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The GaussMount, a vibration isolation system: theory vs. practice

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Abstract
In this paper an analytical model of a magnetic gravity compensator is compared to measurements obtained on a test setup. The results show that compared to the absolute force, the differences are relatively small in the horizontal and vertical direction. These measurements have illustrated that the discrepancy in the vertical direction is mainly caused by manufacturing tolerances and the difference in horizontal direction due to the relative permeability of the magnets themselves. This permeability introduces extra negative stiffness into the system. To account for this negative stiffness, the actuators, which are used to stabilize the system, should have been sized to generate these required forces.

Vibration isolation system, permanent magnets

1. Introduction

Due to advances in the high-precision industry, the influence of disturbances, such as floor vibrations, are becoming larger and larger. To minimalize the inaccuracies due to floor vibrations, vibration isolation systems are used. With the increased precision also demands on these isolation systems increase. To cope with these new demands, besides the traditional isolation systems (i.e. airmounts), also permanent magnet based isolation systems are studied.

Permanent magnet based systems have the advantages of being contactless, which reduces the wear-and-tear to a minimum. Furthermore, it is vacuum compatible and zero stiffness can be approached which results in a low power consumption.

In this paper such a magnetic vibration isolation system is build and compared to results obtained by means of analytical equations. The differences between the results of the analytical model and the measurements are explained and possible causes are mentioned. Finally, conclusions and recommendations are given.

2. Magnetic gravity compensator

The main part of a vibration isolation system is the gravity compensator, which exerts a vertical force and ideally has a zero-stiffness region. In this paper, the gravity compensator uses only permanent magnets. To do this several magnets shapes are possible, such as cylindrical [1] or cuboidal [2]. In this paper a cross-shaped gravity compensator [3] is chosen, which consists of cuboidal magnets.

When assuming that the relative permeability of the magnets, μ_r, is one, the equations of force and stiffness between two cuboidal permanent magnets can be calculated analytically using the surface charge model [4,5]. To calculate the entire structure, superposition is used.

Permanent magnets, however, have a μ_r unequal to one. Therefore, to include this into the equations the remanent magnetization, B_r, is adjusted according to [6].

3. Experimental verification

To verify the model the gravity compensator, a GaussMount, shown in Figure 1, is build. In this set-up the levitated mass is, a stone table augmented by removable disks, 736 kg. The gravity compensator is build according to [3]. Due to the inherent instability issues with magnetic springs, actuators are present to stabilize the system. The moving envelope of the system is 0.5 mm in every direction. In its optimal position the actuators use 0.3 W to stabilize the system.

Furthermore, underneath the system a shake table is placed to generate the floor vibrations for dynamic measurements, such as transmissibility or compliance. This paper is, however, limited to static measurements only.

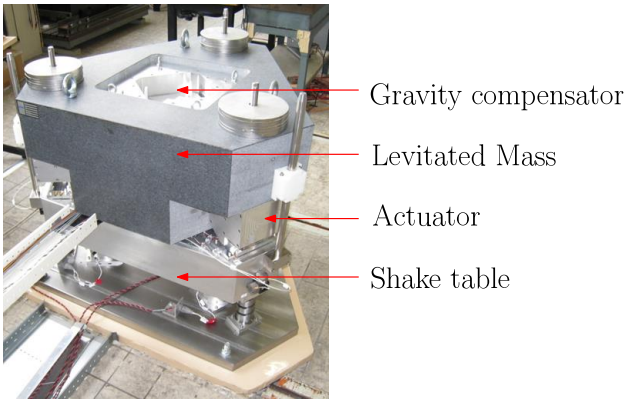

Figure 1. The GaussMount, a vibration isolation system.

4. Results

In Figure 2 the modeled and measured force are shown. In Figure 2a the force in the *x*-direction is given. Since the gravity compensator is symmetrical, the force in the *y*-direction has the same shape and is therefore omitted. In Figure 2b the force in the *z*-direction is given.

As can be seen, there are some differences between the model and the measured force. In the case of the vertical force,

there is a constant difference of 110 N which is relatively a difference of 1.5%.

In the case of the force in the *x*-direction, there is not a constant difference, but a difference which is dependent on the movement in the *x*-direction. This means there is a difference in the stiffness. The stiffness matrix of the model, in N/mm, is given by

$$K_{model} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} = \begin{bmatrix} -0.06 & 0.58 & 0.74 \\ 0.58 & -0.06 & 0.00 \\ 0.74 & 0.00 & 0.13 \end{bmatrix},$$

where $K_{ij} = -\partial F_i / \partial j$. The stiffness matrix of the measurement is

$$K_{measurment} \approx \begin{bmatrix} -53 & 0.5 & 1.0 \\ 0.2 & -58 & 0.5 \\ 2.0 & -0.9 & 1.0 \end{bmatrix}.$$

As can be seen the difference in stiffness is significant, especially in the horizontal directions on the diagonal of the matrix.

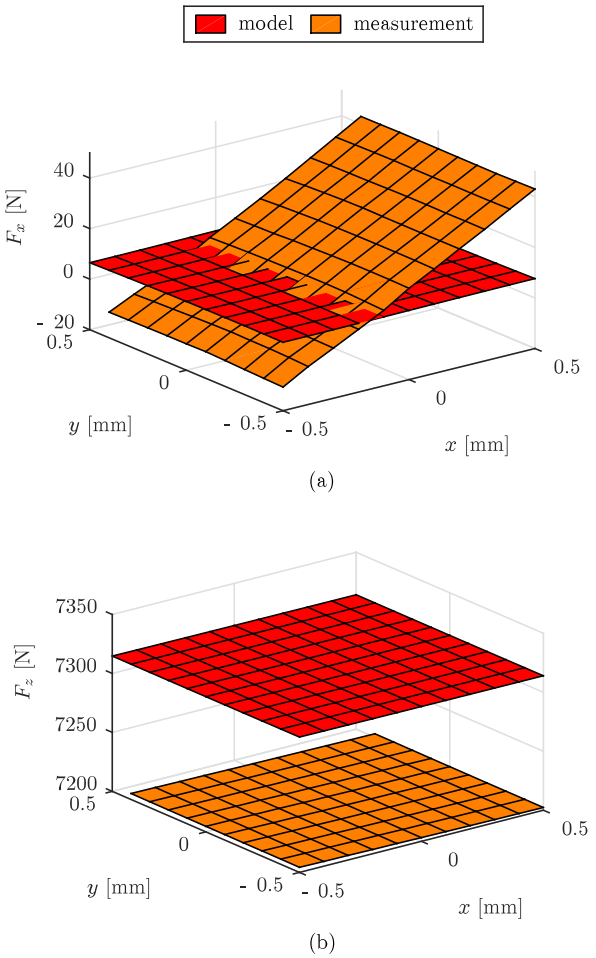

Figure 2. The results of the analytical model and the measurements for (a) horizontal and (b) vertical force.

5. Discussion

As shown in the results there are 2 different types of error, the relatively small difference between the measured and model vertical force and the difference in horizontal stiffness. First, the difference in vertical force can be explained by uncertainties in magnet parameters, such as B_r, μ_r, and magnetization direction [7].

This, however, does not explain the difference in stiffness. According to Earnshaw [8], the sum of the diagonal of the stiffness matrix equals to zero, $\boldsymbol{K_{xx} + K_{yy} + K_{zz} = 0}$, except when soft-magnetic materials are present. Then the sum can be smaller than 0. In the case of the GaussMount, the sum of the stiffness's is -110 N/mm. This is due to soft-magnetic materials being present in the system.

During the design of the GaussMount the use of soft-magnetic materials was kept to a minimum. The gravity compensator itself consists out of just aluminium and magnets. The magnets themselves, however, also have a relative permeability and can cause the negative stiffness.

To calculate the effect of the permeability of the magnets, the method of images [9] is used. For simplicity only one-eighth of the gravity compensator is modelled. This resulted in a force variation of 10.6 N for a movement of 1 mm, which is about 1% of the total force. This force variation occurs in four parts in the x-direction and four parts in the y-direction. This results in a stiffness, $\boldsymbol{K_{xx} = K_{yy} = -42.4\ \mathrm{N/mm}}$. Due to the simplification the real magnitude will be larger.

6. Conclusions

In this paper the results of a modelled gravity compensator are compared to measurements conducted on a test setup. For the vertical force a difference of 1.5% is seen. This difference is mainly caused by tolerances in magnet parameters. In the horizontal direction a large difference in stiffness occurs. This difference is caused by the relative permeability in the magnets, which is not completely taken into account by the analytical model. Comparing the force difference to the total force of the system, this difference is about 0.7%.

Although the relative force variation due to the permeability is small, it can amount to large horizontal force when large masses are levitated. In the design of a vibration isolation system, this force should be accounted for by designing actuators which can deliver that amount of force.

The movement of the system is, however, very small resulting in small power consumption i.e. 0.3 W in the optimal position. This makes the GaussMount a good alternative to commonly used vibration isolation systems for future high-precision machines.

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