PRACTICAL APPLICATION OF A MAGNETIC BEARING AND LINEAR PROPULSION UNIT FOR SIX DEGREES OF FREEDOM POSITIONING.

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ABSTRACT

This paper describes a system for positioning a body in six degrees of freedom by using three electro-magnetic units for suspension and linear propulsion. The X-position and the Y-position can be controlled over a range of 10 mm. The Z-position can be controlled over a range of 1 mm. Angles around X, Y and Z can be controlled over a range of 5, 5 and 50 mrad, respectively.

A single Suspension and linear Propulsion unit (SPU) is an active magnetic suspension (bearing) system combined with a linear, magnetic propulsion system.

Firstly, this paper describes the principle of operation of an SPU. It will show how a stable magnetic bearing has been constructed and how propulsion in the direction perpendicular to the suspension direction is achieved. Attention will be paid to the interaction between the suspension and the propulsion forces. This interaction must be minimised for maximum system performance.

The second part of this paper will concentrate on the application of three SPU's in a system for positioning in six degrees of freedom.

INTRODUCTION

High precision positioning devices require accurate bearings that are free of friction as much as possible. Friction, together with the stick slip that can come along with friction, forms the limiting factor in the overall positioning accuracy in many devices.

Several kinds of bearings are developed to minimise friction. Most principles are focused on eliminating the heat generated by friction. One kind of bearing that has been specifically developed for friction-free performance in applications for high accuracy is the air bearing. There are many satisfying applications of air bearings but they do have their limitations. One very obvious limitation is the impossibility of using air bearings in vacuum. Outside the vacuum, the air stream accompanying this type of bearing is often not acceptable in view of clean room requirements (particle contamination).

It was recognised that bodies suspended by magnetic forces, thus avoiding mechanical contact, are frictionless and could operate in vacuum. Outside the vacuum, the absence of an air stream is advantageous in some specific cases. For these reasons the Laboratory for Micro-Engineering started to develop magnetic suspension units that, at the same time, are capable of applying a propulsion force to the suspended body. The Suspension and linear Propulsion Unit (SPU) was developed as part of this research initiative.

Examples of application are: wafer steppers for the IC manufacturing, microscope slides for scanning tunnelling microscopy and ultra precision slides for manufacturing machines. The Laboratory also develops capacitive position transducers that can be combined with the magnetic bearing and propulsion.

Other groups have done extensive research on rotary magnetic bearings. [1]. These bearings are applied for high speed rotating devices. The main goal there is the elimination of friction in order to achieve high rotational speeds. Two factors are important here: reducing the power losses caused by friction and eliminating heat production. The first magnetic bearing ever built [2], was also used for high speed rotation applications. There is a significant similarity between the theory, modelling and control of rotary bearings and the linear bearings described here.

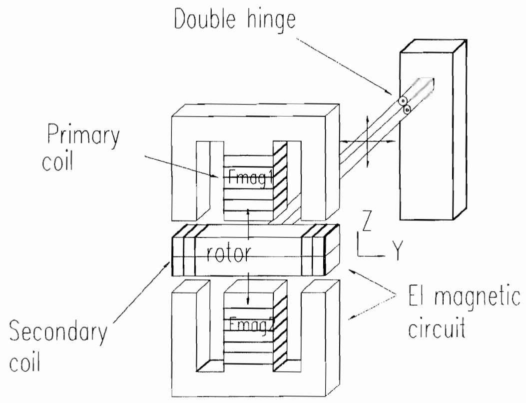

FIGURE 1. Experimental set-up of the Suspension and linear Propulsion Unit (SPU), showing the E-core electro-magnets and windings on the rotor for the generation of the Lorentz propulsion force. The rotor is connected to a fixed point by means of an arm, equipped with a double flexible hinge.

PRINCIPLE OF OPERATION

The principle of operation of the SPU is best illustrated by the experimental set-up shown in figure 1. The figure shows two E-core electro-magnets placed opposite of each other with two I cores placed between them. The I cores are part of the object that has to be suspended. This object is commonly called 'rotor', while the two E-core electro-magnets, being rigidly connected, form the 'stator'.

The rotor is connected to a fixed point by means of an arm that includes a double flexible hinge. Thus, four degrees of freedom are mechanically blocked and two degrees of freedom are left free. One of these degrees of freedom, Z, is controlled by the two EI-magnetic circuits. The bearing or suspension function is created in this direction. The coils generating the magnetic field for suspension are called primary coils.

In the Y-direction, propulsion is achieved by feeding a current to coils wound around the I-cores, thus generating a Lorentz-force. These coils are called the secondary coils. It is important to recognise that the same magnetic field used for the suspension is used for the generation of the Lorentz force. Eventually, the support arm is replaced by two other SPU's that will control the four degrees of freedom initially fixed by the arm.

SUSPENSION FORCES

The rotor is kept in place by two forces generated by applying the principle of electromagnetic reluctance. These forces are:

$$F_{mag1} = K_m \frac{I_1^2}{Z_1^2} \qquad F_{mag2} = K_m \frac{I_2^2}{Z_2^2} \qquad (1)$$

where:

K_m = constant representing magnetic circuit dimensions,
I_1 = current through the upper primary coil,
I_2 = current through the lower primary coil,
Z_1 = width of the upper air gap,
Z_2 = width of the lower air gap.

The forces influence the position of the rotor in the Z-direction. If no controller is used to control the currents through the coils, the position of the rotor will be unstable. It will move in upper or lower direction and stick to the E-core electro-magnet. Using a PID controller, the rotor position can be stabilised. This was thoroughly described in [3] and [4].

MAGNETIC FIELD

Of great importance is the strength of the magnetic field in the air gap of the magnetic bearing. The strength of this field can be found with:

$$B_1 = K \cdot \frac{(I_0 + \delta I)}{(Z_0 - \delta Z)}$$
$$B_2 = K \cdot \frac{(I_0 - \delta I)}{(Z_0 + \delta Z)} \qquad (2)$$

K = constant,
B_1 = magnetic field in the upper air gap,
B_2 = magnetic field in the lower air gap,
I_0 = stationary current,
δI = control current,
Z_0 = width of the nominal air gap,
δZ = fluctuations of the air gap width.

The current flowing through the primary coils is divided into two parts: the stationary current I_0 and the control current δI. Due to the chosen linearisation method, described in [3], the control current acts contrary to the measured displacement δZ. In this case linearisation is achieved by applying two sets of differentially wound coils to the magnetic bearing, producing a first order linearisation of the coil current. One set of coils carries the stationary current, while the other set carries the control current. This way a current controlled active magnetic bearing is created. It will be shown that this first order linearisation is of vital importance to the propulsion force.

PROPULSION FORCE

In order to achieve propulsion, a secondary coil is wound around the rotor so that it is placed within the magnetic field serving the suspension function. This can be seen in figure 2. The method of propulsion has to be free of parasitic forces normal to the propulsion direction, for this would influence the magnetic bearing considerably.

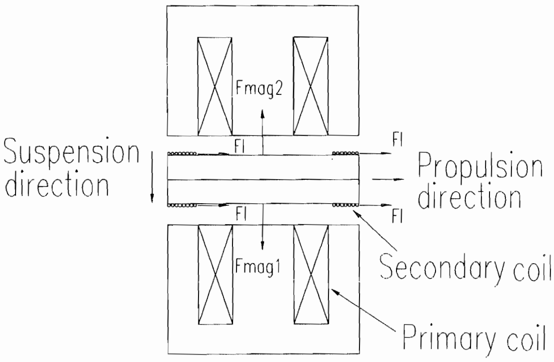

FIGURE 2. Central part of the SPU showing the secondary coils placed between the E-core electromagnets. This way a Lorentz force (= propulsion force), F_L, is generated perpendicular to the suspension forces, F_{mag}.

The force generated by a current flowing through the secondary coil is a Lorentz force, determined by:

$$F_L = B \cdot I_{sec} \cdot L_{eff} \qquad (3)$$

with:

F_L = Lorentz force,
B = magnetic field strength,
I_{sec} = current through the secondary coil,
L_{eff} = effective length of the secondary coil.

Bu substituting (2) in (3) the following equation for the propulsion force is obtained:

$$F_L = K_L \cdot I_{sec} \cdot \left\{ \frac{(I_0 - \delta I)}{(Z_0 + \delta Z)} + \frac{(I_0 + \delta I)}{(Z_0 - \delta Z)} \right\} \qquad (4)$$

with K_L being a constant.

As can be seen in (4) the propulsion force is proportional to the secondary coil current, I_{sec}, as was to be expected. If the magnetic bearing functions properly, that is $\delta Z = 0$, then the propulsion force is also proportional to I_0, and not dependant on the control current δI. In that case, a perfect decoupling between the bearing function and the propulsion function of the SPU is achieved. If, however, the bearing is not centred, or $\delta Z \neq 0$, some degree of coupling between the two forces will occur.

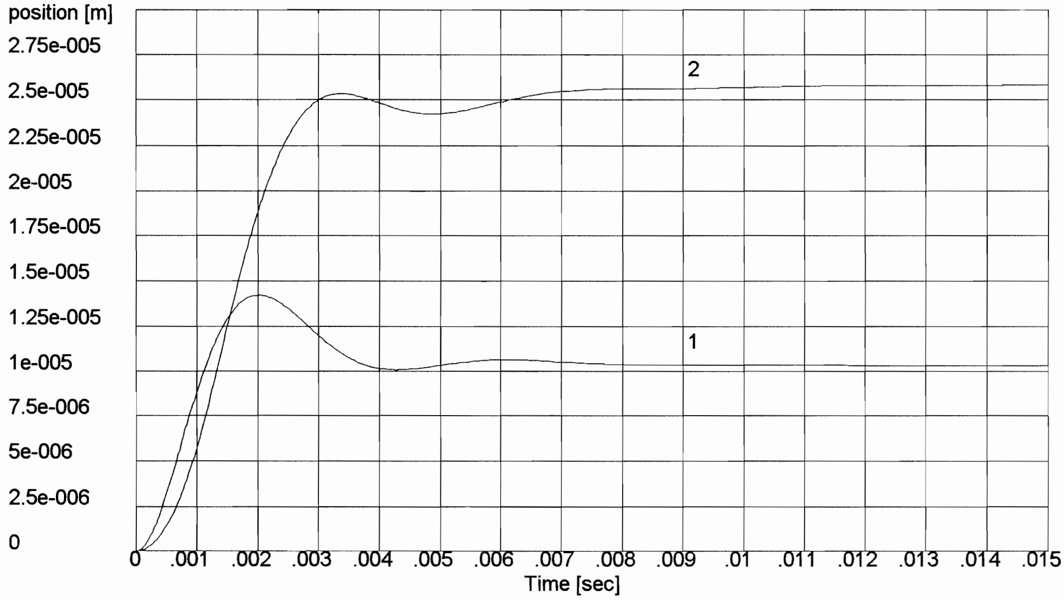

FIGURE 3. Step responses of the non-linear system, simulated by VISSIM. The difference between curve 1 and curve 2 is created by the non-linear current limitation of the amplifier at different step sizes.

A sensitivity study of the magnetic bearing design shows that deviations of the centre position will not exceed 1 μm. In fact, this is what the magnetic bearing is designed for. Considering that δI varies 1% of I_0, simple calculation shows that the propulsion force varies only 10 ppm.

If the interaction between propulsion and suspension proves to be too large to neglect for a certain application, a MIMO controller should be applied. In this way the coupling to the amount of 10 ppm as a function of the momentary position and momentary control current can be eliminated even further.

SPU PERFORMANCE

Several experiments have been performed on the SPU. These experiments have resulted in the following data:

Stiffness of the bearing:	10^6 N/m.
Propulsion force:	5 N.
Noise amplitude of the bearing:	1μm p-p.
Bandwidth:	300 Hz.
Load capacity:	2.5 kg.

These results were measured on the experimental set-up shown in figure 1. The same experiments were done on computer models. These models have been built using several computer programs and are used to analyse the experimental set-up, prior to "real world" analysis. The next section will discuss this in more detail.

COMPUTER SIMULATION OF THE SPU

The experimental set-up is controlled using a TMS320C30 based digital signal processor or DSP, manufactured by dSpace GmbH in Germany. dSpace provides an interface program to MATLAB, making it very simple to implement MATLAB controllers. If computer simulations are done, it is therefore obvious to do it in MATLAB. At the Laboratory for Micro-Engineering MATLAB is used to simulate the linearised magnetic bearing system and to experiment with different controller types and layouts.

MATLAB has one major disadvantage: it can only simulate linear systems using linear models. If a system is built with several non-linear elements, like saturation or non-linear forces, another program should be used. Such a program is

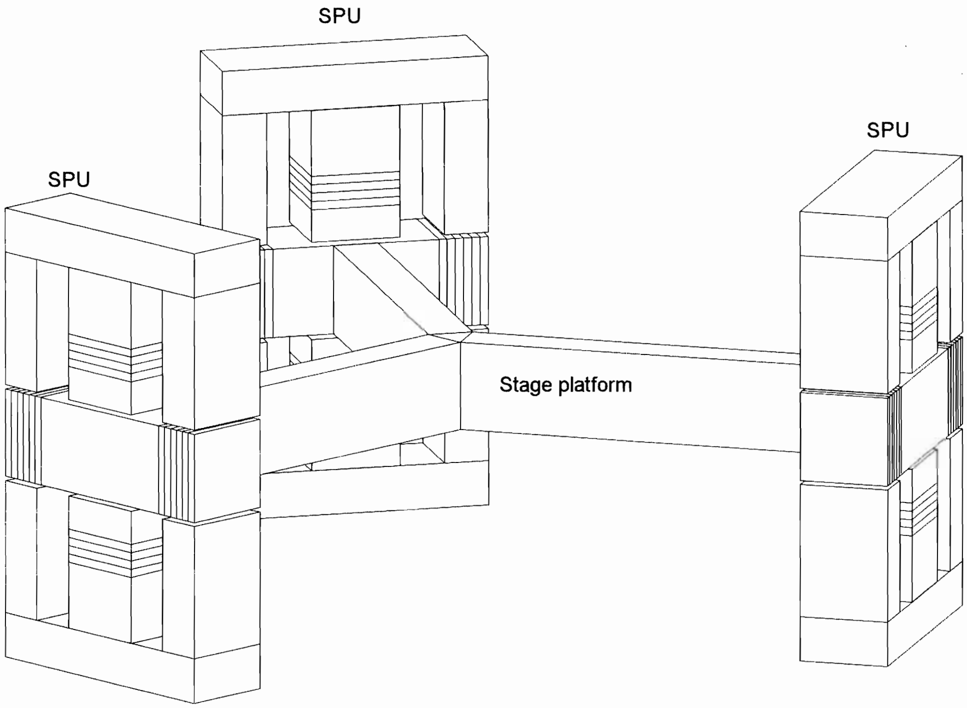

FIGURE 4. Schematic view of the XYΦ stage. Three SPU's suspend the stage platform without any mechanical contact.

VISSIM. VISSIM provides the possibility to create block diagrams using linear and non-linear functions. With VISSIM, the effects of non-linear blocks on the simulation were investigated. One result is presented in figure 3.

Figure 3 shows two responses as a result of step signals on the input, obtained by a non-linear block diagram simulation in VISSIM. It can clearly be seen that the response is dependant on the amplitude of the input signal. This is a typical non-linear effect. This effect is caused by the current limitation of the amplifier used with the magnetic bearing.

In order to analyse the magnetic field itself, a finite element analysis program is used. This program is called MAXWELL and is provided by ANSOFT. Typical results acquired with MAXWELL are magnetic bearing force, magnetic field saturation effects and coil inductances. Experiments with the experimental set-up have shown that results from the simulation are within 1 % in agreement with the results measured on the bearing itself. This topic was discussed in more detail in [3].

APPLICATION OF THE SPU

The research on magnetic bearing and propulsion at the Laboratory for Micro-Engineering in general resulted in the development of the Suspension and Propulsion Unit. It is obvious to implement this unit in a suitable set-up in order to properly demonstrate its possibilities. This is now done and will result in a six degrees of freedom, magnetically suspended and propelled XYΦ stage.

Figure 4 shows the layout of the XYΦ stage. Three SPU's are used to lift the stage platform and control three degrees of freedom. This is achieved using a MIMO controller with three inputs and three outputs. The three degrees of freedom that are controlled are vertical displacement (Z), roll (Θ) and pitch (Ψ). These degrees of freedom can be controlled at any position along a stroke of 1 mm for Z, and 5 mrad for Θ and Ψ.

The same SPU's can be used to position the stage platform in the other three degrees of freedom, X, Y and Φ. The secondary coils around the I-cores are placed on the suspended stage platform. This time six secondary coils have to be controlled using a MIMO controller. The size of the secondary coils limit the stroke of the stage to 10 mm for X, 10 mm for Y and 50 mrad for Φ. Further research will have to prove that the ranges can be extended.

Currently, the research is concentrating on the suspension of the XYΦ stage platform. Once the goals for this suspension are achieved, more attention will be given to the propulsion of the stage platform. The Laboratory has set the following goals for the XYΦ stage:

Stiffness in bearing direction:	10^6 N/m .
Stiffness in propulsion direction:	10^4 N/m .
Range in XY direction:	10x10 mm^2.
Range around Φ:	0.05 mrad.
Accuracy in XYZ:	1 μm.
Accuracy around ΦΘΨ:	5 μrad.

An intensive study carried on with computer models has indicated that these goals can be reached.

CONCLUSIONS

The principle of operation of a Suspension and linear Propulsion Unit (SPU) is described. The unit combines suspension and propulsion using a single magnetic field.

The interaction between the suspension force and the bearing force is minimised by applying two sets of differentially wound coils. In practice using a first order linearisation of the non-linear magnetic bearing force results in a satisfactory behaviour of the unit.

Computer simulations and measured results on an SPU have shown that the propulsion force varies 10 ppm as a function of the momentary rotor position and the momentary control current.

The application of three SPU's in an XYΦ stage is described. Three degrees of freedom are magnetically propelled, XYΦ, and three degrees of freedom are magnetically suspended, ZΘΨ.

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