Control of a magnetically levitated slider with nm-precision

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***Abstract*— Due to increasing demand in accuracy, the semiconductor and optical disc mastering industry are looking for nanometer resolution vacuum compatible positioning systems. Magnetic bearings are ideally suited for this purpose, because here is there is no need for lubrication.**

The IU-module is a modular two degree of freedom magnetic actuator for suspension and propulsion. The uniqueness of this actuator lies in the "moving iron principle" in which only iron is moving and there are no wires going to the moving body. With three IU-modules a six degree of freedom linear slider is constructed. The specifications for the slider are taken from the optical disc mastering industry, where the resolution of a single nanometer is required. To achieve nm-resolution close synergy between mechanical construction and controller design is needed. This paper shows the successful realization and controller implementation of a sub nanometer positioning slider system using the IU-modules.

***Index Terms*— Linear Magnetic Bearing, Precision Engineering, Control, Combined reluctance lorentz actuator.**

I. Introduction

Due to the application of extreme ultraviolet light in precision machines, they will have to be vacuum compatible, otherwise the light would be absorbed by the air. Magnetic bearings are ideally suited for vacuum applications. One of such machines is an optical disc mastering machine. In an optical disc mastering machine an optical disc master (substrate) is manufactured (figure 1). From the optical disc master other optical discs, like CD's and DVD's, are replicated. For manufacturing the optical disc master is placed upon the rotating platform, above which the linear slider moves holding a laser for writing pits on the rotating disc below. The most critical aspect of the optical disc mastering process is the pitch error between two neighboring tracks. Current optical disc mastering machines are build using air bearings, however for vacuum applications these are not ideally suited.

As a solution we propose using three IU-modules to construct a six degree of freedom actively levitated linear slider. The IU-module [1] is a modular two degree of freedom magnetic actuator for suspension and propulsion. The slider serves as a demonstrator for a new linear slider for the optical disc mastering machine. Although the specifications are taken from the optical disc mastering process, the nanometer resolution slider concept is also interesting to other high accuracy machine manufacturers. This paper addresses the design issues and control issues in achieving this nanometer resolution slider.

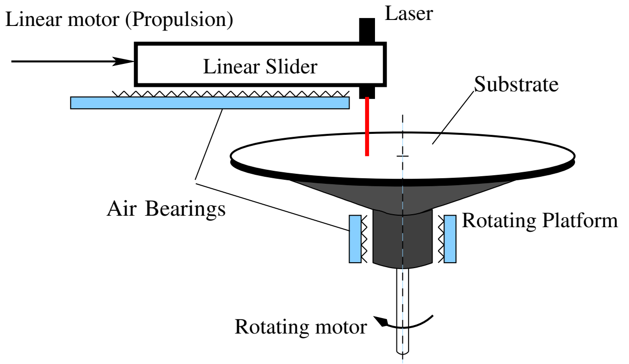

Fig. 1. Current optical disc mastering device, consisting of a linear slider and a rotating platform, suspended by air bearings

A. IU-module

The IU-module (figure 2) is a two degree of freedom electromagnetic actuator. The name "IU-module" comes from the I shaped slider bar and the U shaped stator bars. The suspension (z-direction) operates as a permanent magnet biased magnetic bearing. The permanent magnets create a bias flux through the slider bar (figure 2). This bias flux in the airgap is manipulated by the suspension coils and so a desired force can be created on the slider bar. The permanent magnets linearizes the force current relationship at a position. The linearized force on the slider bar can be described by equation 1, in which F_z is the force on the slider bar in z direction, I_{susp} is the current through the suspension coils, K_T is the motor constant and K_N is the negative stiffness. The advantages of using permanent magnets in a magnetic bearing are low power consumption and linearized operation; the drawback is a large negative stiffness.

$$F_z = K_T \cdot I_{susp} + K_N \cdot z \quad (1)$$

To propel the slider bar in propulsion (x-) direction, the IU-module uses the four propulsion coils on the stator bars. This is done without any wires going to the slider bar; this is the so called "moving iron" principle introduced by Molenaar [1]. The propulsion has a linear current force relationship, like a regular voice coil actuator.

TABLE I

SPECIFICATIONS FOR LINEAR SLIDER

propulsion stroke	50 mm
stability propulsion	1 nm
duty cycle propulsion	20 min
suspension stroke	0.6 mm
horizontal stroke	0.6 mm
stability suspension	5 nm
stability horizontal	5 nm

II. DESIGN OF THE LINEAR SLIDER

To show the possibilities of the IU-module, a nanometer precision six degree of freedom electromagnetic slider system has been developed. The specifications for this slider are taken to comply with the design of an optical disc mastering machine and are given in table I.

For the optical disc mastering process it is not necessary to obtain this high accuracy in an absolute sense, because this type of low frequent disturbance will be distributed over several tracks; the emphasis is on the pitch error between to neighboring tracks.

A. Low stiffness concept

To design the nanometer resolution linear slider system the "low stiffness" design concept is used (figure 3). In the "low stiffness" design concept the stiffness connection between the surroundings is minimized, while the control technical stiffness between the reference and the slider is maximized. The advantages of the "Low stiffness" design concept can best be visualized by comparing it to the normal "high stiffness" concept. This is illustrated by a sketch of the design concepts in figure 3. In the high stiffness concept both the slider and the reference are fixed tightly to a frame to achieve the accuracy. However, because high accuracy is needed, high control stiffnesses and mechanical stiffnesses are needed. This induces high reaction forces from the actuators. Hence the frame will deform and thus limiting the precision.

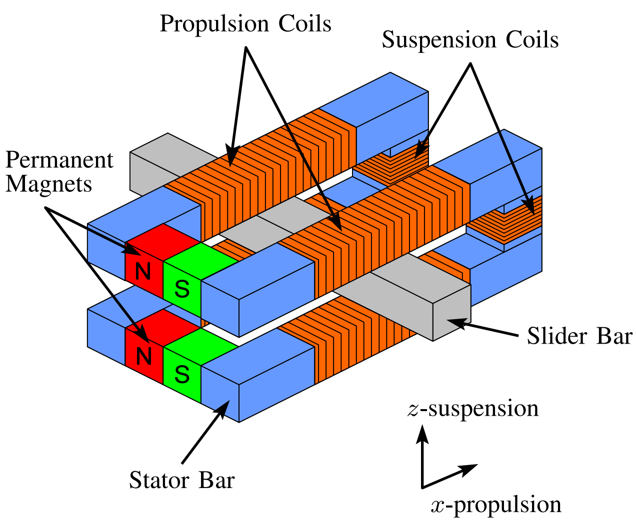

Fig. 2. The IU-module

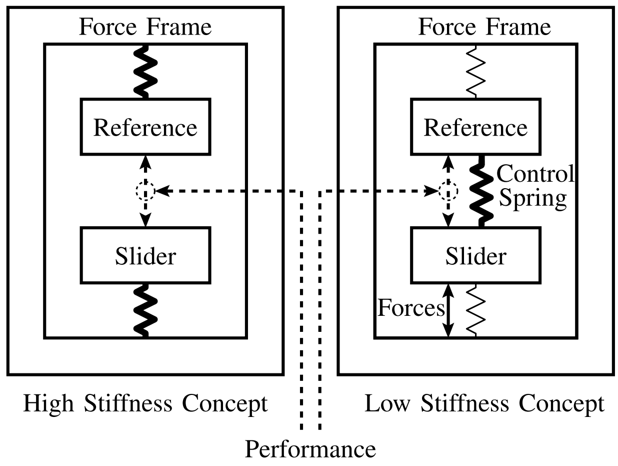

Fig. 3. High and low Stiffness Design Concept for obtaining high accuracy between reference and slider

In the "low stiffness" concept vibrations and disturbances coming from the world itself will not influence the error between reference and slider because they are not passed on due to the low stiffness connection. Forces generated by the system itself will not hamper performance, because they are put on a separate force frame and thereby do not disturb the reference. Thus the "low stiffness concept" enables nm-position error with smaller control bandwidth than needed in the "high stiffness" concept. The smaller bandwidth is made possible by the careful separation between disturbance sources and high accuracy components.

B. Slider Construction

The slider system consists of a force frame (figure 4) and a reference frame. The slider system is placed upon a granite table (figure 4) with a seven Hertz passive suspension, which serves as an initial filter for floor vibrations. To suspend the slider in six degrees of freedom three IU-modules, each capable of actuating on two degrees of freedom, are combined (figure 6). The IU-modules are all fixed to the Force frame, which is made out of one block of aluminum to guarantee that construction tolerances are met. The IU-modules are manufactured using laminated steel to avoid eddy current losses.

To enable wireless propulsion the sensors are not placed on the moving body itself, but on the fixed world. This results in a moving center of gravity with respect to the measurement position, which is taken care of in the control architecture. Inside the force frame (figure 6)there are three MicroE linear encoders and three Micro-Epsilon eddy current sensors to measure the position of the slider with respect to the force frame. The measurements with respect to the force-frame are used for start-up purposes and stiffness compensation (section III).

The suspension of the reference frame is formed by a "Table Stable" active vibration isolation table. This vibration isolation table has an active cut-of frequency of 0.7

Hertz, isolating the high accuracy reference frame from the environment. On top of the reference frame there are three Renishaw laser interferometers and three ADE capacitive sensors to measure the position of the slider relative to the reference frame with sub-nanometer resolution (figure 5).

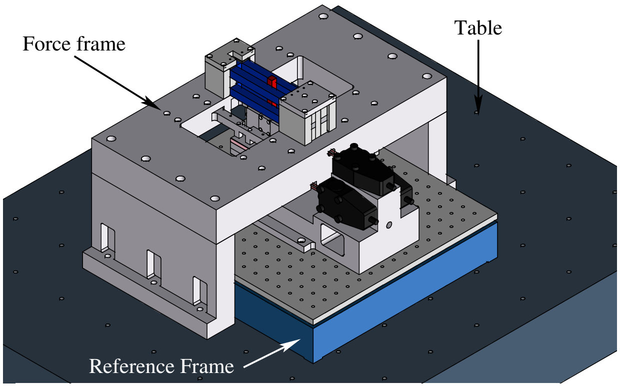

Fig. 4. Linear slider top view, giving the overview of the system

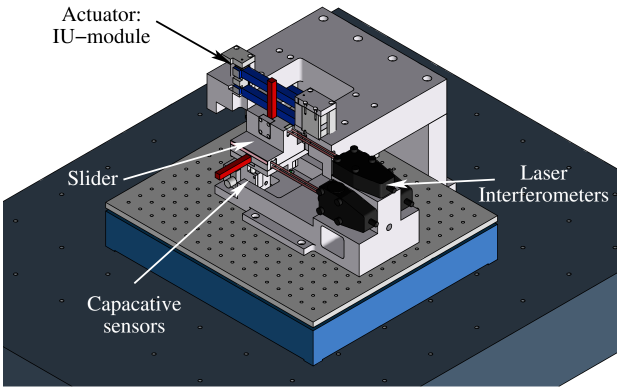

Fig. 5. Linear slider inside view, showing the slider, sensors on reference frame and the top IU-module

C. Dynamic Error budgeting

To evaluate the performance of the slider system in the design phase the dynamic error budgeting technique by Jabben [2] has been used. In this technique the disturbances are assumed to be uncorrelated and stochastic. The noise sources are then described by power spectra in the frequency domain. It is well known that power in the frequency domain is directly related to the power in the time domain (2).

$$\lim_{T\to\infty} \frac{1}{2T}\int_{-\infty}^{\infty} x^2(t)dt = \int_{-\infty}^{\infty} \lim_{T\to\infty} \frac{|X(f)|^2}{2T}df \qquad (2)$$

If a linear model of the system is available and the noise sources are uncorrelated, the noise propagation through the system can be calculated by equation 3. The one sided power spectrum $S_{u_i}(f)$ contains the frequency content of

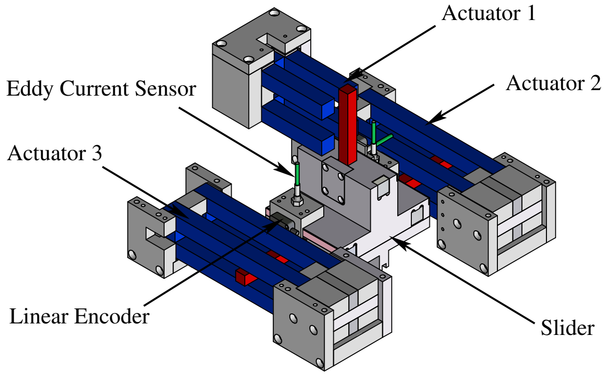

Fig. 6. Linear slider inside view, showing three IU-modules and the slider

your disturbances, while G_{yu_i} is the plant transfer function from disturbance source to plant output.

$$S_y(f) = \sum_{i=1}^{i=n} |G_{yu_i}(j2\pi f)|^2 \cdot S_{u_i}(f) \qquad (3)$$

Using the computed noise spectrum at the output of the system, the standard deviation of the error can be computed using equation 4.

$$\sigma_y = \sqrt{\int_0^{\infty} S_y(f)df} \qquad (4)$$

The error can best be visualized by plotting the Cumulative Amplitude Spectrum (CAS), defined as:

$$CAS(f_o) = \sqrt{\int_0^{f_o} S_y(f)df} \qquad (5)$$

The $CAS(\infty)$ is the same as σ_y. This way of depicting the power spectra clearly shows the error building up over frequency toward the standard deviation σ_y.

A six degree of freedom linear model of the slider system was combined with a model of the controller and the noise sources. The included noise sources were AD-noise, DA-noise, sensor noise, power amplifier noise and floor disturbances. Figure 7 and 8 show the predicted Cumulative Amplitude Spectrum of the error for the propulsion and suspension direction, respectively. These plots clearly indicate that the design is capable of achieving the specifications given in table I.

III. CONTROL STRUCTURE OF THE LINEAR SLIDER

The control structure to obtain the nanometer stability of the linear slider consists of two parts:

1) Stiffness compensation with respect to the force frame
2) Six DoF position control with respect to the reference frame

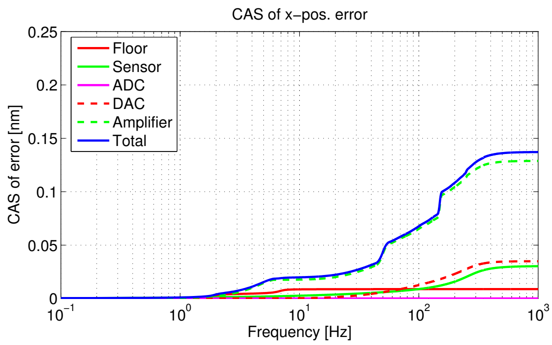

Fig. 7. Position error in propulsion (x) direction

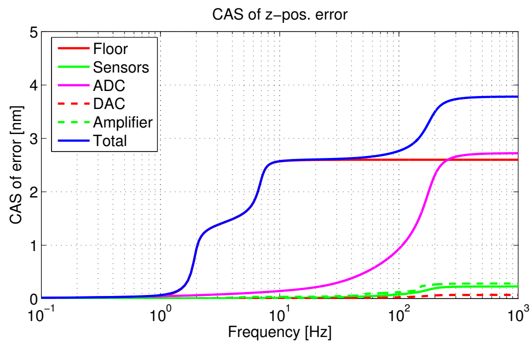

Fig. 8. Position error in suspension (z) direction

In the low stiffness concept it is desired to have as little physical stiffness as possible between the slider and the reference, because only then floor vibrations are not passed on to the slider. Unfortunately the IU-module has a large negative stiffness between slider and force frame, due to the permanent magnets which are present in the actuator. The stiffness compensation loop aims at reducing this negative stiffness.

The high stiffness control loop aims at achieving nanometer precision between the reference frame and the slider. If the stiffness compensation is implemented properly, the dynamics to be dealt with in high stiffness control loop are only that of a mass in six degrees of freedom.

A. *Stiffness compensation loop*

In the stiffness compensation the effects of the negative stiffness caused by the permanent magnets are eliminated from system. The negative stiffness with respect to the force frame is compensated by placing a positive control loop in parallel to the negative one from the permanent magnets, resulting cancellation of the stiffnesses. First the the position dependence of the negative stiffness was experimentally determined on a single separate IU-module. The stiffness measurement was performed by doing swept sine measurements, while the system was being actively controlled. Open-loop transfer functions, given by equation 6, were fitted upon the measured swept sine measurements of the open-loop system. From these fitted transfer function matrices K_T (motor constant) and K_N (negative stiffness) were extracted, the results are shown in figure 9.

$$F(s) = \frac{K_T(z,x)}{s^2 - K_N(z,x)} \tag{6}$$

From figure 9 it is clear that there is a rather large position dependence present in the actuator. However the slider will only make small displacements with respect to the force frame in suspension direction, (less than 0.05 mm) when it has to achieve the nanometer resolution. Using the dynamic error budgeting it was established that an error of 15% was allowed in the negative stiffness . From figure 9 it is seen that position dependance is less than 15% on the z deviation of 0.05 mm.

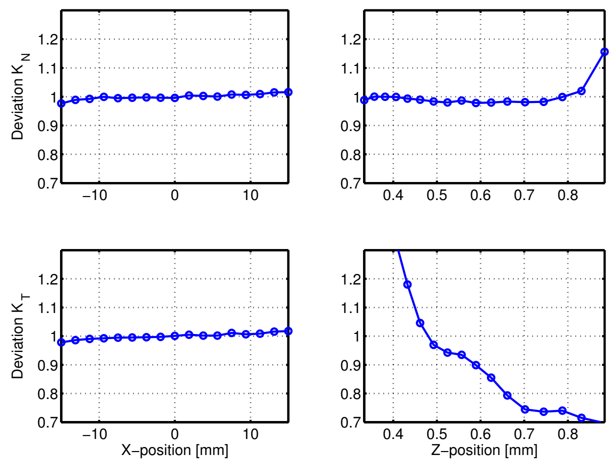

Fig. 9. Negative stiffness measurement, showing negative stiffness K_N (top) and motor constant K_T (bottom); the position dependence is less than 15% per 0.05 mm z displacement

In the two degree of freedom IU-modules the directions of suspension and propulsion are easily separated and the negative stiffness of the magnetic bearing can easily be found. In the six degrees of freedom electromagnetic suspended slide system the rotational degree of freedom ϕ and the horizontal degree (y-)of freedom are coupled, due to the layout of the system (figure 10). The degrees of freedom connected to the propulsion direction (perpendicular to the view in figure 10) have no influence on the negative stiffness compensation.

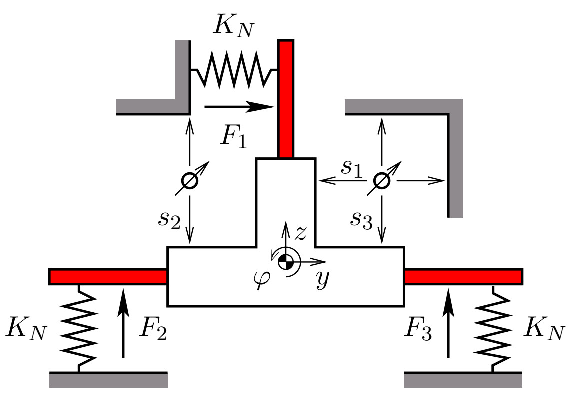

Fig. 10. Front view of the slider, indicating measurement position s, negative stiffness K_N and actuation points K_F

A means of decoupling is needed to extract the stiffnesses from the system, this is found in the technique described by Vaes [3]. Vaes uses the theory by Owens [4] of dyadic transfer function in a practical way. A system is called dyadic if there exist two constant real matrices T_U and T_Y which diagonalize a system (7).

$$G(s) = T_Y \cdot diag\{g_1(s), ..., g_p(s)\} \cdot T_U \tag{7}$$

Our system fulfills the properties of a dyadic system, because the position dependencies are small if the z-position remains constant. The columns of the matrix T_Y can be computed by taking the eigenvectors of $G(c_2) \cdot G^{-1}(c_1)$, where c_1 and c_2 are two distinct frequency points, from the frequency range where the decoupling is of interest. The columns of T_U^{-1} can be calculated as the eigenvectors of $G^{-1}(c_1) \cdot G(c_2)$. Vaes shows it is possible to use just the measured transfer functions of $G(s)$ for obtaining T_Y and T_U. Owens decoupling technique applied to the negative stiffness is similar to modal decoupling of the system.

After applying the decoupling technique the uncompensated transfer function measurement remain (figure 11). The decoupling is only of interest in the low frequency region (below 200 Hertz) because here the effects of the negative stiffness hamper the performance of the system. Upon these transfer functions a second order system of equation 7 are fitted and K_T and K_N are obtained. Then the factors K_T and K_N can be used in a static feedback scheme to eliminate the negative stiffness. The result after feedback is shown in figure 11 by the compensated line. In the ideal situation just the -2 slope of a mass would remain. The stiffness compensation is not perfect, but is sufficient to achieve the specifications. The stiffness compensation can be improved by using the optimization technique described by Vaes and by compensating for the position dependencies.

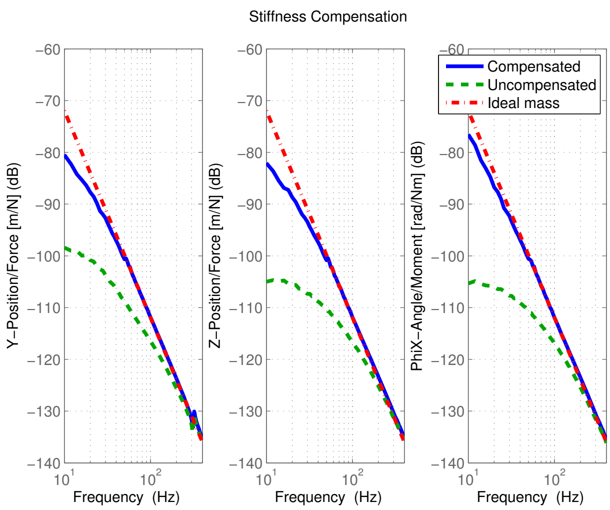

Fig. 11. Stiffness compensation in x, y and ϕ direction, showing that the stiffness compensation works well enough to get rid of low frequency disturbances

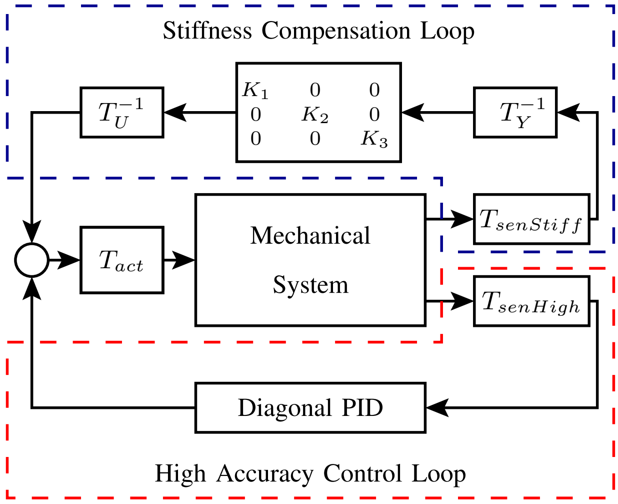

Fig. 12. Control Structure of linear slider, showing the two control loops, with T_{sen} transformation matrices to transform measurement co-ordinates to center of gravity co-ordinates for force and reference frame sensors, T_U^{-1} and T_Y^{-1} are the dyadic decoupling matrices and T_{act} is the force coupling matrix

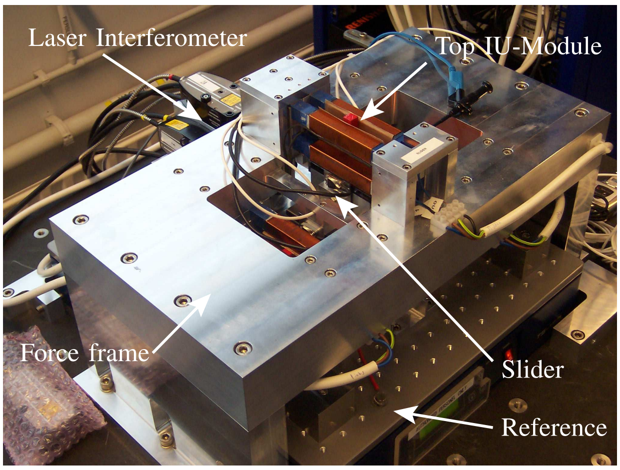

Fig. 13. Photograph of the slider setup, showing top IU-module

B. High accuracy control loop

The feedback with respect to the reference frame is done to achieve nanometer position resolution. With an effective stiffness compensation in place, the dynamics of a rigid body remain. These dynamics can be controlled by transforming the measurements of the system to co-ordinates of the center of gravity of the slider. The remaining loop transfer can be controlled by using six PI^2D controllers, which operate on the diagonalized system around the center of gravity of the slider. A static decoupling matrix is used to make sure forces act on the center of gravity of the slider.

IV. Results of the Magnetically Levitated Slider

The Slider was built and a picture is found in figure 13. In figure 14 the cumulative amplitude spectrum of the error of the slider in the zero position is shown, all position errors are within the given specifications in table I. Figure 15 shows that the system remains within specs on all its propulsion (x-)positions . The error in figure 15 at $x = -25mm$ has a different shape because a wire was touching the slider causing an additional source of disturbance. The specifications have been met at standstill, however the system has to obtain its specifications while undergoing motion. This is one of the future challenges we aim to achieve with the slider system.

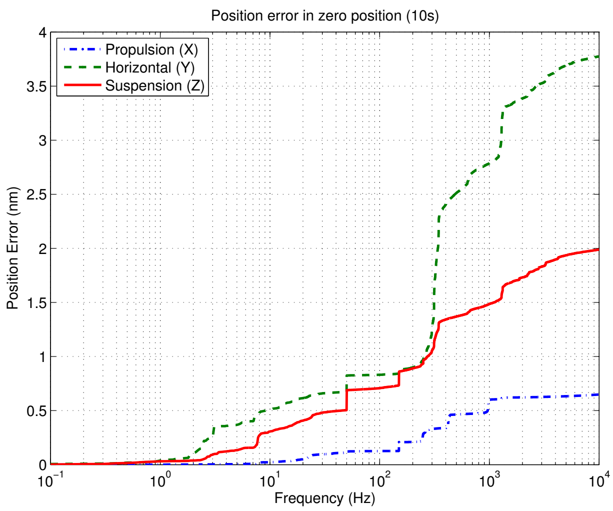

Fig. 14. Cumulative Amplitude spectrum of the position error in zero position

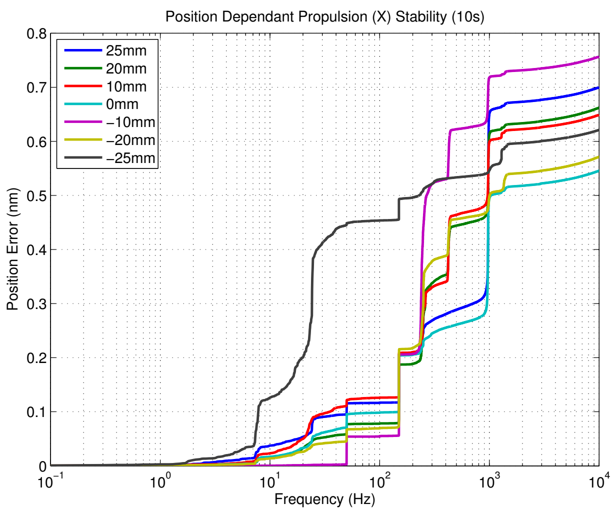

Fig. 15. Position Dependency of propulsion (x-) position error on propulsion position, large error buildup is caused by electronic disturbances at 50 and 150 Hz, at a 1000 Hz a mechanical resonance is excited

V. Conclusion and Future Work

The six degrees of freedom actively levitated slider was constructed by using the IU-modules. The IU-modules are a good building block to achieve nanometer position accuracy. The standard deviation/position stability in propulsion direction is within a single nanometer and the suspension and horizontal direction are within five nanometers. The specifications meet with the requirements of the optical disc mastering device, showing that magnetic bearings have a clear future in high precision vacuum compatible systems.

VI. Acknowledgments

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