Research article

Mastering high-density optical disks: a new concept design

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Keywords

Optical instruments, Error analysis, Computer discs, Design and development

Abstract

Mastering high-density optical disks, like the Blu-ray™ disk, requires new equipment design. Active magnetic bearing technology seem well suitable for this purpose, but challenges arise in obtaining the required extreme accuracy. Creating a very low mechanical coupling between the system and the external world is the potential solution to this challenge pursued in this paper. Design considerations on actuators, amplifiers, sensors and overall design are discussed and the system performance is predicted using an error-budgeting estimation. This prediction indicates the feasibility of the concept, while the first prototype has been assembled and is being tested.

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1. Introduction

The optical disks industry (CDs, DVDs) is one of the fastest growing industries of all times. Whether they are used to hold music, data, or computer software, they have become the standard medium for distributing large quantities of information in a reliable and compact package. In order to reproduce optical disks (ODs) at commercial scales, two main techniques are actually in use: duplication and manufacturing.

1. OD-duplication utilizes the process of burning blank ODs in an OD-writer. Duplication is a well established industry allowing multiple copies to be done at once. Small to medium commercial quantities can be done very quickly using this process.
2. OD-manufacturing, sometimes identified as OD-replication, is a much more complicated process, but allows large quantities of ODs to be made at a very low cost. The process includes:
   - glass mastering;
   - electroforming;
   - injection molding;
   - screen printing; and
   - packaging.

OD-manufacturing can be viewed as two separate operations. The first operation is stamper making, which includes mastering and electroforming. The second operation is replication, which includes utilizing the stamper for injection molding, finishing, and printing the replica.

With the advances in information technology and computer systems, increasing the information density on optical media storage becomes an urgent need. This is particularly true in order to meet the requirements for HDTV, where DVDs-based capacities fail. In this respect, a huge market is expected for larger capacity ODs.

The DVD format, which can hold up to 4.7 GB per layer, has been available since 1997, and already new formats with yet more capacity are being developed and are expected to become available by about 2006. One of the most ambitious attempts to substantially increase the information density of optical media storage is the Blu-ray™ technology. The Blu-ray™ format is being developed by the Blu-ray™ founders group comprising leading companies in the ODs

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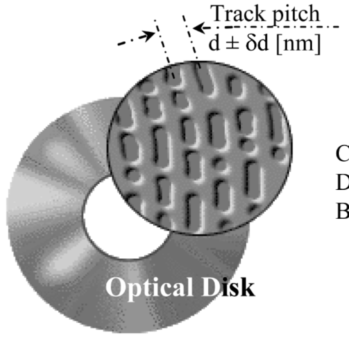
industry. Blu-ray™ disks are expected to offer a capacity of up to 27 GB per layer. This is achieved by the use of a blue laser at 405 nm wavelength, an increase in numerical aperture to 0.85 and a reduction in the cover layer from 0.6 mm for DVD to 0.1 mm.

While attempts at Blu-ray™ duplication were demonstrated successfully (up to 23 GB); replication of Blu-ray™ disks presents significant manufacturing challenges and requires new mastering and replication equipment and processes. At the Advanced Mechatronics department of the Delft University of Technology, the Netherlands, we introduced a novel concept design for mastering high-density OD. This paper presents the new concept and the latest technical developments achieved so far.

2. Mastering ODs

Glass mastering is the first step in the manufacturing process of ODs. This process involves transferring data to a glass substrate. After applying a special coating of photo-resist, a Laser Beam Recorder is used to record data onto the glass-master. The mastering process puts pits into the glass in a spiral manner. The pits are the actual data. Once formed, the glass-master is eventually metallized with nickel vanadium to provide a conductive surface for "Electroforming" to produce the metallic-master. This latter has the negative impression of the OD data and can be used to do actual OD replication via the process of injection molding of molten polycarbonate. On the finished polycarbonate disk, the data are written in spiral tracks containing bumps and pits as shown in Figure 1. An important figure here is the distance between two tracks (or the track pitch) and the tolerances; or the error; allowed on this distance. Also the track pitch specifications of different ODs (CDs, DVDs, Blu-ray™) are shown in Figure 1.

Figure 1 Track pitch specifications of various ODs (single layer)



CD	: 1600 ± 100 [nm]
DVD	: 740 ± 30 [nm]
Blu-ray	: 320 ± 8 [nm]

2.1 OD-mastering device: current state-of-the-art

Basically, the OD-mastering device consists of two moving parts:

(1) a rotating platform that holds the glass-master; and
(2) a linear stage where the laser used to record the data on the master is mounted.

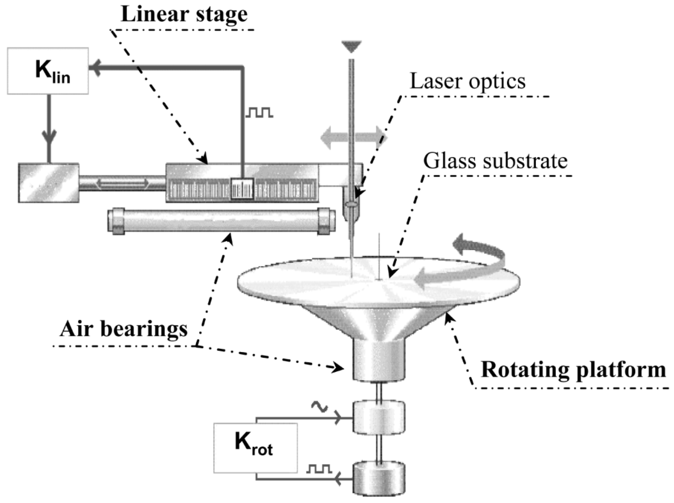
Figure 2 shows a general view of an industrial OD-mastering device. To write the data in the conventional spiral shape, the platform that holds the glass-master is rotated while the laser performs a translation movement from the inside to the outside of the platform.

In the current state-of-the-art of OD-mastering industry, air-bearings are used for both platform and linear stage. In this case, the accuracy that is needed at the position where the laser beam is writing on the glass-master is obtained by a series of high stiffness components, which also includes the machine frame. One of the main sources of errors in the writing process is the stochastic radial movement of the platform; which is identified as the asynchronous radial error motion (AREM, for short).

3. OD-mastering device: new concept design

To increase the information storage capacity on ODs, the track pitch needs to be decreased (Figure 1). For the Blu-ray™ format, this means that to be able to form the pits in the glass-master, extreme deep ultra violet (EUV) light or even an electron beam must be used in vacuum. For the current air-bearing technology, this brings

Figure 2 OD-mastering device, current state-of-the-art



increased fabrication costs. Furthermore, air-bearings introduce high-stiffness between the rotor (moving parts: platform, linear stage) and the stator (fixed world, force frame), making it difficult and expensive to isolate the rotor from external world's disturbances. This is particularly important when aiming at nanometer precision in the positioning of the rotating platform.

Thus, for the OD manufacturing industry, there is a need for an alternative to the air-bearing technology. An interesting candidate is the active magnetic bearing technology. It works contactless and can be made vacuum compatible. It is a well developed technology except for the extreme accuracy that is required for the OD-mastering industry. In this paper, we will focus on the new concept for the rotating platform only. A new concept for the linear stage is being developed at our department under a different research grant.

3.1 Specifications

Although the specifications for the Blu-ray™ disk have recently been laid down, they are not publicly available. We have derived the specifications from those of the DVD (ECMA, 2001). For the Blu-ray™ disk the nominal distance between two adjacent tracks is 320 nm, with an allowed deviation of ± 8 nm.

The total radial error motion of the rotor consists of a synchronous radial error motion (SREM) and an asynchronous radial error motion (AREM). The SREM is defined as the mean contour of the total radial error motion polar plot averaged over the number of revolutions (typically 20 revolutions are taken). The AREM is defined as the deviations of the total radial error motion plot from the SREM plot (Slocum, 1992, p. 67). Because of the asynchronous character the AREM will here be considered as being stochastic for analytical reasons, although this is not necessarily so. The peak specification on the track pitch variation is then approximated by four times the standard deviation, so $1\ \sigma = 2$ nm. In the process of writing the OD-master there are several independent error sources that contribute to the AREM. Error budgeting over these sources leaves an AREM for the rotor of approximately 1 nm ($1\ \sigma$).

The SREM of the rotor is mainly limited by the maximum acceleration that is allowed for tracking when reading an OD, which is $3.4\ \mathrm{m/s^2}$. In practice this means that the specification for the AREM is the most difficult to achieve. In this paper, we will only consider the AREM.

3.2 Concept design consideration

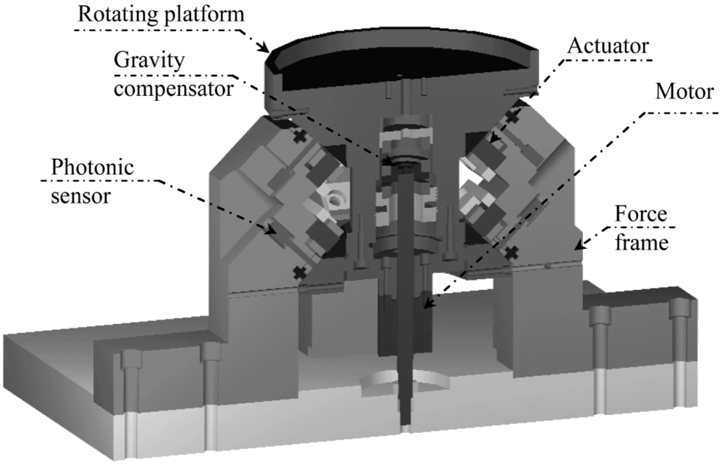
The decision on choosing the overall concept and the building blocks of the new design is the result of several meetings that were organized with experts from the industry and university. This resulted in the concept design being laid out with the outline specifications of each component.

The basic concept adopted is the notion of a rotating platform with very low mechanical couplings to its environment in 5 degrees of freedoms (DoF), so that no disturbance from the environment can perturb the rotor. From this, it follows that the platform should rotate around its principal axis of inertia. The required accuracy will be achieved with respect to the so-called metrology frame, which is separated from the frame on which the actuation forces will act (the force frame). Details on this will be developed in subsequent section.

3.3 System description

Figure 3 shows an overview of the new concept for the rotating platform: in order to achieve high precision positioning, the system should exhibit a very low mechanical coupling between the platform and the external world to ensure a sufficient level of vibration isolation and disturbance rejection. A breakthrough in that direction was the introduction of the passive "Gravity Compensator" (Nijsse, 2001; Nijsse and Spronck, 2000), which exercises a vertical force on the rotor in order to compensate for the rotor's weight with very low vertical mechanical stiffness around the equilibrium position. To maintain the rotors 5 DOF fixed at the required position, reluctance type actuators combined with position sensing and closed loop control are used. At the same time the motor drives the rotor shaft at the required speed. The new concept is a hardware solution that should allow bringing the AREM of the rotating platform down to the nanometer scale.

Figure 3 OD-mastering device, new concept design. The linear stage and the metrology frame are not shown in this figure



In the following sections, details on the different parts of this new design will be discussed.

4. Sub-system components

4.1 Separation of force and metrology frame

The decision was made to separate the force frame from the measurement frame; the forces that are needed to let the rotor follow the metrology frame are exerted on a force frame. If the frames are completely decoupled, no forces will disturb the metrology frame, making it relatively simple to create a quiet reference world. This is a commonly used technology, e.g. wafer scanners for lithography in IC-production, where the lens acts as a metrology frame for the moving stages.

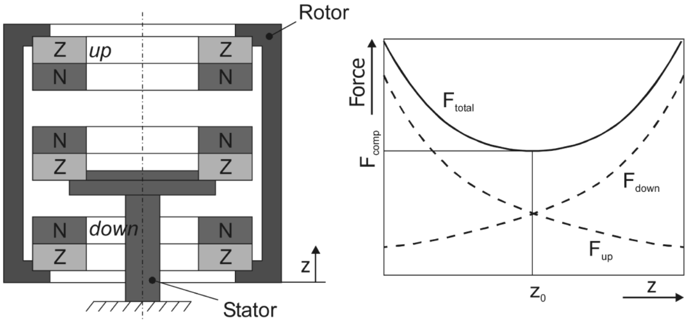
Since we have a low mechanical coupling to prevent disturbances from entering the rotor, resonances in the force frame have a decreased destabilizing effect on the control loop; the lower the mechanical coupling, the less observable the resonances become for the controller.

4.2 Gravity compensator

The weight of the rotor is compensated for by a gravity compensator (GC) to relieve the actuators from a constant effort. This has two major advantages: firstly, the continuous dissipation of power will result in a continuous generation of heat in the system, which could introduce deformations. This problem is even more severe when the system is to be operated in vacuum conditions. There the lack of heat transport by conduction and convection will lead to even higher temperature rises. Secondly, it allows the actuators to be smaller, since no large forces are needed by the actuators. This has the effect of reducing disturbances, since, e.g. smaller amplifiers with low-noise level can be used.

In order to prevent disturbance coupling to the rotor, it is important that the GC has a stiffness as low as possible. In ECMA (2001) a principle using permanent magnets is described that meets our demands. The working principle is shown in Figure 4. In the figure, the middle magnet is attached to the force frame, and the two ring magnets are attached to the rotor. The fixed magnet in combination with the upper magnet ring reject each other, resulting in a force F_{up} while the combination with the lower magnet ring gives an attracting force F_{down}. The total force then has a region around z_0 where the resulting stiffness is approximately zero. By choosing the size of the magnets and the distance between the upper and lower magnet rings, the total force at z_0 can be tuned to compensate the mass of the rotor. Typical values in our design are a (negative) stiffness of about 150 N/m in the z-direction, and 75 N/m in the radial direction. The mass of the rotor to be compensated for is approximately 2.6 kg.

Figure 4 Working principle of the GC



Note: Left: The configuration with permanent megnets rings. Right: The forces acting on rotor. At a certain height z_0 the compensation force equals the gravity force on the rotor, at zero stiffness

4.3 Actuators

A starting point of the project was the use of active magnetic bearings (AMBs) as an alternative to air bearings, which are usually used in high precision applications. Within AMBs, reluctance type actuators (RTAs) are used, which have a non-linear behavior. The force f generated by a RTA is given by:

$$f = k_{\mathrm{rta}} \frac{i^2}{x_{\mathrm{gap}}^2} \qquad (1)$$

with k_{rta} a constant representing the properties of the RTA, i the current through the coil and x_{gap} the gap distance. Normally, AMBs are linearized by pre-loading the RTAs with a bias current. This results in a constant dissipation, with the disadvantages as stated in the previous section. The biggest disadvantage here is the relatively large (negative) stiffness that results.

In the robotics control community it is common to compensate the non-linearity of the system in the controller, referred to as *feedback linearization*. This technique is also applied to AMBs (Lindlau and Knospe, 2002; Trumper *et al.*, 1997; Lévine *et al.*, 1996). For example, the compensation algorithm (for a positive force) would simply be:

$$i_r = x_{\mathrm{gap}} \sqrt{\frac{f_{\mathrm{des}}}{k_{\mathrm{rta}}}} \qquad (2)$$

with i_r the current to be generated, and f_{des} the desired force. Since the control force is usually bi-directional, one must use two (opposite) RTAs, in between some switching is involved. The influence of switching can be reduced by applying a (small) bias causing a small negative stiffness (Motee and

Queiroz, 2002). We used feedback linearization as in equation (2), and for validation applied it to a one DoF AMB setup, as described in Jabben *et al.* (2002). The algorithm was implemented in a discrete environment. Measurement showed that the resulting position dependency can be approximated with a stiffness of 1,000 N/m.

The specific geometrical placement of the actuators around the rotor is a compromise between minimizing the number of RTAs and decoupling in the planes of movement that include the axis of rotation.

4.4 Amplifiers

In combination with high-resolution sensors, a key feature in achieving high precision in the position of the platform is the implementation of low-noise power amplifiers for the RTAs (Carabelli *et al.*, 2000). Owing to the fact that the platform's weight is compensated for by means of passive magnetic bearing (GC), the force needed to keep the rotor in position is relatively small, so is the bias current needed to generate this force. This implies a relatively low energy to be delivered by the amplifiers and, consequently, a linear power amplifier is suitable for the application. Furthermore, the amplifier need not provide bi-directional current, since the force generated by the RTA is proportional to the square of the current, regardless of its direction.

A classic single-ended, MOSFET-based power amplifier was chosen for its low-noise figure, linearity and low-cost development (Holmes and Trumper, 1996; Poovey *et al.*, 1994). Figure 5 shows a schematic description of the amplifier that depicts the relevant signals for analysis.

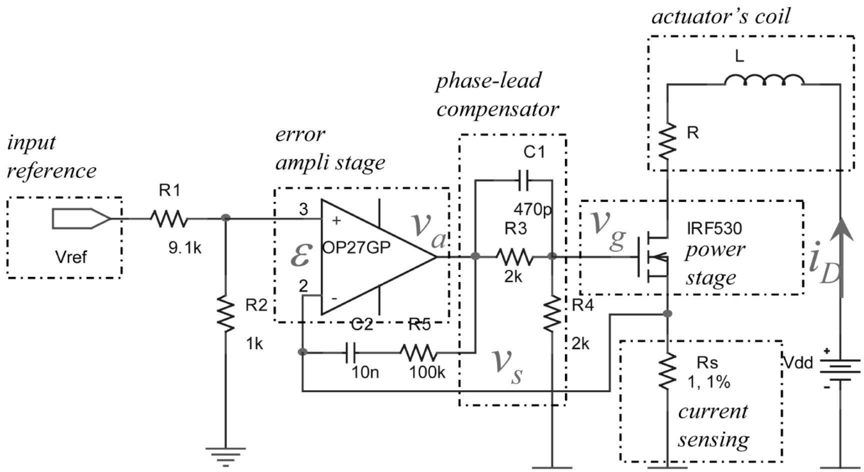
We distinguish the error amplification stage, the power stage and the feedback stage. The amplifier works in a transconductance mode, which means current flows in the actuator's coil linearly proportional to the reference voltage (V_{ref}) at the input. The current sensing resistor gives an image of the current in the form of voltage and feeds it back to the error amplification stage to be compared with the reference voltage. The amplifier allows 0.5 A continuous with 1.5 A peaks.
In El-Husseini *et al.* (2003b), a model and detailed performance analysis of this amplifier are given.

4.5 Sensors

Two sets of sensors are used for positioning the rotor. The first set consists of eight optical sensors that are mounted in the force frame, close to each actuator. Their purpose is to measure the gap between the rotor and each actuator, as the behavior of the actuators is non-linearly dependent on the gap-size. For this purpose the optical sensors were chosen with a range of 1 mm and a resolution of 0.4 μm at 207 kHz. As this resolution is not sufficient for achieving nanometer positioning precision, a second set of sensors is implemented. The second set consists of capacitive high resolution sensors (resolution = 0.2 nm at 1 kHz), having a range of ± 25 μm. These capacitive sensors are mounted on the metrology frame, measuring the relative position between the rotor and the metrology frame.

To keep the rotor at a fixed position, not the gap between the rotor surface and the metrology frame, the distance of the rotors' axis of inertia to the metrology frame should be kept constant.
In rotation, due to non-roundness of the rotor, the gap-size will vary by several micrometers, even when the position of its axis of inertia does not change. To compensate for these gap-changes, an algorithm will be used to subtract the repetitive

Figure 5 Schematic description of the linear power amplifier



error motion of the rotor from its non-repetitive part.

In the rotor start-up phase the rotor is expected to move more than the range of the capacitive sensors. Therefore, the rotor will be started up at some distance from the force frame and the metrology frame. During the start-up phase, the rotor position will therefore be controlled by a feedback control via the optical sensors. After the rotor has come to a stable rotation, the rotor will be moved towards the capacitive sensors. Once the rotor is in range of the capacitive sensors, the feedback loop will be redirected to the capacitive sensors on the metrology frame for high accuracy position control.

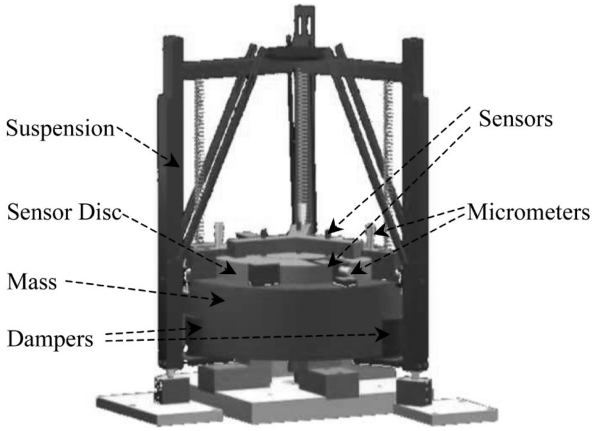
4.6 Metrology frame

The purpose of the metrology frame is to serve as a stable position reference for the capacitive high resolution sensors. To create a stable reference, position disturbing influences must be minimized. As the metrology frame is not in direct contact with the force frame, actuator reaction forces will not have a big influence on the metrology frame. Therefore, floor vibrations form the biggest source of disturbance.

To minimize the influence of floor vibrations, the metrology frame was designed to have eigenfrequencies as low as 1 Hz in the horizontal direction and 2 Hz in the vertical direction and a roll-off at frequencies above. As can be seen in Figure 6, the metrology frame was built-up as a damped mass – spring system. A large solid aluminum ring of 22 kg is supported by three springs. Three dampers under the solid ring are filled with oil selected to provide the required damping.

On top of the metrology frame a sensor disc is placed, which can be repositioned by micrometers to bring the rotating platform in range of each sensor. Two capacitive sensors are mounted in the sensor ring, to measure horizontal movements of the rotor. Three capacitive sensors are mounted on a frame resting on top of the sensor ring, to measure the vertical rotor movement and rotations other than the rotor spin. An optical encoder, that continuously measures the rotor angle, is mounted hanging on this frame, in the center of the rotor. This rotor angle is necessary for the motor control and for the algorithm to subtract the repetitive error motion of the rotor from its non-repetitive part.

Figure 6 Metrology frame design

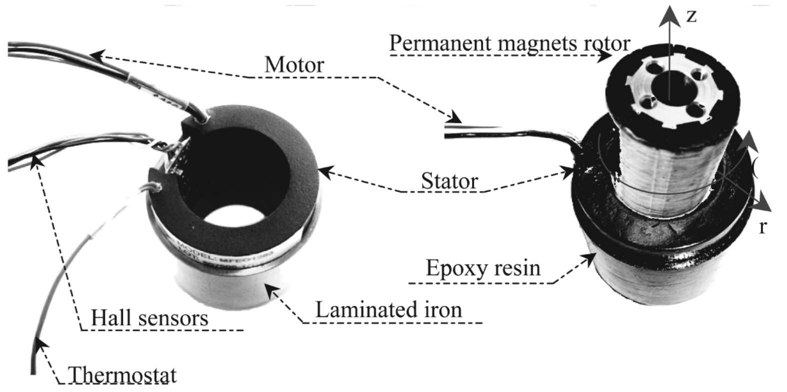


4.7 Motor

The principle of separation between the force and metrology frames (resulting in a low-stiffness concept) implies the use of a special motor where the attraction force between the rotor and stator should be independent of the rotor position in the air gap. This is possible by using a brushless permanent magnet motor where the stator does not include any iron. The static stiffness (defined as the derivative of the force to the position) of such a motor would be zero and the dynamic stiffness is ideally in the direction of rotation only. Such a motor is not commercially available because of the low-efficiency that the ironless motor has when compared to a standard motor of the same volume. Nevertheless, in collaboration with the Aerotech Company, an ironless low-stiffness motor has been built. Figure 7 shows the ironless low-stiffness motor and its standard counterpart, both provided by Aerotech. Standard brushless motors usually contain laminated iron on the stator for magnetic flux return. In the new custom-designed motor, the laminated iron was replaced with epoxy resin in such a way that no attraction force is built-up between the stator and rotor in static conditions, e.g. when the motor is not energized. The rotor has eight permanent magnet poles that are magnetized in a Halbach array structure to ensure sinusoidal flux density distribution in the air gap and therefore, allowing good motor performance with sinusoidal currents commutation. The ironless motor is rated 1.5 A continuous for 0.12 N m stall torque. These figures are 2.8 A and 0.42 N m for the standard motor. The two motors have the same physical dimensions (diameter: 50 mm, length: 52 mm).

We investigated the suitability of using the standard brushless motor in our ultra high precision application. The experimental results conducted on the standard motor proved its inadequacy for this application because of the significant mechanical coupling introduced by the motor stiffness (20 kN/m). More details on the experimentations are described in Section 5.2.

Figure 7 Standard (left) and low-stiffness motor (right)



It was deduced that the use of a brushless ironless motor will definitely help cancel the AREM and SREM associated to the motor. It is also believed that usage of the ironless motor will minimize the overall effort and expenses associated with motor-related SREM correction and perfect rotor centering.

4.8 Parts assembly

The components described in the previous section are being manufactured and assembled together at our department as a part of the feasibility study in an attempt to prove that this technology is suitable for ODs glass-mastering. Plate 1 shows a picture of the system that includes the rotating platform and the force frame (left) and the metrology frame (right). The metrology frame will be lowered on top of the platform.

5. Dynamic performance

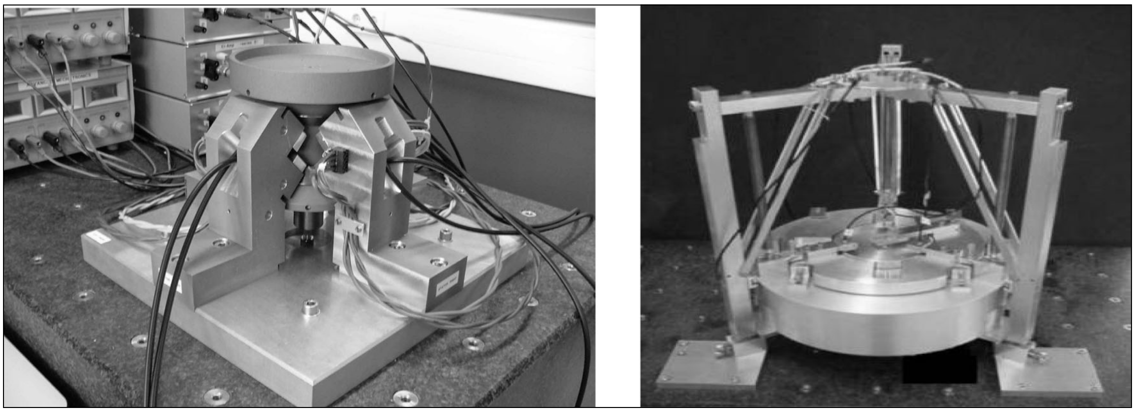
The system will perform basically two functions on the platform: suspension and rotation.

5.1 Suspension

To validate the design, closed loop simulations were made. Since the main specification of the Blu-ray™ disk is on the AREM, to validate the performance only disturbances that are asynchronous with the rotation are considered. As a matter of fact, the asynchronous are the disturbances that act on the system when it is suspended. In order to be able to calculate with these disturbances, they are considered to be stochastic of nature. Translating the peak-peak value for the AREM on the Blu-ray™ disk to a six sigma value, we have a one-sigma value of 2.2 nm. Error budgeting over different error sources leaves an AREM of 1 nm (one-sigma) for the AREM of the rotating platform.

When the system is suspended, it is controlled at a certain position using the positional information of the sensors, to calculate the currents for the RTAs. This is called the feedback loop, and the suspended system is referred to as being in closed loop. On such a closed loop system many disturbances act that allow stochastic modeling. In our case we considered disturbances like ground vibrations, amplifier noise, quantization and electronic noise in the analogue to discrete and

Plate 1 Rotating platform and force frame (left). Metrology frame (right)



discrete to analogue converters, and sensor noise. The disturbances are modeled via their power spectrum densities (PSDs), which describe the distribution of power over frequency. By taking the cumulative integral of a PSD, we obtain a monotonic increasing function, which clearly indicates the increase of power of the signal at each frequency.

In Figure 8, the final predicted performance of the suspended system is shown. The final performance is well below 0.5 nm.

5.2 Rotation

Given that the suspension function of the platform is still under investigation, there was the need for testing the low-stiffness motor separately. For this motor, two figures of merit are of particular importance and need to be evaluated: the radial stiffness and the velocity. For the testing, the motor has to be mounted on an appropriate bearing. We choose an available active magnetic bearing system from MECOS[1]. Figure 9 shows a 3-D cross-sectional sketch of the test setup. The motor is coupled to the MECOS shaft with the ability of precisely positioning the rotor within a sufficient radial displacement range (500 μm), while the shaft is free for rotation at any position. The stator of the motor is stiffly connected to a 6 DoF force/torque sensor, this is particularly necessary to evaluate the radial forces and thus, the radial stiffness of the motor. The resolution of the force sensor is 0.04 N in the radial (*xy*) plane.

The stiffness of the motor was evaluated in two steps. In the first stage, the static stiffness of the motor is measured and compared to the equivalent standard motor (Figure 7). The static stiffness is identified as the reluctance stiffness resulting from the attraction forces between the rotor's magnets and the stator's iron. Obviously, the ironless motor showed no static stiffness; since it has no iron, while the standard motor showed a static stiffness of 20 kN/m. Despite the relative low-stiffness of the standard motor, the error budgeting model, described in the previous section, predicted the unsuitability of the standard motor for our

Figure 8 Square root of the cumulative power spectrum of the predicted performance

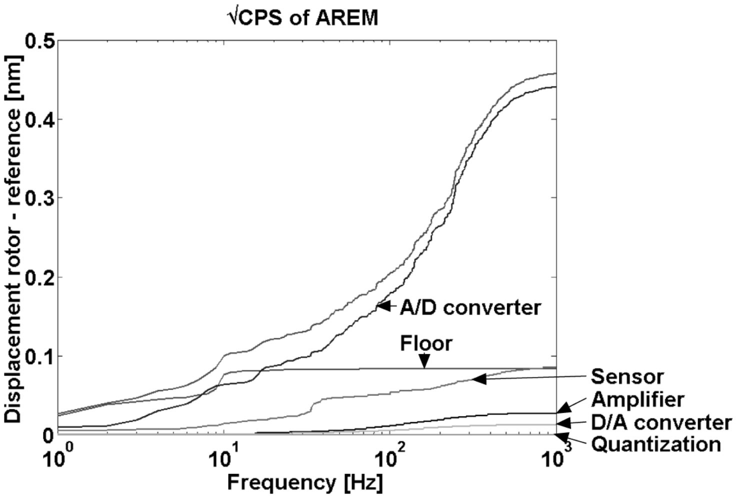
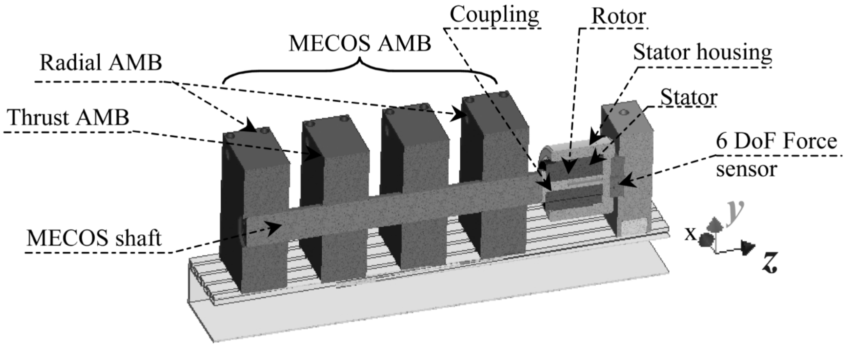


Figure 9 For testing purposes, the low-stiffness motor is mounted on a magnetic bearing and force/torque sensor



application. Details on that are reported in Jabben *et al.* (2003) and El-Husseini *et al.* (2003a).

In the second stage, the ironless motor were energized and rotated at a specified speed in order to evaluate its dynamic stiffness. Figure 10 shows the servo-control test setup used for this purpose. This is a classic PI servo-control mechanism combined with three-phase sinusoidal power drive.

The radial forces are measured at different speeds and the results are shown in Figure 11. The measured radial forces are small for all speeds and fall within a few orders of magnitude of the force sensor's sensitivity, independent of the position of the rotor in the air gap. This makes it difficult to measure the exact radial dynamic stiffness of the motor. However, it is possible to draw a worst case stiffness value from this figure, which turned to be less than 500 N/m; meeting or even exceeding the specifications.

Figure 10 Dynamic test setup for the low-stiffness motor

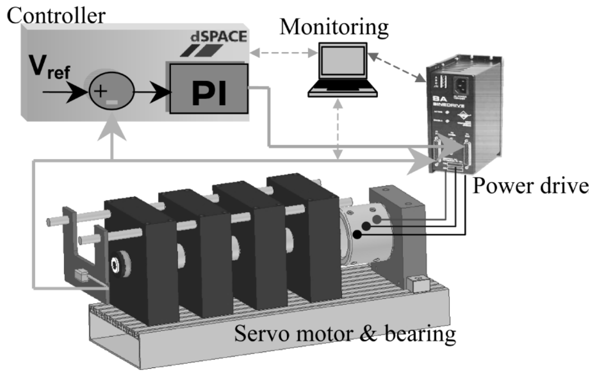
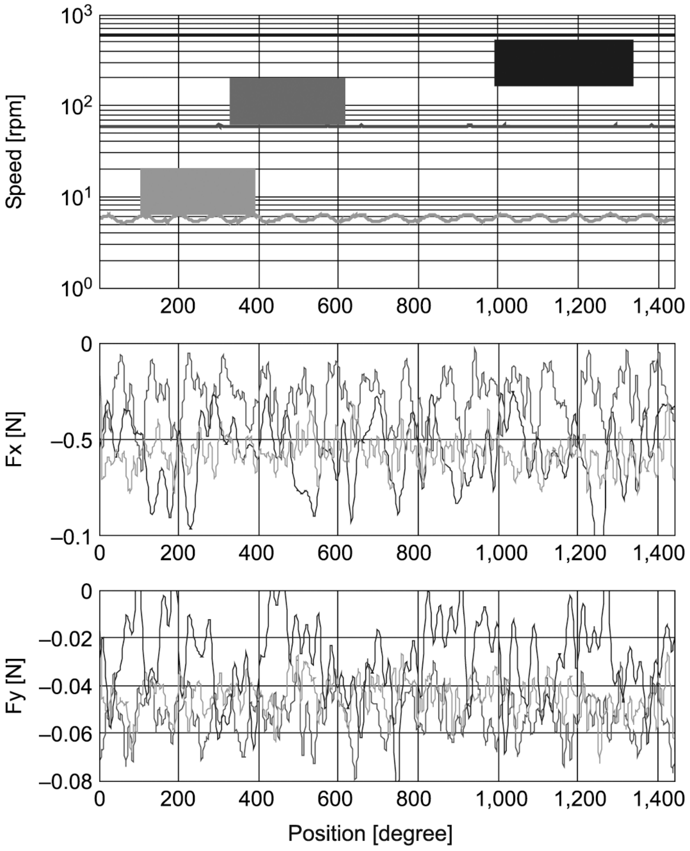


Figure 11 Radial forces at different speeds



6. Conclusion

The current state-of-the-art in OD-mastering equipment is based on a high-stiffness design with air-bearings. A vacuum-compatible alternative is needed to meet the high-density Blu-ray™ specifications. In this paper, we described a new low-stiffness design concept for an OD-mastering device. This new concept is based on a permanent magnet gravity compensator; eight reluctance type actuators for the magnetic bearings and a brushless ironless permanent magnet motor, with all these components having low-stiffness characteristics. Predictive modeling, based on error-budgeting estimation, indicates the feasibility of the chosen approach. Different parts of the system have been built and tested successfully. A first prototype is assembled and its suspension functionality is under investigation. The motor will be implemented in a later stage in order to investigate the overall dynamic performance of the new concept.

Note

1 MCOS Traxler AG, available at: www.mecos.com

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