Long Range, Direct Drive XY-(Φ=0)–Stage with Sub-micrometer Resolution

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1 Introduction

In precision engineering, often an accurate movement in one plane is needed. Processes where this is the case are: laser cutting, coordinate measuring, photo plotting, and step–and–repeat processes. There is a large variety of stages available that perform this XY-movement. Most of these stages use the stacked structure, where the X-drive carries the entire Y-drive, or vice versa.

At the Laboratory for Micro Engineering at the Delft University of Technology, it was recognized that a *direct drive* system can have a better dynamic performance (also see [1]). In such a system, the drives are not stacked, but all work between the rigid world and the moving part.

In this paper, an XY-stage is presented, based on this direct drive principle. Using linear motors and feedback control, a position stability better than 0.2 μm is achieved. The angle of rotation around the Z-axis, Φ, is electronically controlled to zero within 0.36 μrad. The propulsion system allows a travel of 100 × 100 mm^2.

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2 Design Approach

In this project the *Mechatronic Approach* is applied. Here, unlike in 'traditional engineering', the cooperation between different fields of engineering is taken into account from the beginning.

In order to eliminate cross-talk between the guidances of the X- and the Y-drive, only one guidance system is used. Thus, only one moving part (*rotor*) remains, that moves in the XY-plane.

With this direct drive setup, the dynamics of the system can be improved compared to the 'traditional' stacked configuration. These better dynamics are partly due to the fact that no transmission is needed between motion generating element and rotor. More important is the fact that the vertical dimension of the rotor can be kept small, minimizing the out-of-plane forces. Thus, the stage will be much less subject to tilting.

It is possible to design the system such that there are not many parts that need accurate manufacturing, reducing the cost of the system. In the system presented here, the only expensive parts are the sensor system, and the electronics used to implement the controller.

3 System Description

In this Section, the functions of the system are described separately. However, according to the mechatronic approach, all have to be considered simultaneously during the design phase.

The requirements on the system are:

- *Contact-free* operation,
- Travel 100 × 100 mm^2,
- Maximum speed 200 mm/s,
- Bandwidth 100 Hz,
- Position accuracy better than 2 μm,
- Angular accuracy better than 20 μrad, and
- Acceleration up to 20 m/s^2.

3.1 Propulsion

For a contact-free, direct drive XY-stage, propulsion is most practically implemented with *linear motors*. Attention has to be paid to the fact that the propulsion in one direction, does not limit the movement in the other direction.

The type of linear motor used is the *Moving Core Motor*, short: MCM (also see, [2] and [3]). This motor uses the *Lorentz-force*.

The motor consists of the following elements (see Figure 1): (1) a stationary element, generating the magnetic field, (2) a moving coil that carries the current into the magnetic field, and (3) a moving core, that carries the coil, and guides

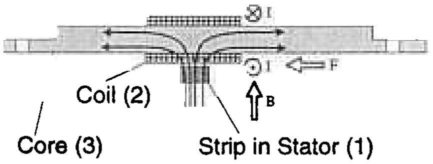

Figure 1: Essential to the Moving Core Motor is the bending of the magnetic flux along the axis of the coil. Would the field not be bent, two oppositely directed forces are generated, yielding a zero resultant force.

the flux along the axis of the coil. The MCM is simple, both in construction and use.

Essential to the MCM is the fact that the magnetic flux is bent to run parallel to the coil axis, after crossing the windings once. If the field would cross the windings at the opposite side of the coil, an oppositely directed force would be generated, yielding zero resultant force. The field is bent by a core inside the coil, made of a magnetically conducting material.

The coil, on which the Lorentz-force acts, and the core are made as one rigid unit to ensure high stiffness. Also the construction is simplified.

The system uses four motors, in pairs parallel to each other. Each pair is used for driving either the X-, or the Y- direction. Both pairs are used to generate the torque needed to control the angle Φ. The controller divides the necessary torque over the two pairs, equally.

By using a square configuration, the rotor becomes extremely simple, see Figure 2. The magnetic field is used twice: when entering and when leaving the rotor.

In the stator, also see Figure 2, the magnetic fields are generated by permanent magnets under the stator surface. The magnetic field is for every point of the travel directed towards the rotor by a steel magnetic circuit. The distance between lines of action of the forces and the center of gravity of the rotor, does not change. This reduces the complexity of the controller.

Advantages of this propulsion system are:

1. The amplifier needed for current supply is simple.
2. The rotor is easy to manufacture.
3. The rotor is a self-supporting structure. Extra elements can be connected to the rotor. Also, a high mechanical stiffness is ensured.
4. The vertical dimension of the rotor can be kept small. Thus Abbe's law is easily obeyed, and tilting of the rotor is minimized.
5. Extension of the travel of the system is expected by expanding the stator.

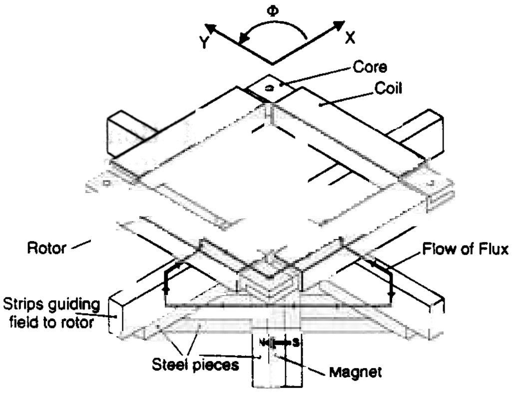

Figure 2: The propulsion system. The rotor consists of four cores in a square, each carrying a coil. The magnetic field is generated by the permanent magnet. The steel pieces and the 'strips guiding field to rotor' direct the field to the rotor. Where the field crosses the coil, the Lorentz force is generated.

However, there are also disadvantages:

1. Current has to be supplied to the rotor. To minimize the parasitic forces caused by this connection, bent flexible printed circuit board is used, mechanically comparable to the buckled leaf spring.
2. The coils are used inefficiently. Only 3 % of the coil is used for force generation. Improvement is expected by only supplying current to parts of the coil.

3.2 Bearing

To ensure contact free movement of the rotor, air bearings are used. The bearing system has to reduce the number of degrees of freedom of the rotor from six to three, i.e. X, Y and Φ.

A location problem occurs when three air bearings are used. Therefore, four air bearings are chosen. Two bearings are connected via a bending lever that is halfway connected to the rotor. There, a virtual bearing point is created, suspending the rotor at three points.

The air bearings, designed in the Laboratory, are simple and function satisfactorily.

The necessary air supply hose is kept thin, made from flexible material, and bent. Thus, the parasitic forces on the rotor are small.

3.3 Position Measurement

The measurement system has to provide three coordinates: X, Y, and Φ. Because of the direct drive setup, two two-dimensional measurement systems (*Heidenhain PP109R*) are chosen. These systems use an optical grating on glass as *form standard*. The position of the measurement heads relative to the grating is obtained incrementally. Two *reference marks* define an origin, reproducible within the sensor resolution (0.1 μm).

Each PP109R system outputs two signals, S_x and S_y. The angle Φ is calculated using:

$$\Phi = K_{\text{sens}} \frac{S_{y1} - S_{y2}}{d} \tag{1}$$

where d (0.275 m) is the distance, between the two Y-measurement heads, measured parallel to the X-axis, and K_{sens} is the sensitivity of the measurement system. The second X-signal is not connected in the system presented here.

The absolute accuracy of the measurement system is 2 μm, for both directions. Using equation 1, the accuracy for Φ is found to be 15 μrad.

The resolution is increased with interpolation electronics (*Heidenhain EXE-units*) to 0.1 μm for the X-direction. The two Y-measurements are averaged, yielding a position resolution of 0.05 μm. For Φ, the resolution is 0.18 μrad.

The measurement system allows only a small angle of rotation (0.5°). An 'emergency off' is implemented in the controller that is activated when Φ exceeds a given value.

The entire electro-mechanical system is shown in Figure 3. The mass of the rotor is 2.4 kg. This includes the air bearings, the form standards and a small platform for objects. The size of the stator surface is 340 × 340 mm^2. The maximum load is 0.5 kg.

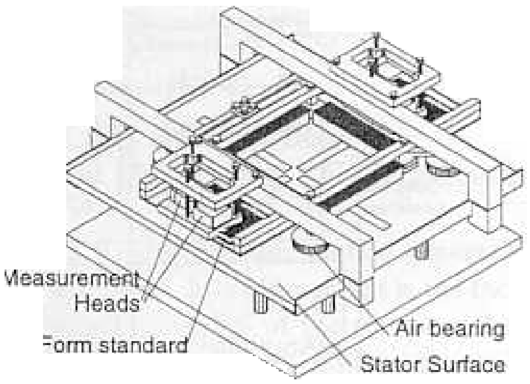

Figure 3: The entire electro-mechanical system.

3.4 Control

The complete controller is based on three independent controllers, one for each of the directions X, Y, and Φ. The design of the complete controller is simplified greatly by eliminating the dependency between Y and Φ, using coordinate transformations. One transformation is used to calculate x, y, and Φ from the signals S_x, S_{y1}, and S_{y2}. Another is used to calculate the four motor currents, I_{x1}, I_{x2}, I_{y1}, and I_{y2} from the controller outputs I_x, I_y, and I_Φ.

The controllers are of the tame PID–type. The tame PID–action is designed as to give (1) the desired bandwidth (100 Hz), (2) a stable process, (3) sufficient suppression of high-frequency noise, and (4) small enough static error (1 μm). Using the measured transfer functions of the electro–mechanical system in the three directions, the parameters for the controllers are calculated.

The controller is implemented in a *Digital Signal Processor* using a TMS320C30 processor. The software used to build the controller program is provided by dSpace GmbH.

4 System Performance

The most important performance parameters of the realized system are: top-top position stability better than 0.2 μm, top-top angular position stability: 0.36 μrad, stiffness larger than 610 kN/m, maximum speed: 0.21 m/s, and travel: 42 × 42 mm^2.

The accuracy achieved is limited by the accuracy of the measurement system only. The top-

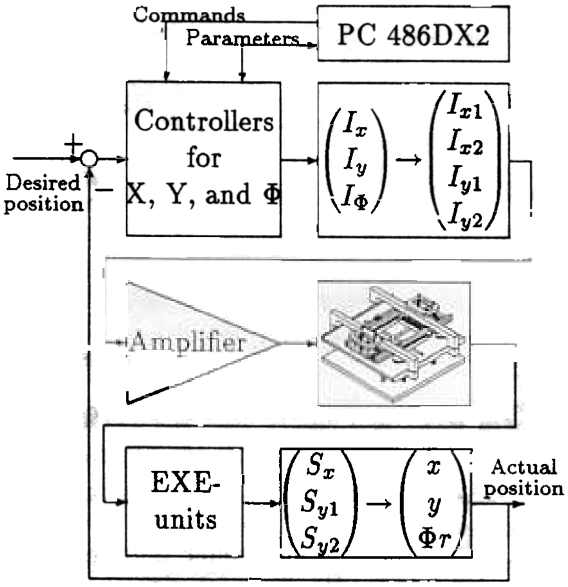

Figure 4: Setup of the controlled system. The coordinate transformations mentioned in the text are shown, as well as the interpolation of the sensor signals (EXE-units).

top position stability equals twice the measuring resolution. Therefore, higher accuracy and higher resolution are expected to be achieved with a modified measurement system.

The travel is limited by the measurement system. The propulsion system was designed for a 100 × 100 mm^2 travel, which can be increased modularly by enlarging the stator.

In Figure 5 the measured response on a 100 μm step in the Y-direction is shown. The controlled system functions very well. The response is fast and sufficiently damped.

The requirement for the accelerations has not been met. The maximum acceleration measured is 1.6 m/s^2. The forces that can be generated by the propulsion system as is, are too small to achieve 20 m/s^2. However, it is expected that with an optimized magnetic circuit, the required forces can be generated.

5 Conclusions

A mechanically simple, contact-free XY(Φ=0)-stage is presented.

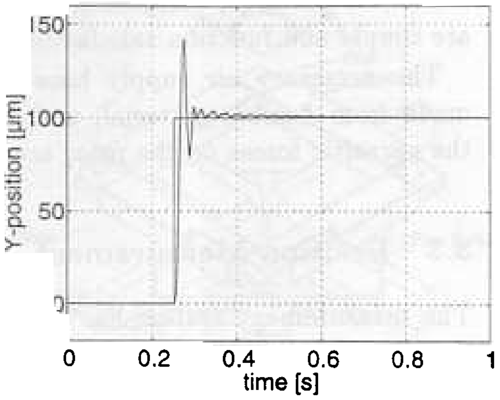

Figure 5: Measured step response of the system in Y-direction.

A new type of linear motor is presented, the *Moving Core Motor*. This motor is easy to use and to manufacture. Moreover, the position accuracy of this type of motor is limited by the measurement system used only. This motor is suited for applications where one direction is driven, whereas a direction perpendicular to the drive direction should not be confined, such as direct drive XY-stages.

Apart from the air bearings, no precision engineered parts are needed. The accuracy is achieved using an advanced measurement system and feedback control.

Interesting for future research are: extension of the travel by expanding the stator, the use of magnetic instead of air bearings, and increasing the position accuracy and stability by modifications of the position measurement system.

References

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