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Adjustable passive magnetic constant force actuator

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Abstract— This paper presents an adjustable passive magnetic system that provides constant force along its stroke. Gravity is an undesirable force in most linear stages that operate in non-horizontal and specifically in vertical directions. Active systems consume extra energy to compensate for this force. In addition, they impose complexity, heat and cost to the systems. Pneumatic counterbalance systems have been proposed for the past two decades; however they need compressed air and are not reliable. This design provides a passive, reliable and adjustable counterbalance that works based on shear magnetic force.

Index Terms— ***Direct drive, Linear motor, Linear stage, Magnetic counterbalance, precision motion, passive magnetic, Z stage .***

I. Introduction

Actuators working in a non-horizontal orientation have to consume extra energy to overcome their own weight and the payload due to gravity. Therefore these actuators are larger and generate more heat, which in turn affects the stage accuracy. To address this problem pneumatic and magnetic counterbalances have been proposed in the literature [1], [2] and [3]. The pneumatic systems need pressurized air, maintenance and are not quite reliable. A passive magnetic counterbalance has been proposed and built by LinMot[4]; however these systems are capable of providing a fixed force. Moreover, the force is not quite constant throughout its motion stroke. This paper provides an adjustable passive magnetic constant force generator system. In this case the user is able to adjust the amount of force to either compensate for the gravity or apply a biased force for the desired motion profile. This design provides constant force which has been verified both theoretically and experimentally. This design is very simple, yet very effective and practical for high precision stages.

II. Configuration

Figure 1 shows the basic proposed system configuration which includes a typical linear stage or linear bearing in a vertical or a non-horizontal direction that hold a payload. A magnet is placed between the base and the forcer both of which are made out of ferromagnetic materials in this case 1018 steel. The linear stage tends to fall due to gravity (constant force), however by means of this design the stage remains at its position until an external force is applied to it. In other words this magnetic counterbalance eliminates the effect of gravity that the stage experiences.

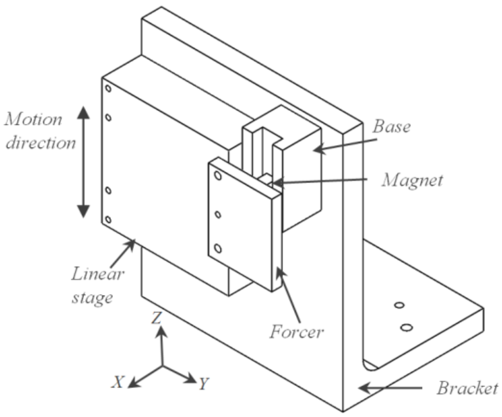

Fig. 1. Basic passive magnetic counterbalance configuration.

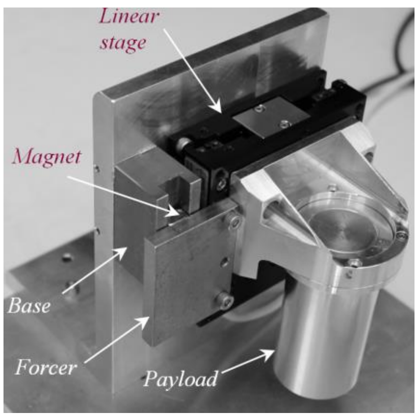

Fig. 2. Experimental prototype.

This design works based on shear magnetic force that is generated between the base and forcer. As will be shown in the next section the shear magnetic flux density remains constant along the forcer stroke which provides constant force in vertical direction. This force varies with the gap between forcer and the base. This gap could be adjusted by means of any mechanism. In this work, shimming was used to change the gap. Figure 2 shows the experimental setup that was built to verify the proposed design.

III. Principle of operation

Figure 3 shows the top view and equivalent magnetic circuit of the system. In this figure X_1 is the air gap between the magnet and the base and X_2 and X_3 are the air gaps between the base and forcer. The permanent magnet is modeled as a constant magnetic flux source φ_m with internal reluctance R_m and leakage reluctance R_L .

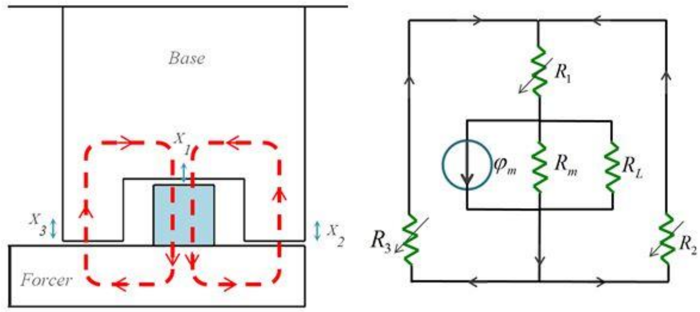

Fig. 3. System top view including magnetic path shown in dotted lines .

According to electromagnetic theory we have:

$$R_i = \frac{X_i}{\mu_0 A_i} \quad where\ i = 1,2,3.$$

$$R_m = \frac{L}{\mu_0 A_M}$$

"A" denotes the area cross section of the air gaps. As we can see from the above equations the total magnetic reluctance varies linearly with the air gap which can be set by gap adjuster. We use Maxwell's stress tensor to calculate the net shear force acting on the forcer. In this case the normal force is compensated by bearings and we are interested in tangential magnetic flux intensity. The magnetic force acting in the i^{th} direction on the forcer F_i is calculated,

$$F_i = \int_A T_{ij} n_j da \ , \qquad (1)$$

where *i* and *j* are the coordinate direction and T_{ij} is the magnetic tensor:

$$T_{ij} = \mu_0 H_i H_j - \frac{\mu_0}{2} \delta_{ij} H_k H_k \qquad (2)$$

The δ_{ij} is the Kronecker delta and

$$H_k H_k = H_x H_x + H_y H_y + H_z H_z \qquad (3)$$

In order to find the magnetic field intensity in the z direction we use finite element analysis. The tangential magnetic field intensity (z direction) remains constant along the moving magnet stroke. Thus we can integrate over the surface *A* to calculate a constant force along the z axis,

$$F_z = -A \frac{\mu_0}{2} H_z^2 \ . \qquad (4)$$

By changing the gap we can change the magnetic reluctance and in turn the shear magnetic flux intensity. The user can attain the desired force by adjusting the air gap.

The FEA and experimental result for a specific size is shown in figure 4. As it is shown, a constant force is generated by this system to compensate a 1 Kg mass. This system has been verified experimentally shown in figure 2.

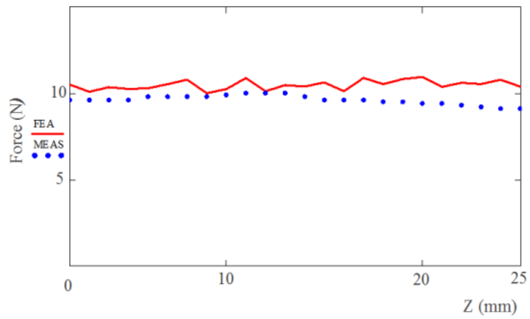

Fig. 4. The net force in Z direction. The solid line is the FEA results and the points are measured data.

The design proposed in figure 1 has normal force which has to be compensated by the stage bearings. There are applications that this normal force can't be tolerated. Figure 5 shows FEA simulation for another alternative design which the normal force is canceled out by symmetry.

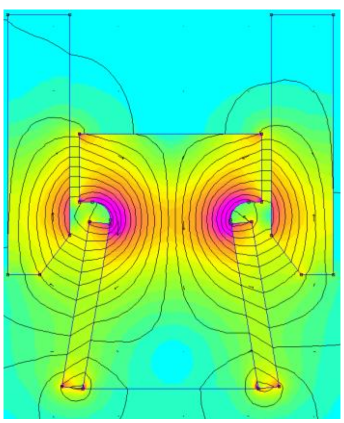

Fig. 5. FEA simulation for alternative design without normal force.

IV. Conclusion

In this paper, a passive magnetic constant force actuator is proposed and verified experimentally. For those applications that normal force can be tolerated by stage bearings, a very simple yet effective design is presented. This design includes two simple parts made out of ferromagnetic materials and a magnet. An alternative design presented provides zero normal force, but at the cost of more parts. It is worth mentioning that both designs provide damping in the motion direction due to eddy current effect which could augment the servo control loop for high precision stages.

References

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