

TWO DEGREE OF FREEDOM ACTUATOR FOR SUSPENSION AND PROPULSION

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Abstract

In this paper a new two-degree of freedom actuator for suspension and propulsion is presented. The actuator has the potential to become a building block in a high precision six degree of freedom motion system. The actuator is called the IU-module, the topology stems from the I-shaped rotor and the U-shaped stator. The working principle behind the suspension of an IU-module is the reluctance force. The propulsion works on the moving iron principle, presented by Molenaar [1]. Improved modeling using a network of variable reluctances and finite element models give a good indication about the static performance of the IU-module. A demonstrator has been constructed to evaluate the dynamic performance of the IU-module. The achieved resolution for this demonstrator is $1 \mu\text{m}$ in suspension direction and $0.3 \mu\text{m}$ in the propulsion direction. The limiting factors are the used position sensors.

1 Introduction

In the laboratory of Advanced Mechatronics (former Micro Technology) at the Delft University of Technology, research is performed on high precision positioning systems. Magnetic bearings are more and more being integrated in these systems. The PhD-research performed by Molenaar, led to the development of the novel Planar Active Magnetic Bearing, the PAMB [1]. The performance of the PAMB excelled in low energy consumption and a large planar stroke. However the control bandwidth was limited, this was caused by mechanical and electromagnetic cross couplings. To overcome this problem the IU-configuration [1] is proposed. The IU-module is a two-degree of freedom actuator for suspension and propulsion. Using three of these IU-modules it will be possible to actuate a six-degree of freedom system. In this article the workings of a single IU-module are explained. A finite element model and a network of reluctances model are presented to

evaluate the performance of the IU-module. To further evaluate and verify the workings of the IU-module an experimental setup was built to verify the models and gain insight into the possibilities of an IU-module.

2 Working principle of the IU-module

The IU-module is a two-degree of freedom actuator for suspension and propulsion. A permanent magnet biased magnetic bearing generates the suspension force. A schematic diagram of the IU-module is given in Figure 1.

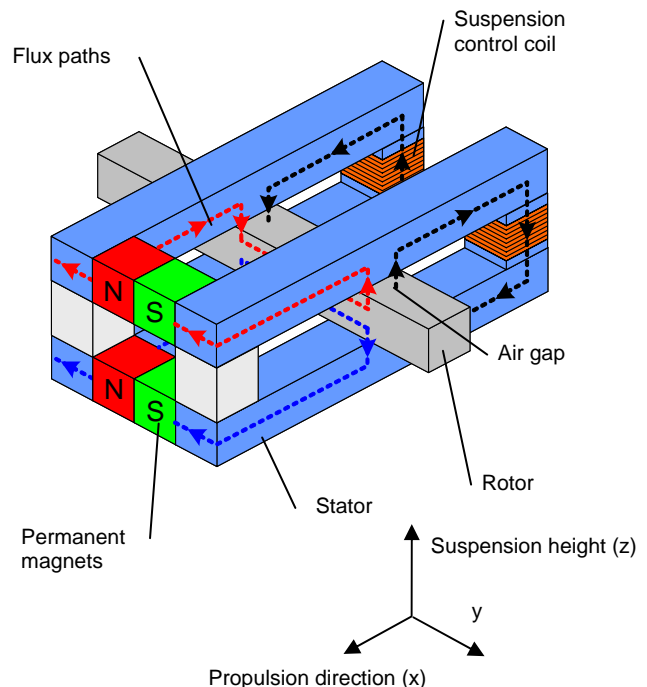


Figure 1: Flux paths in the IU-module

A three-dimensional flux path is created by the permanent magnets through the stator bars, the air gaps and rotor. This magnetic flux forms the bias flux for the magnetic bearing. To achieve stable suspension the control coils are added; the control coils influence the flux in the air gaps.

The total force generated by fluxes in the upper air gap and lower air gap is given by:

$$F_{suspension} = \frac{1}{2\mu_0 A_{airgap}} (\phi_{upper, airgap}^2(z, i) - \phi_{lower, airgap}^2(z, i))$$

This equation is linearized to obtain the following relationship:

$$F = K_z z + K_i i$$

The actuator stiffness is represented by K_i and the negative stiffness of the magnetic bearing itself is given by K_z .

By putting the rotor slightly above the middle position, an offset force is generated by the permanent magnets. This offset force is used to compensate for the gravity forces acting on the rotor without any power consumption.

The propulsion force is generated with the “moving iron” principle, developed by Molenaar [1]; a description of the principle can also be found in Jabben [2]. The “moving iron” principle uses coils on the stator bars of the system to propel the system. The schematic of the setup is given in Figure 2. With the flux paths as in Figure 1 the rotor serves as a virtual source for the magnetic flux. The force generated by the propulsion coils is proportional to the current and the magnetic field density, such as the Lorentz force.

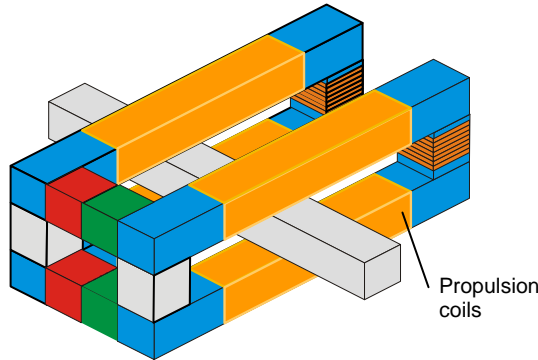


Figure 2: IU-module with propulsion coils

The force generated by the propulsion coils is expressed as:

$$F_{propulsion} = 4nBi l$$

In which n is the number of turns, B is the magnetic field density, i the current, and l the length of coil in the magnetic field.

The advantage of the IU-module is first of all that it is a compact actuator for manipulating two degrees of freedom. Secondly it enables suspension of a mass with low power consumption. The third advantage is that all current carrying wires for both suspension and propulsion are positioned on the stator. The IU-module leads to true wireless suspension and propulsion.

However there are drawbacks to a combined two-degree of freedom actuator, namely the interaction between the two directions. In the next section different modeling techniques are presented to evaluate the performance of an IU-module and this interaction.

3 Modeling of the IU-module

The presented linear equations for suspension and propulsion force have only limited validity. To improve the knowledge about the workings of the IU-module two modeling strategies are applied: a network model using variable reluctances and a finite element model.

3.1 Network of reluctances model

For a performance estimation of the electromagnetic characteristics of the IU-module with different geometry settings a magnetic field analysis is required. The linear approximations do not contain every effect in the IU-module. The following effects play a vital role in the performance of the IU-module: rotor saturation, leakage fluxes and a separate flux path through the suspension coils.

Finite element solutions are time consuming. A less time consuming and therefore a more suitable starting point is based on modeling the magnetic circuit on the analogy of an electrical circuit. The conversion of the basic magnetic circuit components is shown in Table 1.

Electric circuit	Magnetic circuit
Voltage, V	Magnetomotive force (M.M.F.), Ni
Current, I	Magnetic flux, ϕ
Resistance, R	Reluctance, P

Table 1: Conversion table for magnetic to electric circuit

A basic example of this conversion system is shown in Figure 3, where a magnetic circuit with an air gap is modeled.

Other magnetic circuit components, like permanent magnets, can be modeled by a combination of magnetic components. In like manner an electrical equivalent circuit is developed for the IU-module to analyze its magnetic characteristics. The conversion for the magnetic circuit of the IU-module to an equivalent electrical circuit is visualized in Figure 4.

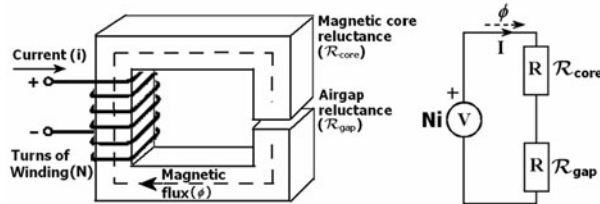


Figure 3: Example conversion of magnetic to electric circuit

Saturation effects, an important aspect of the IU-module design, can be integrated in the existing model by modification of the constant reluctances into variable reluctances.

Solving the equivalent electrical circuit is based on Kirchhoff's current law (KCL) extended with an algebraic loop solving for the variable reluctances.

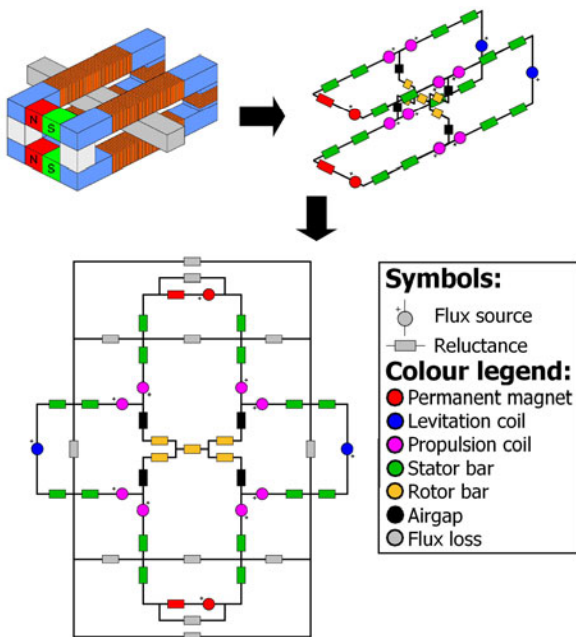


Figure 4: Network of reluctances model

3.2 Finite element model

To fully and accurately analyze the IU-module a finite element simulations are performed. For these finite element calculations the software

package Ansys® is used. The three dimensional magnetic field is calculated using the magnetic scalar potential.

In the finite element model non-linear material properties are used. Air is modeled around the IU-module and in this manner leakage fluxes are incorporated in the model.

For control the main interest is on the forces, which act upon the rotor. The force on the rotor is calculated using the virtual work principle implemented in the Ansys® software.

In Figure 5 the flux density distribution derived by the finite element simulation is shown. In Figure 6 the forces on the rotor in suspension direction versus air gap position are plotted. More information on finite element modelling of an IU-module can be found in [3].

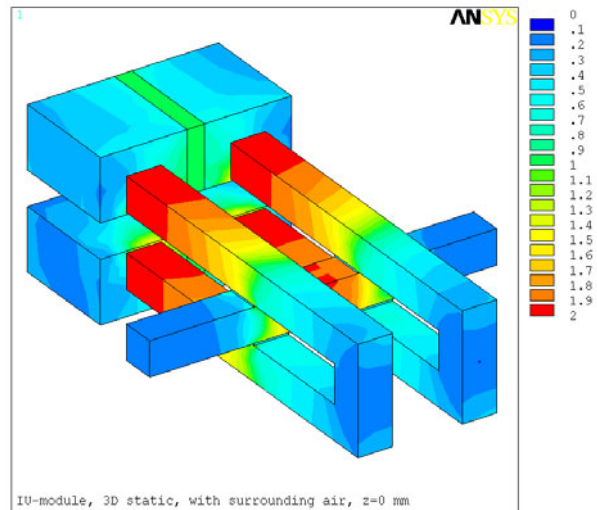


Figure 5: Picture of flux density calculated with finite element model

The interaction between the propulsion and suspension has been analyzed using the finite element simulations, by applying current to the propulsion coils and evaluating the forces on the rotor. The results are depicted in Figure 7. The Lorentz like force in propulsion direction is clearly visible.

The interaction between the force in propulsion direction and the force in suspension direction limits the performance of the IU-module. The interaction reduces when the rotor is positioned closer to the middle position (exactly between the rotor bars), however less force is generated by the permanent magnets to compensate for gravity

forces. Eventually the interaction will form a limit on the carried load. A decoupling controller can be used to compensate for this problem.

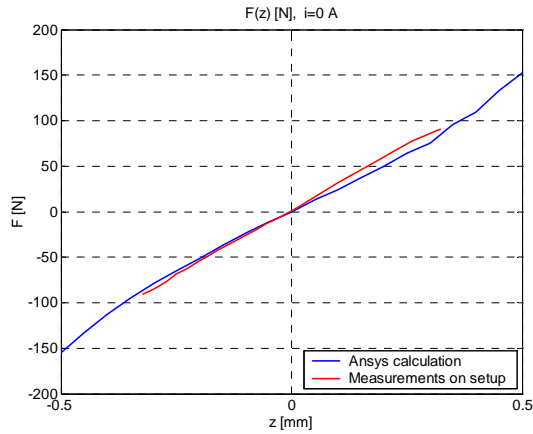


Figure 6: Force in z-direction on rotor versus air gap position

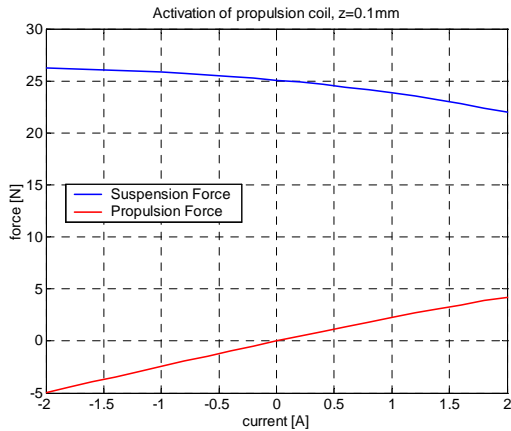


Figure 7: Simulated force resulting from current in propulsion coils, while rotor is 0.1 mm above the middle position

4 Demonstrator

To evaluate the performance of the IU-module, a demonstrator is constructed. Upon this demonstrator static measurements and dynamic measurements can be performed. Static measurements are done to determine the forces acting on the rotor exerted by the magnetic field. The dynamic measurements have the goal to relate the static performance of the IU-module to position accuracy.

4.1 Static measurements

The static measurements have the primary goal to evaluate the modeling and determine the forces on the rotor. The forces on the rotor are measured using strain gage force sensors. Figure 8 shows a picture of the static test setup.

The general dimensions of the IU-module test setup are presented in Table 2.

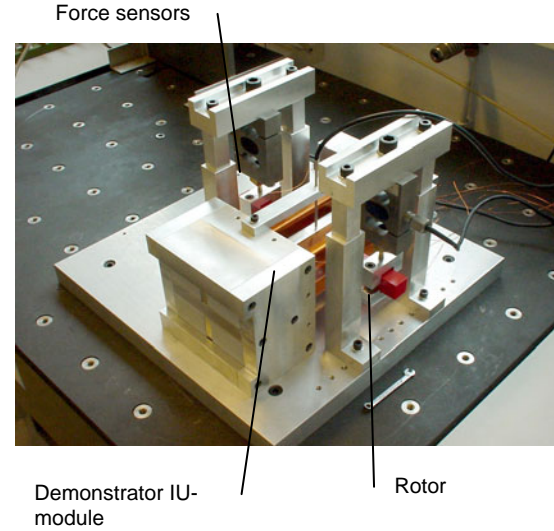


Figure 8: Static test setup

	Dimension
Stator bar area	20 mm x 20 mm
Rotor bar area	20 mm x 20 mm
Stator bar length	200 mm
Clearance between stator bars	40 mm
Single air gap height	1.1 mm
Permanent magnet size	63 mm x 36 mm x 10 mm
Number of suspension coil windings	50
Number of propulsion coil windings	210

Table 2: General dimension of the demonstrator

The used permanent magnets are NdFeB magnets. These types of magnets are strong, commonly available, and have linear characteristics.

The stator and rotor bars are manufactured from laminated steel plates, minimizing eddy current losses in the rotor and stator bars.

In Figure 6 a comparison between the simulated and measured suspension forces are plotted with respect to the rotor position, validating the finite element model.

4.2 Dynamic demonstrator

To evaluate the closed loop dynamic performance of the system an air bearing is attached to the IU-module. The IU-module actuates two degrees of freedom, namely the suspension and the propulsion, the other four degrees of freedom of the rigid body are constrained using this air bearing. In a future setup we envision the combination of three IU-modules, each actuating two degrees of freedom to suspend a body in six degrees of freedom. For now an air bearing is chosen to keep the system simple from a control point of view. The choice for an air bearing is motivated by its frictionless operation. A drawing of the dynamic setup is given in Figure 9.

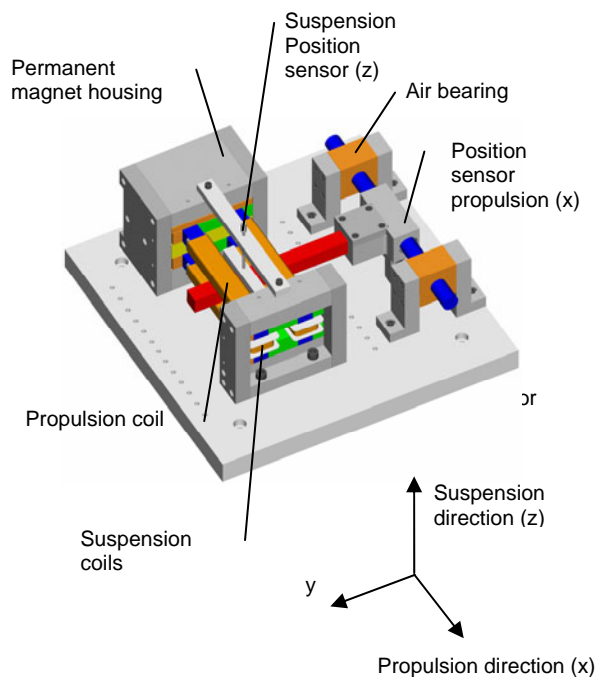


Figure 9: Dynamic demonstrator

The magnetic bearing allows the rotor to rotate around its axis through the air bearings. Because the length of the rotor is relatively long the, the IU-module is being used in the intended way: as an actuator for suspension and propulsion.

For suspension position measurement a Philtec photonic sensor is used. The target of the sensor is a flat aluminum strip, which is attached to the

rotor in such a way that the suspension position is measured on the entire stroke of the system. The propulsion position is measured on the connection block to the air bearings. Underneath this block a MicroE optical linear encoder is mounted. The MicroE linear encoder has a resolution of $0.1\mu\text{m}$.

The suspension and propulsion coils are current driven. Pulse width modulated amplifiers supply the current to the coils.

A digital control board closes the control loop. The control board used in this setup is a dSpace control board.

To investigate the interaction between the suspension and propulsion direction, a static force measurement is performed. The current in the propulsion coils is plotted against the force in suspension direction in Figure 10. Theoretically there is no interaction between the propulsion and suspension direction when the rotor is exactly in the middle of the two stator bars. Since the suspended mass of the rotor is relatively low and the IU-module is operated close to the middle position the interaction does not play a role. The two directions of the IU-module can be controlled independently without using a coupled multi input multi output controller.

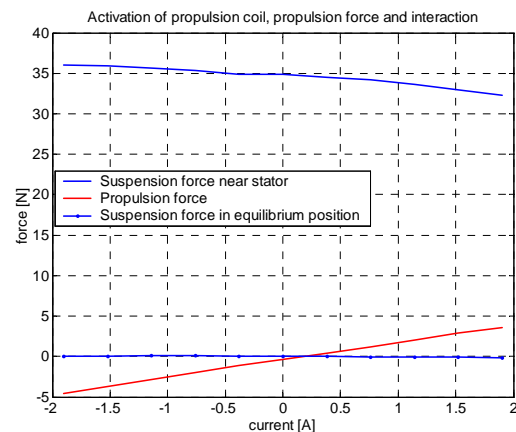


Figure 10: Measured forces on rotor for setup with air bearing while activating propulsion coils

One final remark must be made while evaluating the results of the dynamic demonstrator, namely that the dimensioning of the magnetic circuit is not optimized for dynamic performance. The main goal of this dynamic demonstrator was to validate the concept of the IU-module. Therefore some

results presented in the next paragraph are not optimal.

5 The dynamic control of the system

To stabilize the system, a position loop is closed between the position sensors and the current amplifiers. Simple PID controllers are used to stabilize both the suspension and the propulsion. The open loop bode diagram of the suspension with PID controller is given in Figure 11. It can be clearly seen that the negative stiffness in the suspension direction is relatively large compared to the suspended mass; the stiffness has a large eigen-frequency. In a future design this can be overcome by choosing smaller magnets. Eddy current losses and non-linearities cause the phase lag at higher frequencies. The usage of soft magnetic powder composite materials might reduce this problem. The bandwidth that was achieved using a PID controller in suspension direction was 180 Hz.

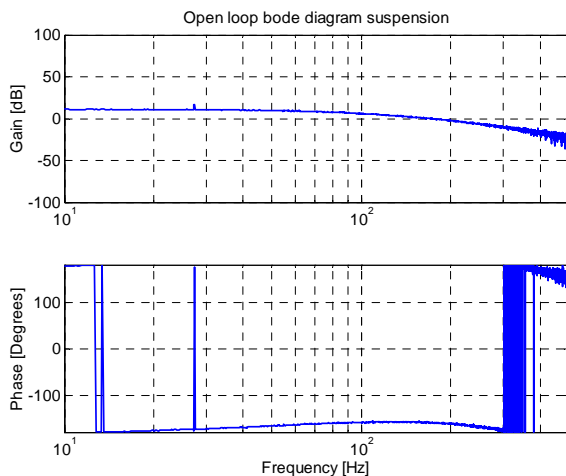


Figure 11: Open loop bode of the suspension

The open loop bode diagram of the propulsion is given in Figure 12. The crossover frequency lies at approximately 60 Hz. The bandwidth is limited because of the oscillations at 210 Hz. The oscillations are caused by the low stiffness of the air bearings. The phase loss is caused by a mismatch between the amplifier and the load; adapting or changing the amplifier can easily overcome this problem.

The setup has achieved stability in the suspension direction of 1 μm . The accuracy of the propulsion direction was 0.3 μm with a stroke of 50mm.

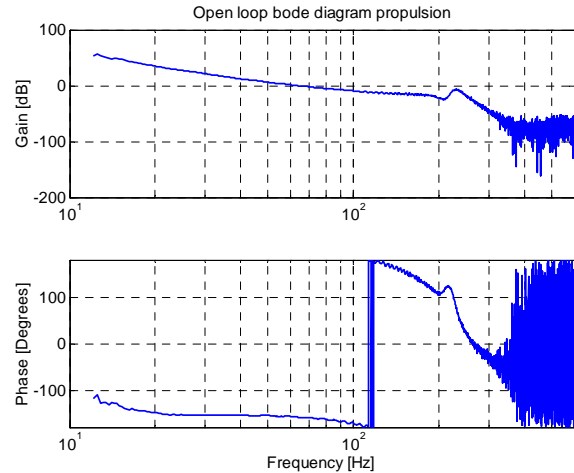


Figure 12: Open loop bode diagram of propulsion

6 Conclusions

The IU-module is a compact two-degree of freedom actuator for suspension and propulsion. Accurate models are presented, using a network of reluctances and finite element modeling. The models were verified with a static test setup. A dynamic demonstrator is constructed to verify dynamic performance. Bandwidths of 180 Hz for suspension and 60 Hz for propulsion were realized. The obtained accuracy is for 1 μm suspension and 0.3 μm for propulsion. The limitations in bandwidth and accuracy were not caused by the IU-module itself, but by devices surrounding it, like position sensors and air bearings.

The concept of a single IU-module is proven and it shows to be a good building block for a six-degree of freedom setup. It is our belief that nm accuracy can be achieved with such a six-degree of freedom setup. However still more research needs to be performed before combining three IU-modules into a single six-degree of freedom setup.

References

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- [2] Jabben L., Overschie P.M., Molenaar A., Beek van H.F., *Lorentz Motor with stationary magnets and coils applied in a 6-DOF stationary coil motion stage*, ASPE Topical Meeting, April 2001
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