over a large displacement range (10s of cm), a laser position sensor has been choosen: a laser beam is reflected on a small target fixed to the conveyor (Fig.3) and the distance is computed by triangulation between the emitted and the reflected light rays.

The driving force exerted on the flotor is a repulsive force and has the same expression as the force exerted on the ring of a jumping ring device. It can be shown [4], with some simplifying hypothesis, that the average value of this force has the following expression (2):

$$F = K\frac{I_c^2}{X} \quad (2)$$

where I_c is the maximum current in the fixed coil and K is proportional to ω. A finite element analysis of our system, using *femm* [5], confirmed (Fig.5) that this equation (2) is applicable in our case.

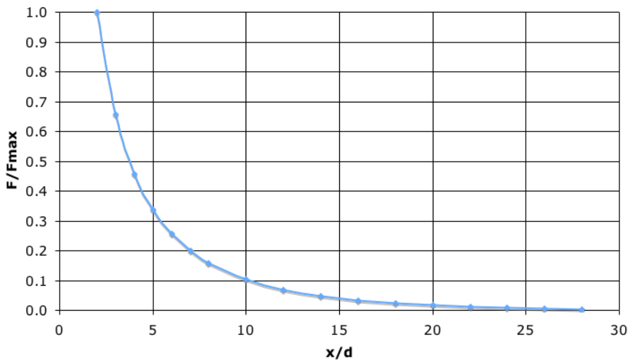

Fig. 5. Average driving force as a function of x/d

We have chosen to drive the conveyor using a square shaped current instead of a sinusoidal current because the faster the current variation, the higher the magnetic force. Thanks to Fourier series theory, a square shaped current can be written as a sum of sinusoidal currents; Hence, we can use the sinusoidal approach to analyse this linear drive and then, using the superposition theorem, we can conclude for the square shaped current case. As a matter of fact, because of saturation and hysteresis phenomena, the analysed magnetic system is not linear and the superposition theorem should not strictly be applied, however this approach gives us a fair enough information on the overall behavior of the system and on the parameters of interest.

As we can see (Fig.5) d being the diameter of the rod, the propulsion force F is:

- $F_{max}/3$ when the center of moving coil is $6d$ away from the driving coil.
- and only $F_{max}/20$ when the center of moving coil is $15d$ away from the driving coil

Thus, to lose as little energy as possible and to exploit the maximum of the propulsion force on the longest range as possible, we have implemented a controller which drives only one coil at a time: i.e. the controller switches from coil1 to coil2 when the sign of the computed propulsion force is changing. The experimentally implemented position controller is a PID controller which parameters have been tuned by hand through a Matlab xPC realtime system.

The best positioning precision achieved with our prototype was $\pm 50\mu m$ and it is obtained when the levitated shuttle is close to the driving coil ($x \leq 6d$). In the region in the vicinity of the driving coil, we took advantage of a passive natural phenomenum that traditionally occurs near the extremity of the permanent magnets arrays used for diamagnetic levitation: without any current in the driving coils, the diamagnetically levitated element is attracted towards the extremity of the permanent magnet arrangement (region with a low magnetic induction); this phenomenum together with the force created by the farther driving coil, contributes to the restoring force needed when the moving coil goes past the desired position. Then, given both the high value of the force and the rapid variation of the propulsion force with regards to displacement (high rigidity), it was thus possible to precisely control the levitated shuttle close to the driving coil. However, it was not possible to precisely control the position of the shuttle far away from the driving coil ($x \geq 15d$) because of both the low value of the force and the slow variation of the force with regards to the displacement (low rigidity).

D. Optimization of the load carrying capacity

The load carrying capacity has been optimised using the V-shape angle α as a parameter and a good lateral stability as a constraint.

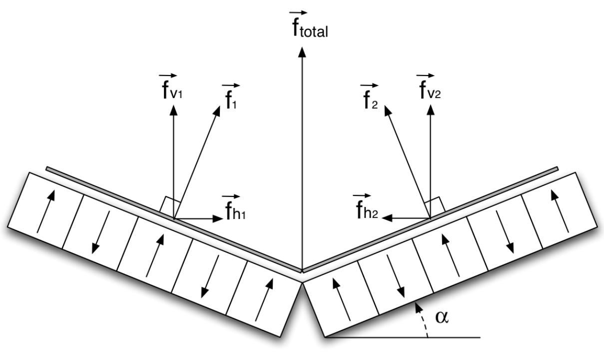

Fig. 6. Diamagnetic forces on the conveyor

As we can see (Fig.6) the total diamagnetic force $\vec{f}_{total}$ exerted on the diamagnetic shuttle by the permanent magnets, is the result of the summation of two diamagnetic forces $\vec{f_1}$ and $\vec{f_2}$ which are acting orthogonally and symmetrically on each diamagnetic plate constituting the shuttle. The lateral stability is related to $sin(\alpha)$ and the load carrying capacity is related to $cos(\alpha)$.

Originally the angle in between the two graphite plates, was 90°, ($\Leftrightarrow \alpha = 45°$). The optimal angle was found to be $\alpha = 22°$ since, compared to the original V-shape angle of $\alpha = 90°$, it results in:

- a 25% increase of the load carrying capacity ($\Leftrightarrow 95\% f_{max}$)
- and only a 40% decrease of the lateral stability ($\Leftrightarrow 30\% f_{max}$)

IV. Power transfer optimisation

The optimisation of the power consumption of the electrodynamic linear drive has consisted in increasing, as much as possible, the efficiency of the energy transfer from the stator to the flotor (i.e.: the diamagnetic shuttle).

To optimise the power consumption of the proposed conveyor, we must maximize the power transferred from the power amplifier to the fixed coils as well as the power transferred from the fixed coils to the moving coil.

In our case the principal sources of power losses are:

- Eddy current losses
- Mismatch between the fixed coils and the power amplifiers
- Bad design of the moving coil

In the following sections we will successively address these three points.

A. Minimizing eddy currents losses

When a conducting media is subjected to a time varying magnetic field, eddy currents appear and result in energy losses. In our specific case some eddy currents are generated in the rod used to guide the magnetic field through the shuttle coil (Fig.3: coil 3) and, because of the axisymmetrical geometry of the jumping ring linear drive, it is quite easy to find a good approximate analytical expression of theses eddy currents. Indeed the Maxwell-Faraday's equation (3)

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} = -\mu \frac{\partial \vec{H}}{\partial t} \quad (3)$$

implies that

$$\oint_{coil} \vec{E}.d\vec{l} = \mu \oiint_{coil} \frac{\partial \vec{H}}{\partial t} d\vec{S} \quad (4)$$

and, with the simplifying hypothesis that the magnetic induction $\vec{B}$ inside the rod is only a function of z, (4) can be simplified as (5)

$$2\pi r E = -\mu \pi r^2 \frac{\partial H}{\partial t} \quad (5)$$

and since

$$\vec{j} = \sigma \vec{E} \quad (6)$$

we can finally write the expression of the eddy currents generated in the rod section:

$$j(r,t)\vec{u}_r = -\frac{\mu \sigma r}{2} \frac{\partial H}{\partial t} \vec{u}_r \quad (7)$$

In the case of a sinusoidal magnetic field, (7) can be simplified as

$$j(r,t)\vec{u}_r = -\frac{\mu \sigma r}{2} \omega H_0 \cos(\omega t) \vec{u}_r \quad (8)$$

and the power losses due to eddy currents in the rod can thus be expressed as

$$P_{ec} \propto \mu^2 \sigma r^2 \omega^2 H_0^2 \tag{9}$$

Using a laminated structure would minimize these eddy current losses by an additional factor inversely proportional to the square of the number of laminations; In our specific case we need a lengthy (tens of cm) and slim (diameter $\simeq$ 5mm) cylinder with laminations parallel to the length. However we could not encounter such a slim and lengthy laminated cylinder and it would be difficult to manufacture it from a laminated plate without damaging the lamination during the process.

As we can see from (9) a solution to minimize eddy current losses and allow rapid flux variations is to select a low conductivity material for the rod. When a ferrite ($\mu_r = 2000$, $\sigma = 1[\Omega^{-1}.m^{-1}]$) is used instead of an iron rod ($\mu_r = 1000$, $\sigma = 10^7[\Omega^{-1}.m^{-1}]$), the power losses due to eddy currents become totally negligible.

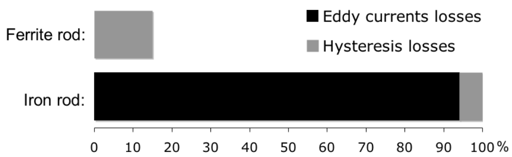

Fig. 7. Total power losses @400Hz, normalized with respect to $P_{total\ iron}$

A finite element analysis of our problem, using *femm* [5], confirmed this analytical result (Fig.: 7).

B. Matching the fixed coils and the power amplifiers

In a second phase the stator coils (Fig.3: coils 1 & 2) have been optimised, using finite element analysis, in order to match the power amplifiers used to drive them.

Generally speaking a power amplifier is designed to optimally drive a specific load: the power transfer from the amplifier to this load is then maximum.

The process of selecting the right load to maximize the power transferred from a power amplifier is known as impedance matching and, indeed, it consists of matching the value of the internal impedance of the power amplifier to the impedance value of the load. In this case it can easily be shown that the transferred power is maximal and corresponds to half the total power.

In our case the power amplifier used is a Linear Servo controller LSC 30/2 made by Maxon® motor and it is designed to drive a load $Z_l = R + jL\omega$ with $R = 2.1\Omega$ and $L = 0.68mH$. Since the inductance of a multi-turn coil has a very complex analytical expression [6] we have used finite element analysis to design the fixed coil and match its impedance to the output impedance of the linear amplifier.

C. Moving coil design

The design of the moving coil has a direct impact on the expression of driving force F (2) exerted on the flotor by the stator. Indeed, assuming that the inductance L_c of the fixed coil and the inductance L of the moving coil are independent of x, the driving force (11) can also be derived from the change of the magnetic energy W_m (10); i_c and i being the current flowing respectively in the fixed and the moving coils:

$$W_m = \frac{1}{2} L_c i_c^2 + \frac{1}{2} M i_c i + \frac{1}{2} L i^2. \tag{10}$$

$$F = \frac{dW_m}{dx} = i_c i \frac{dM}{dx} \tag{11}$$

(11) shows that, to maximize the driving force, we should maximize the variation of the mutual inductance M with respect to x and maximize the current i induced in the moving coil. Knowing this, we will now determine the key parameters that should be tuned in order to carry on the design optimisation of the moving coil.

First of all, let us note that, because of the axisymetrical geometry of the drive based on the jumping ring device, the total magnetic induction $\vec{B}$ flowing through the core can be written as the sum of a horizontal component $\vec{B}_x$ and a radial component $\vec{B}_r$

$$\vec{B} = \vec{B}_x + \vec{B}_r \tag{12}$$

The mutual inductance M between the fixed stator coil and the moving flotor coil, is not simple to calculate. By definition we can write it as (13)

$$M = \frac{N\varphi(x)}{i_1} \tag{13}$$

where N is the number of turns of the moving coil and $\varphi(x)$ the flux of the magnetic induction B_x flowing though the moving coil.

Similarly we can write the inductance L_c of the fixed coil (which is designed to match the amplifier output impedance) as:

$$L_c = \frac{N_c \varphi_c}{i_c} \tag{14}$$

where N_c is the number of turns of the fixed coil and φ_c the flux of the magnetic induction B_x flowing through the fixed coil.

Hence from (13) and (14) we can write that:

$$M = \frac{N}{N_c} L_c \frac{\varphi(x)}{\varphi_c} \tag{15}$$

It is not easy to evaluate $\varphi(x)$ but we can simplify the analysis by supposing that B_x is a decreasing linear function of x; however, when the size of the fixed coil is in the range of the rod diameter d, this hypothesis only holds as long as the distance x inside the rod is not too high compared to its diameter d. In our case, as we can see, thanks to a finite element analysis, the average magnetic induction B_x can be expressed as a concatenation of two decreasing linear functions of x over two contiguous segments (Fig.8).

Therefore the flux $\varphi(x)$ of the magnetic induction B_x through the section of the rod can also be written as

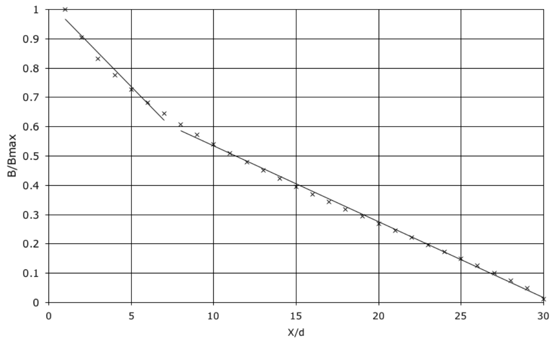

Fig. 8. Average magnetic induction along the rod

decreasing linear functions (16) (17) over each of the contiguous segments $[0, 7d]$ and $[7d, L]$

$$\forall x \in [0, 7d]: \quad \varphi(x) = \varphi_\alpha - k_\alpha x \tag{16}$$

$$\forall x \in [7d, L]: \quad \varphi(x) = \varphi_\beta - k_\beta x \tag{17}$$

Hence, putting in (15) the expression of $\varphi(x)$ as calculated from (16) and (17) we respectively obtain:

$$\forall x \in [0, 7d]: \quad M = \frac{NL_c}{N_c\varphi_c}(\varphi_\alpha - k_\alpha x) \tag{18}$$

$$\forall x \in [7d, L]: \quad M = \frac{NL_c}{N_c\varphi_c}(\varphi_\beta - k_\beta x) \tag{19}$$

As for the current i induced in the moving coil, it can be expressed as (20):

$$i = \frac{v}{Z} \tag{20}$$

where v is the induced voltage in the moving coil and $Z = R + j\omega L = |Z|\, e^{j\omega\Phi}$ is the impedance of the moving coil. The analytical expression of the moving coil self inductance L is too complex [6] to allow us to quickly draw a conclusion relative to the optimisation of the moving coil design.

The induced voltage in the moving coil is related to the electric field $\vec{E}$:

$$v = \oint_{coil} \vec{E}.\vec{dl} \tag{21}$$

In the case of a sinusoidal magnetic induction, $B_x = B_{x\max}\ sin(\omega t)$, hence (4) together with (21), implies that

$$i = -\frac{\pi d^2 \omega B_{x\max}\cos(\omega t - \Phi)}{4\sqrt{R^2 + (L\omega)^2}} \tag{22}$$

From equations (11), (18), (19), and (22) we can thus conclude that the expression of the propulsion force is:

$$F = i_c \frac{\pi d^2 \omega B_{x\max}\cos(\omega t - \Phi)}{4\sqrt{R^2 + (L\omega)^2}} \frac{kNL_c}{N_c\varphi_c} \tag{23}$$

As we can see from the previous equation, the following parameters should be as large as possible to optimize the propulsion force:

- The rod diameter d which is only limited by the dimensions of the micro factory.
- The longitudinal component of the magnetic flux induction $B_{x\max}$ which is limited by the rod material saturation and the fixed coil design.
- The number of turns N of the moving coil which is only limited by the size and the load carrying capacity of the diamagnetic shuttle

and the following parameters should be as small as possible to optimize the propulsion force:

- The resistance R of the moving coil which can be lowered by choosing a conductive material such as copper.
- The inductance L of the moving coil which, roughly said, can be lowered by lowering the diameter of the coil.

All the conclusions of the previous paragraph have been implemented on a prototype and, experimentally, the total power consumption has been decreased by a factor of 3 compared to the un-optimised prototype of linear diamagnetic conveyor described in our previous study [1].

V. Conclusion and perspective

Diamagnetic levitation in conjunction with electrodynamic impulse drives based on the jumping ring principle, opens up promising applications in the field of contact-free linear conveyors. A careful magnetic and mechanical design as well as a careful selection of magnetic materials can considerably improve the power consumption of such linear stages. One of the drawback of such linear drives is that precise positioning of the conveyor is difficult to implement over a large displacement range due to the fast decrease of the propulsion force. However this technology is particularly interesting for the design of linear stages used in pick and place applications where precise positioning near the edges of the conveyor's displacement range is sufficient; Furthermore, since this contact-less technology is particularly suited for short range precise positioning, it also opens up promising applications for the design of a new generation of sensitive contact-less inertial sensors such as accelerometers and inclinometers.

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