



# Bidirectional Bearing with Actively Coupled Magnetic and Pneumatic Actuator

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## Abstract

Producing large, high-quality workpieces requires precise axes with accurate guidance systems, which results in a demand for tighter tolerances in the corresponding guide surfaces. However, these tight tolerances and rigid structural requirements in the surfaces lead to high manufacturing and assembly costs. This causes an increased manufacturing and adjustment effort, especially for long linear axes, because the assembly cost scales with the axis size. A novel approach to circumvent these tight tolerance requirements lies in compensating for the errors in the guide surface by actively positioning the guide carriage. For this purpose, a double-sided actuator consisting of an electromagnet and an air caster is used. The advantage of such a system is the increased flexibility since it is not necessary to build a mechanical wrap-around structure for the guide rail. The elimination of the wrap-around structure is advantageous because it also makes the parallel alignment obsolete. Existing bidirectional active guide systems are limited to micro-precision applications due to the air gap of aerostatic bearings in the single-digit micrometre range. An air caster decouples the air gap from the lifting height with an elastic bellows, resulting in a higher and broader operating range of the actuator. These properties enable the usage of the actuator in larger machine tools, for example, to manufacture wing frames for aircraft. Furthermore, the guiding system can be extended by adding further guide segments at the end to extend the axis. This paper presents this new guiding system by investigating the achievable forces and the stability towards disturbance. The air caster is capable of a levitation force of up to 7,100 N with a levitation range from 250 to 280  $\mu\text{m}$ , which makes ultra-precise surfaces unnecessary. The magnetic actuator provides attraction forces up to 2,300 N within this range. Induced disturbance forces of up to 250 N could be compensated by a PI controller with position errors below 1  $\mu\text{m}$ .

## Keywords

Guidance system; electromagnet; air caster; machine tools

## 1. Introduction

The machining of large and precise components such as aircraft spars demonstrates significant technical challenges in manufacturing. The needed machine tools rely on rigid structural designs and precise axes with accurate guide systems. Hydrostatic guides are widely used in ultra-precision machine tools due to their high stiffness and motion accuracy. However, hydrostatic guides require a hydraulic system and an oil return, which has a negative impact on the required installation space and potential leaks. In order to circumvent pollution from the hydraulic oil, compressed air can be used to separate the guide surfaces. An aerostatic planar guide with a straightness and planarity of 5  $\mu\text{m}/\text{m}$  and an axis stroke of 300 mm with air gaps between 5 and 7  $\mu\text{m}$  was realised [1]. With axis compensation switched on, a position accuracy of 2.1  $\mu\text{m}$  and a stiffness of 315 N/ $\mu\text{m}$  along the z-axis were achieved. The

aerostatic principle allows precise positioning and obtains smooth surfaces in natural diamond processing [1]. However, errors during the manufacturing process in aerostatic bearings have a significant influence on the static load and stiffness [2]. With an opposing air bearing arrangement, a linear motion carriage is preloaded. Nevertheless, this configuration requires high parallelism between the opposing bearing surfaces and high-precision guides due to the small operating ranges under 10  $\mu\text{m}$ . By integrating a compliant mechanism behind the air bearing pad, the parallelism and the flatness requirements can be lowered. It was shown that the displacement error could be reduced from 2.04  $\mu\text{m}$  to 0.88  $\mu\text{m}$  [3].

Magnetic bearings are another option for media-free bearings. Active magnetic guides eliminate friction and provide good damping characteristics [4]. Operating a magnetic guide system requires an active control system to position the guide carriage in a levitation state [5, 6] and a mechanical wrap-around structure. In order to circumvent the need for a precise model, a Fuzzy controller and a PID controller were combined to enhance the robustness of a magnetic suspension system in a machine tool [7]. In a high-precision dual-servo stage with magnetic bearings, a stability of 73.1 nm along the z-axis was achieved with a PID controller using capacitive distance sensors with high resolution [8]. In order to achieve the high dynamic behaviour, high magnetic forces are required. These forces cause a deformation of the magnetic guide, which has to be accounted for [9]. Since the deformation of the guide rail influences the precision of magnetic guides too, the guide rails have to be precisely manufactured. These high precision requirements lead to high manufacturing costs, especially due to the increasing costs for larger linear axes [10]. Lower-tolerance guide surfaces and low adjustment efforts reduce costs. However, this would reduce the workpiece quality.

In order to achieve a similar precise guide system at a lower cost, the development of a novel linear guide that actively compensates for occurring tolerance errors in the guide surfaces is necessary [11]. Conventional systems often exhibit a limited compensation range and require mechanical wrap-around structures [12]. A proposed preloaded air bearing eliminates the need for such structures [11]. Additionally, a single guide surface has higher mechanical stiffness, and therefore, actor-induced deformations are negligible. However, the compensation range is limited to a few micrometres due to the small air gaps of the air bearings, ranging from 5 to 7  $\mu\text{m}$  [1]. The presented guides target the optimisation in high-precision applications.

Unlike these systems, the proposed actuator uses a magnetically stabilised air caster instead. This adjustment makes the error compensation feasible for a wider range due to an elastic deformation of the bellows while maintaining a small air gap. This air gap between the bellows and the guide surface eliminates direct mechanical contact and minimises friction and wear significantly without oil pumps and expensive maintenance. In addition, the elastic bellows allows higher tolerances in the guide surfaces and are therefore suitable to reduce manufacturing and assembly costs. This characteristic enables the actuator to support large and heavy workpieces, as the air gap of the air caster consistently remains within the single-digit micrometre range, irrespective of the lifting height in the millimetre range, thereby ensuring high load capacity. This elastic bellows behaviour with the broader operating range also enables the expansion of the axis length since it is not necessary to align additional guide surfaces as precisely as in conventional aerostatic guides. The following sections describe the operating principle, structural implementation, and performance characteristics of a single hybrid actuator and its potential to drastically reduce the manufacturing costs of linear guides.

## 2. Methods and Materials

The proposed actuators' application lies in a large linear axis for the manufacturing of aircraft parts. In order to demonstrate the working principle, a small actuator with load capacities up to 7,100 N and a diameter of 200 mm is used. The proposed actuator requires a minimal preload force of 1,000 N to increase the stiffness of the actuator. Stabilising the actuator requires an active controller to respond to static and dynamic disturbance forces. Due to the non-linear behaviour of magnets, the direct use of a simple linear controller is not feasible.

The hybrid actuator consists of two main components, allowing a guide system without any wrap-around structure. Figure 1 shows the concept of the hybrid actuator. The repulsive component is an air caster B8HD from Aerofilm Systems GmbH. It can be operated with a maximum pressure of 4 bar and can carry a theoretical load of up to 10,000 N, fulfilling the required load capacity. In addition, it allows adaptation to errors in the guide surface and a frictionless movement. These error compensation capabilities of the air bellows enable the use of guide surfaces without special manufacturing precision. Here, a connected mounting plate ensures the compressed air supply. Moreover, the mounting plate is used to connect an electromagnet to the actuator. The magnetic actuator is the attractive component of the actuator with forces up to 2,500 N, and it is integrated into the centre of the air caster.

The reason for this arrangement is to achieve an actuator with forces along one axis to prevent the use of multiple magnets in a single actuator. Additionally, this enables a compact actuator. The integration of the electromagnet obstructs the airflow under the actuator, possibly resulting in a different airflow below it. The mounting height of the electromagnet is adjusted to operate the air caster within its recommended lifting range. O-ring sealings are used to prevent air leakage between the electromagnet and the mounting plate.

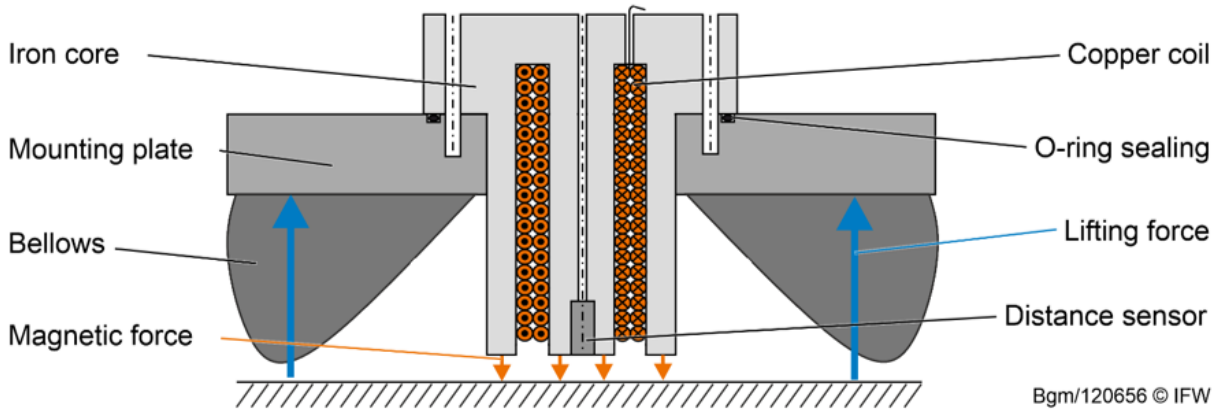


Figure 1. Combined hybrid actuator.

The magnetic force is proportional to the inverse square of the distance between the electromagnet and the iron surface. As a result, minor air-gap changes have a major impact on the magnetic force, so an accurate air-gap measurement method is essential. In order to achieve an accurate air gap measurement, the distance sensor is integrated into the actuator. This sensor placement eliminates the usual signal transformation shown by Choi [8], since the centre of gravity and the resulting forces from the air caster and the electromagnet are on the same axis. In order to avoid electromagnetic interference, a capacitive sensor CSE05/M8 from Micro Epsilon GmbH & Co. KG with a resolution of 0.01  $\mu\text{m}$  and a measuring range of 500  $\mu\text{m}$  is used. The measuring principle of this sensor is nearly independent of magnetic fields and therefore suitable to measure the height of the air gap inside a strong magnetic field. The direct measurement approach and its underlying principle help minimise measurement errors. Lastly, the sensor has a high bandwidth to precisely detect dynamic changes in the lifting height.

## 2.1 Air Caster

Air casters are generally used for the transportation of heavy machines and workpieces. They operate by generating a thin air film between the surface of the air caster and a stationary guide surface [13]. This air film is produced by supplying an elastic bellows with compressed air. Openings in the bellows allow the air to flow to the sides of the air caster and ultimately into the surrounding air.

The geometry of the used air caster is round with a diameter  $D_{AC} = 200$  mm. The air caster is operated with a pressure  $p_{AC} = 3.2$  bar and an airflow rate  $\dot{V} = 430$  l/min. The air pressure is required to achieve a load capacity of 7,100 N, and the airflow rate is required to maintain that pressure. The lifting force of an air caster can be calculated with the air pressure  $p$  and the area  $A$  (1). Since only the area with pressure is generating a lifting force, the effective pressure area  $A_p$  is 15 % lower. In addition, (1) does not include occurring air and pressure losses. In (2), the factor  $\eta = 0.9$  accounts for these losses.

$$F_{lift} = p * A \tag{1}$$

$$F_{lift,real} = p_{Sensor} * A_p * \eta \tag{2}$$

Equation 2 accounts for the 15% reduction in effective pressure area due to design constraints and pressure losses, resulting in a lifting force of 7,691 N. Since the lifting force is dependent on the pressure and a constant area, the force changes with different pressures, and parameters like airflow, leakage, and load on the actuator remain constant. The pressure is determined only by the air gap between the bellows and the guide surface. Due to the elastic bellows of the air caster, this air gap is nearly independent of the lifting height and therefore almost constant for small height ranges up to 50  $\mu\text{m}$ . This assumption could be verified in a preliminary test. The measured force  $F_{Sensor}$  during the experiment was between 6,900 and 7,100 N and thus lower than the calculated force. This force difference

can be explained by the magnetic force  $F_{mag}$  of the magnet. Since this force minimises the lifting force of the air caster according to the following formula:

$$F_{Sensor} = F_{lift,real} - F_{mag} \quad (3)$$

## 2.2 Magnetic Actuator

The second component of the hybrid actuator is a magnetic actuator. As the electromagnet is positioned within the air caster, the installation space is restricted to the bellows' inner diameter  $d_{AC} = 80$  mm. As a result, the outer diameter of the electromagnet cannot exceed 79 mm. In an electrostatic simulation, the geometric parameters of the electromagnet were optimised. The simulation aimed at achieving a high electromagnetic force. In order to increase this force, the inner and outer diameters of a copper coil were varied. This led to an optimisation problem, whereby the largest possible magnetic core could only be magnetised with a sufficiently large copper coil. Lastly, the influence on the possible force gain with increased height was investigated. Finally, a coil with a 46 mm inner diameter, a 66 mm outer diameter, and a 50 mm height was selected. In order to manufacture the magnet, an insulated (PEI) copper coil with 290 (N) turns and the specified dimensions was inserted into a pure iron core with high magnetic permeability. The connection between the coil and the magnetic core is ensured by encapsulating the coil with Elantron W5710. The diameter of the wire used for the coil was set to 1.12 mm to allow coil currents up to 7 A. This coil current ( $I$ ) induces a magnetic flux in an iron core with magnetic permeability  $\mu$ . The pole surfaces of the electromagnet lie above a metal plate that closes the magnetic loop.

The Maxwell force, also known as the reluctance force, acts at the boundary between regions of different magnetic permeability. It arises from the system's tendency to minimise its magnetic energy by shortening the magnetic field lines. This leads to an attractive force between the iron core and the metal plate.

$$F \approx \frac{N^2 I^2 A * \mu}{2h^2} \quad (4)$$

$$A = A_{outer} + A_{inner} = 16.3 \text{ cm}^2 + 14.8 \text{ cm}^2 = 31.1 \text{ cm}^2 \quad (5)$$

To characterise the magnet, it should be placed in a holding device as shown in Figure 2 so that the reluctance force can be measured. This holding device is connected to the traverse of a Zwick Roell Kappa 100 DS. Moving the traverse allows changing the air gap between the electromagnet and the backplate, while the distance sensor inside the electromagnet measures the current air gap. The diameter of the upper part of the electromagnet is enlarged to 100 mm so that it can be mounted more easily and finally connected to the air caster.

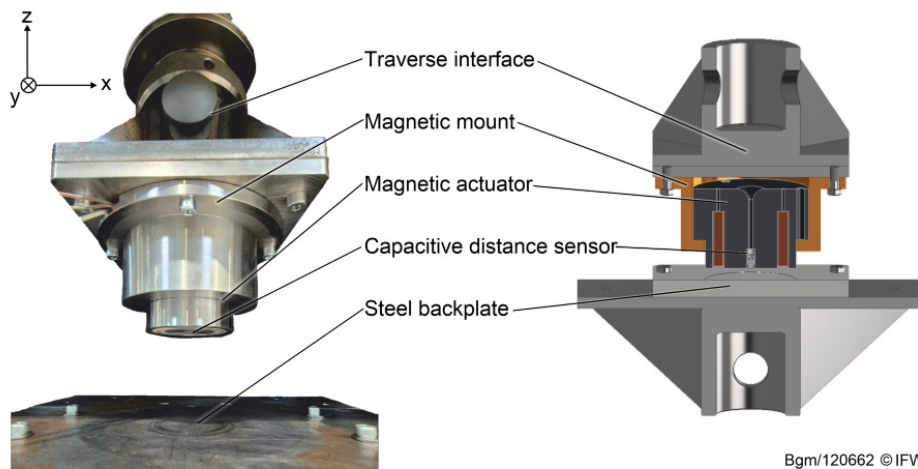


Figure 2. Testing setup for the characterisation of the magnetic actuator.

At the same time, this arrangement reduces magnetic saturation in the magnetic core and thus increases the force, as shown in Figure 3b. The characteristic field in Figure 3a illustrates the magnetic force  $F_{mag}$  of the electromagnet in dependence on the electric current  $I$  and the air gap  $h$ .

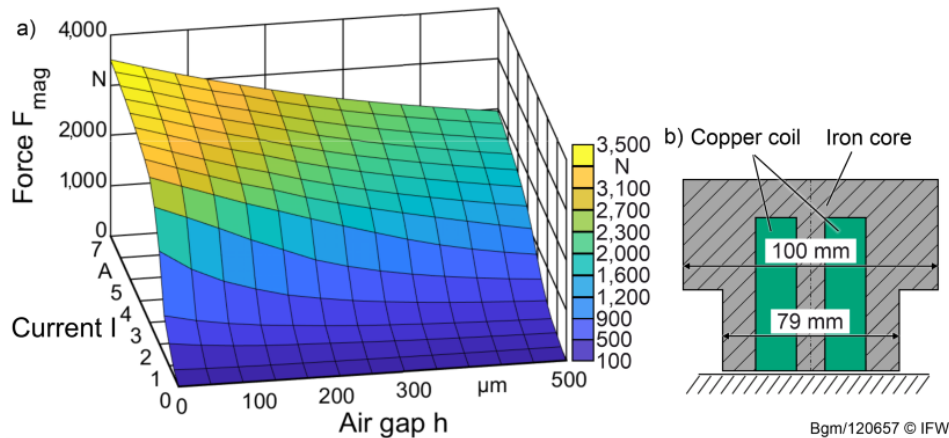


Figure 3. Characteristic field of the magnetic actuator.

The maximum reluctance force for each air gap was achieved by inducing a current  $I$  of 7 A. A further increase in the current does not result in a higher attracting force due to the magnetic saturation effects of the iron core. It can be observed that the maximum magnetic force is 3,500 N with a minimal air gap. A wider air gap and a lower current lead to a non-linear force decrease. This behaviour can be explained by the inverse quadratic dependence of the force on the air gap  $h$ , as shown in (4). The non-linear behaviour of an electromagnet can be verified by that. In the operating range from 250 to 280  $\mu\text{m}$ , the maximum magnetic force is 2,500 N, ensuring a consistent minimal preload and higher stiffness. A linear PI controller without adjustments to this non-linear behaviour is not precise. By using the characteristic field to linearise the system, a standard linear controller can be used to solve this context.

### 3. Control Design and Experimental Testing

Magnetic levitation is unstable and requires an active control system to reach a stable operating point [5]. The innovative approach of a magnetically preloaded air caster must be controlled in only one axis. Therefore, a simple control approach is preferred here. For that purpose, a PI controller with feedforward control is used to adjust and stabilise the air gap corresponding to the lifting height of the actuator. This control strategy is advantageous since it does not require a system model, unlike a state-space controller.

#### 3.1 Control System for Hybrid Actuator

Due to the control task of positioning the actuator in a single axis, a simple controller is suitable for that task. The proportional part of the controller enables a quick response to a deviation in the lifting height. The integrator is needed to eliminate the steady-state error. However, a proportional controller is not capable of controlling non-linear forces. In order to utilize a linear PI controller, a characteristic field of the magnetic actuator is used to linearize the system with respect to the non-linear magnetic force caused by changes in the air gap. This allows the controller to compensate for these forces with higher precision. To implement the feedforward control, the characteristic field of the electromagnet is used to determine the acting magnetic forces as precisely as possible and thus simplify the control task. The lifting force of the air caster is almost constant within the planned operating range of 250 to 280  $\mu\text{m}$ . The resulting control loop structure is illustrated in the block diagram in Figure 4.

The setpoint variable  $w$  is the air gap (position of actuator), and is supposed to be achieved through the control. The control objective is to precisely regulate the position  $z$  of the actuator despite the presence of external disturbance forces  $d$ . The error between the measured air gap and the setpoint variable represents the input value  $e$  for the controller. The output control variable  $u$  is a force that guides the actuator to the setpoint. To determine the required magnetic force  $F_{mag}$ , a summation of the acting forces is computed. These forces are the lifting force of the air caster, the load on the actuator, and an output force from the controller to guide the actuator in the desired direction. Based on an inverse magnetic characteristic field, the required coil current  $I_{mag}$  for the magnetic actuator is determined. The magnetic actuator influences the lifting height of the actuator by changing the attractive force. The output variable  $z$  is then measured with the distance sensor and is fed back to close the control loop.

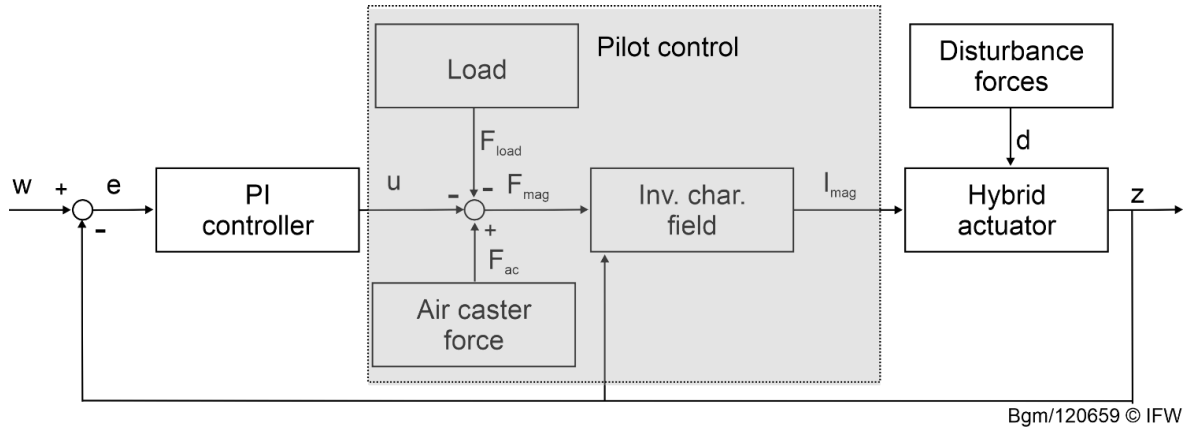


Figure 4. Block diagram of the closed control loop.

### 3.2 Experimental Investigation

A test setup was constructed to demonstrate the actuators’ operating range. Besides, the testing setup was used to investigate the influence of disturbance forces on the stability of the system by applying an additional force on the actuator. Figure 5 shows the testing setup for the combined hybrid actuator.

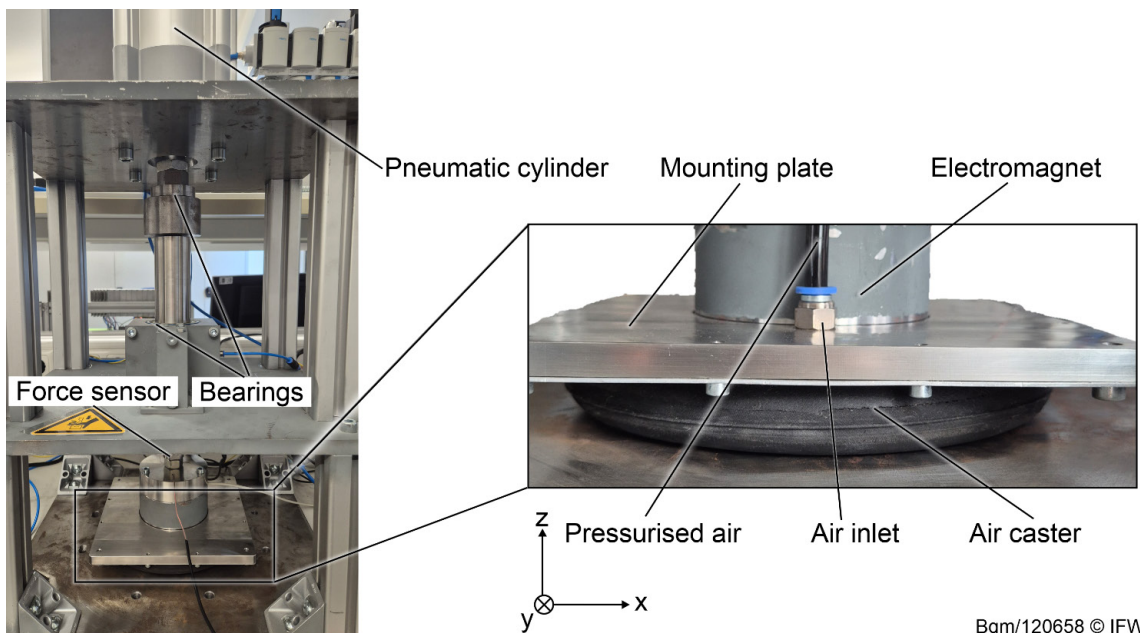


Figure 5. Testing setup to investigate the hybrid actuator.

The test setup consists of a surface plate on which the actuator is placed. A force sensor is mounted to measure acting forces on the actuator. An aerostatic bearing along the shaft prevents movement in the x- and y-axes to first examine the functionality of the actuator in the z-axis. In addition, an axial ball bearing allows rotation around the z-axis to verify the absence of friction. A pneumatic cylinder applies an almost constant force of 7,000 N on the actuator. This force is used as a substitute force for the weight force of a guide carriage to circumvent the need for a heavy and large constant weight.

An IPC from Beckhoff Automation is used to integrate the control system. A PI controller was implemented in TwinCAT to control the attractive force of the magnetic actuator. For the investigation of the actuators’ operating range, a pneumatic cylinder was used to apply an axial force  $F$  on the actuator. This load is necessary to simulate the weight of a guide carriage with a workpiece. The experiment was conducted to determine the maximal lifting height of the actuator. For that purpose, the actuator is set to operating point  $w = 250 \mu\text{m}$ . In order to test the feasible

operating range, the setpoint is increased by increments of 10  $\mu\text{m}$  using TwinCAT. In addition, the dynamics of the controller response were investigated by setting a new setpoint. Figure 6a displays the measured resulting lifting height. It can be shown that the actuator can be lifted to a maximum of 280  $\mu\text{m}$ . A further increase would result in an insufficient magnetic preload and was therefore not carried out. Furthermore, Figure 6a presents that during the experiment the controller always reaches the new setpoint within  $t_{set} = 1.5$  s and the positioning accuracy  $z_{acc}$  is below 1  $\mu\text{m}$  in a steady levitation state. The applied force on the actuator ranges from 6,900 N to 7,100 N, as shown in Figure 6b. It can be assumed that this inconsistent force can be explained by stick-slip effects occurring on the cylinder walls of the pneumatic cylinder. A slight inclination of the actuator, which generates a radial force on the pneumatic cylinder, could amplify this effect further. The resulting force changes (Figure 6b) can be explained by a change in the air pressure of the cylinder due to the movement of the cylinder. The coil current to control the electromagnet and to stabilise the lifting height lies between 2 and 5 A (Figure 6c) and compensates for the changing forces on the actuator (Figure 6b). Figure 6d displays the air consumption and the pressure in the air caster and shows their constant behaviour independent of the operating point.

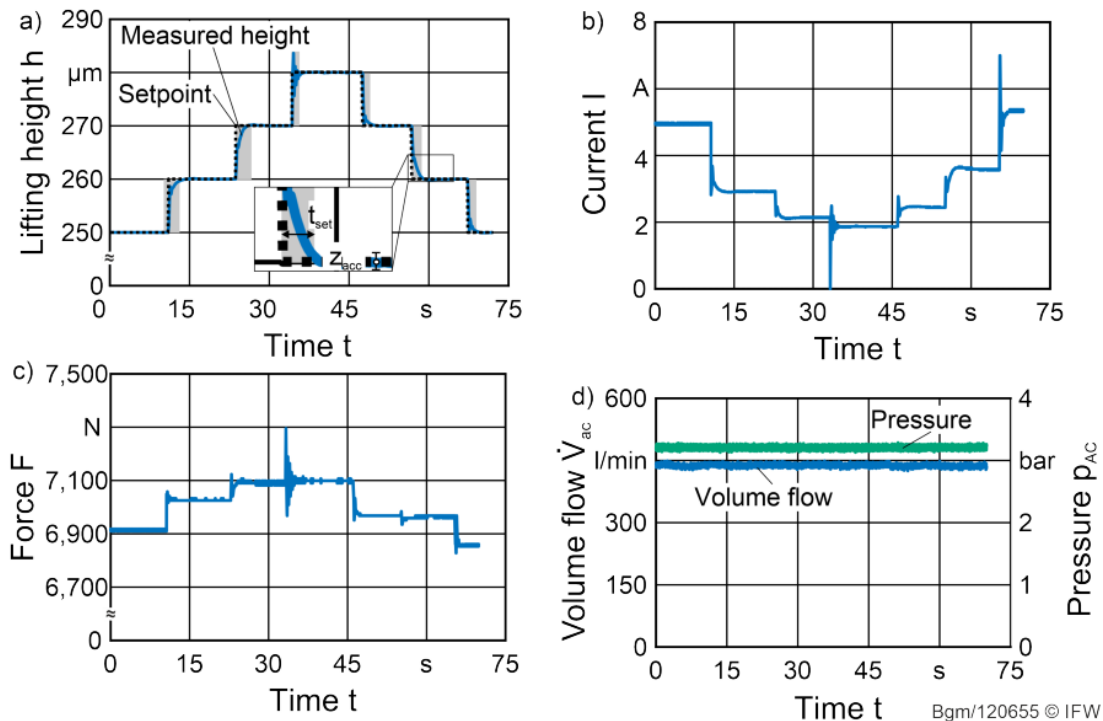


Figure 6. Results of the levitation test.

The results of the shown investigations demonstrate the fundamental feasibility of a magnetically preloaded air caster, as the lifting height can be precisely controlled. The usage of the hybrid actuator in machine tools shows a new application possibility for air casters. Additionally, the actuator can be operated at an operating point with a larger air gap compared to the air gaps in the  $\mu\text{m}$  range for aerostatic guides [1]. This is made possible by decoupling the air gap from the levitation height using the elastic bellows of the air caster. A larger air gap is now advantageous, as unevenness in the guide surfaces is potentially less significant. In addition, it was shown that a change in the load on the actuator can be accounted for. This property also occurs during a machining process when the mass of a workpiece decreases. These characteristics enable the construction of a wrap-free guide system using multiple actuators. However, further research is necessary to improve the dynamic behaviour during settling and to improve the high air consumption of the air caster.

Further experimental testing investigated the influence of disturbance forces on the system. In order to examine the disturbance behaviour of the control loop, an external disturbance force along the z-axis was applied by manually operating the test setup. To validate the concept of the hybrid actuator, pulling forces up to 600 N and pushing-down forces up to 250 N were used. Figure 7 shows the influence on the lifting height and the corresponding magnetic force to stabilise the actuator.

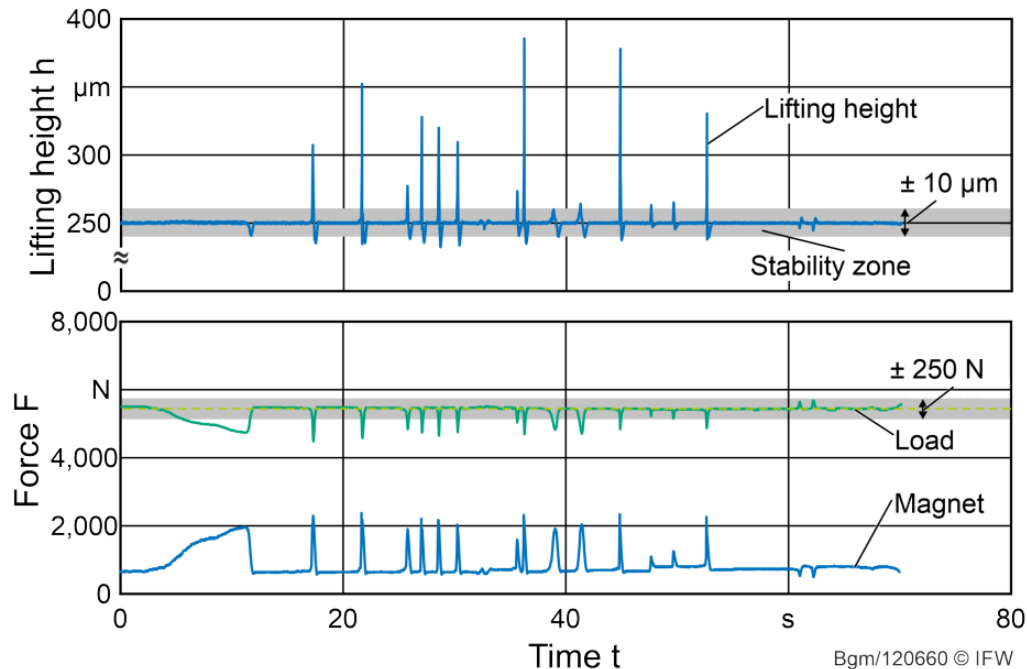


Figure 7. Disturbance forces and actuator response.

It can be shown that the controller is able to compensate for disturbance forces by stabilising the actuator at the lifting height of 250  $\mu\text{m}$ . To limit the maximal offset of the setpoint to 10  $\mu\text{m}$ , the disturbance forces must not exceed 250 N. This boundary of 10  $\mu\text{m}$  was selected to guarantee high precision despite external disturbance forces. Higher disturbance forces can be compensated for, but the control difference exceeds the limit of 10  $\mu\text{m}$  and results in an unstable actuator. Therefore, the maximal load for a single actuator is limited to 250 N. Pushing and pulling disturbance forces up to 250 N can be controlled within 500 ms. The occurring overshoot is below 5  $\mu\text{m}$ . Higher disturbance forces result in an unstable lifting state.

#### 4. Conclusion and Outlook

A hybrid actuator for use in linear guidance systems was introduced. The application of air casters in machine tools presents a new approach to circumvent tight tolerances in guides while achieving high load capacities in a broader operating range compared to aerostatic guides. In addition, the usage of air as a separating medium eliminates the pollution from hydraulic oil and intensive maintenance. The air caster was able to generate a maximum lifting force of 7,100 N at the operating point, reaching higher lifting forces than state-of-the-art aerostatic guides. The proposed electromagnet was able to generate an attracting force of 2,000 N at an air gap of 400  $\mu\text{m}$  with an electric current of 7 A. The two actuators were combined in a hybrid actuator, which can account for levitation and attraction forces, making a mechanical wrap-around structure obsolete for large-scale axis. This increases the construction possibilities of large machine tools. The characteristic field for the magnetic actuator was measured and used to implement a real-time PI control system. This approach was used to levitate the hybrid actuator at a height of 250  $\mu\text{m}$  while a load of 6,900 N was applied. Ultimately, a lifting height from 250 to 280  $\mu\text{m}$  was achieved. In a steady levitation state, the absolute control error in the lifting height was below 1  $\mu\text{m}$ , and the settling times were below 1.5 s. Induced bidirectional disturbance forces up to 250 N could be compensated by the PI controller while maintaining the current lifting height.

To reduce the inconsistent load on the actuator, the test bench height is lowered to reduce the influence of the actuator's tilting. In the next step, the actuator tilt is measured, and the alignment of the pneumatic cylinder is finely positioned so that only axial forces are transmitted to the actuator. As a result, it is assumed that the load force on the actuator remains constant regardless of the suspension height by reducing the stick-slip effects. This would increase the lifting range of the actuator further. Subsequently, various ground conditions and the stability of the actuator on these conditions are investigated. Various roughnesses and steps in the surface plate are examined to show the stability on a segment transition.

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## Author contributions

A.B. wrote the manuscript. H.B. contributed to the concept and design of the article and revised the article. B.D. revised the article and authorised its publication. A.B. carried out the experiments, processed the resulting data, and created all figures.

## Data availability

The data is also available on demand from the corresponding author.

## Conflict of interest

The authors declare that they have no conflict of interest.

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