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Fluiddynamic planar drive with unrestrained rotational degree of freedom

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Abstract

In this paper, a new planar drive system for the use in small machine tools is introduced. It is based on an innovative fluid dynamic drive principle, which generates thrust forces by the deflection of fluid jets on flow grids integrated into the slide. In addition to the translational movements in x- and y-direction, this drive allows unlimited rotation around the z-axis in any position. Advantages are the reduced number of necessary machine components and a frictionless movement by magnetically pre-stressed, aerostatic bearing. The working principle of the drive is explained and its geometrical constraints are investigated. The arrangement of the nozzles and the design of the grid profiles are optimized. Finally, the technical implementation of the drive is presented.

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Keywords: Direct drive; Desktop machine; Precision engineering

1. Introduction

The trend of miniaturization can be observed in many industrial sectors. Smaller parts with increasing complexity pose high demands on the future production technology which cannot be met by today's machine tools. Most machine tools that are used for micro machining processes reveal a disproportion in the size ratio between machine and work piece. This disproportion is directly related to economical, ecological and technical disadvantages. While big machines obviously need more resources in production and have a larger footprint, further drawbacks occur in the context of operation. Despite the small size and mass of the work pieces, actual machines have to carry out long movements due to great pivot lengths. In combination with the relatively great masses of the moving machine parts this leads to high energy consumption and limits the dynamic performance. The effort for controlling the temperature of the workspace increases with its volume while the effect of thermal errors increases with the length of the machine components [1], [2]. Further influences on the machine accuracy like Abbe or pivot errors are also increased by the size of machine structures and the resulting cantilever lengths [3].

The priority program SPP1476 "Small machine tools for small work pieces" (www.spp1476.de) has the objective to develop and research innovative modular machine tools for micro parts that overcome the mentioned problems. To meet this objective, size reduction by further down scaling of known machine designs and components is not sufficient. Rather, an attempt is made to integrate multiple functions into single components or structures and to employ completely new kinematic chains [1]. In [4], [5] and [6] innovative drive and guiding principles are investigated and used to design highly integrated machine axes for the small machine tools.

Following the same approach, a fluiddynamic planar positioning stage (Fig. 1) has been developed and tested [7], [8]. This stage integrates the drive and guiding functionality of two conventional machine axes in a very compact design. It consists of only two main components, namely the moving slide and the stationary frame. Slide and frame are separated by four magnetically pre-stressed aerostatic bearings that can be actively controlled by means of air-gap sensors and proportional valves. Thrust forces are generated by four

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actuator units that utilize the dynamic forces of free air jets. Each unit consists of a set of periodically arranged, triangular drive profiles incorporated in the slide and an opposing set of three nozzles in the frame. The air flow through each nozzle is set continuously by an individual proportional valve. In Fig. 1 an air jet from nozzle w is deflected on the profile flank above the nozzle. The change of momentum of the jet equals the size of the perpendicular reaction force on the flank. The horizontal component of this reaction force acts as thrust force. Depending on the direction of inclination of the impinged flank, two directions of force can be generated with each actuator. By appropriate commutation of the nozzles u, v, w, depending on the positon of the slide, continuous motions and long strokes are possible.

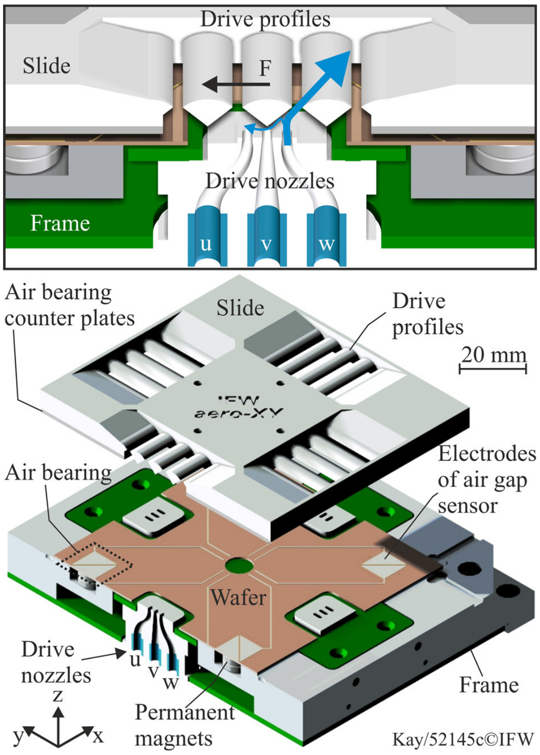

Fig. 1. Fluiddynamic drive principle and design of the XY-stage

With the four actuator units, forces in x- and y-direction and torque about the z-axis can be generated. To provide position and orientation information, three laser triangulation sensors are used, measuring the displacements of two orthogonal side surfaces of the slide. Given the position and rotation angle of the slide, a set of values for the twelve proportional valves can be calculated that affects the slide as intended. Therefore, position controlled movements in x and y become possible and the rotational DOF about the z-axis can be blocked by the controller.

The stage can generate a maximum of 1 N thrust force in both directions at an air intake of 170 l min^{-1} and 6 bar of supply pressure. The positioning accuracy strongly depends on the measurement accuracy and the mass of the slide. At a slide mass of 70 g and a standard deviation of the position sensor noise of 1 µm, a circular reference path could be followed with a maximum deviation of 20 µm [8]. The suitability of the drive principle for higher accuracy could be shown on a one-axis prototype with a slide mass of 231 g and a linear encoder with 10 nm resolution. Here a stationary deviation of 72 nm was measured [9]. First milling tests have been carried out in a micro milling setup with the stage used as work piece table. The results were promising but also showed a lack of dynamic stiffness due to the little mass of the slide and the little power reserve of the drive [2].

In this work, a new version of the positioning stage is proposed, that integrates even more functionality by adding an unconstraint rotational degree of freedom. It therefore allows more complex feed motions and can replace additional components like rotational machine tables. The simple and compact design is maintained.

Starting from the existing XY-stage, in a first paragraph different arrangements of the triangular drive profiles are investigated. This leads to the necessity of modifying the drive principle and using flow grids instead of the triangular profiles. In the following paragraphs these grids are optimized by means of CFD simulations and the resulting design of the stage is presented.

Nomenclature

d_D	nozzle diameter
s	gap width
τ_P	angular pitch of the drive profiles
τ_D	angular pitch of the nozzles
r_D	nozzle pitch radius
δ	angle corresponding with the flank width
δ_D	angle corresponding with the nozzle width
δ_s	angle corresponding with the gap width
n	number of profiles
t_G	spacing of flow grid
h_P	height of drive profiles

2. Triangle profile arrangement for an XYC-drive

The main objective in the design of the profile and nozzle arrangement is to enable the full motion in three degrees of freedom. Further goals are the maximization of the thrust forces and the minimization of the installation space. Based on the basic design and the drive principle of the XY-stage the first step is to assign areas on the slide to its functions.

2.1. Functional areas on the slide, workspace and external dimensions

There are three partial functions that have to be integrated and therefore need a dedicated area on the slide:

- Generation of thrust forces (drive profiles)
- Guiding (counter faces for aerostatic bearings)
- Clamping of work pieces

Profile and guide areas have to overlap the respective nozzles and air bearings in the frame to enable their interaction. This has to be guaranteed regardless of the position and orientation of the slide. Because of the endless rotation capability, an arrangement in concentric, ring shaped areas is mandatory (Fig. 2). The function areas of the XY-slide could be arranged alternating with identical distance to the midpoint of the slide. In the new design the drive profiles have to be placed on the outer diameter and therefore with greater leverage in respect to the midpoint than the aerostatic bearings on the inner diameter. The actuator units generate less force than the bearings and therefore greater leverage is needed to generate high torque. External drive profiles are also favorable in regard to the compactness of the stage. The guiding area can overlap the clamping area on the reverse side of the slide because no fluid jets have to pass through. Thus, the outer diameter of the slide can be kept small.

The annular function areas and the overlap condition result in a circular-shaped workspace. To cover the full 15 mm x 15 mm square-shaped workspace of the XY-stage, a workspace diameter of 22 mm is defined. To maintain comparable outer dimensions, the outer diameter was limited to 120 mm. With an ideal nozzle diameter of $d_D = 2$ mm, the profiles can be arranged in an annular area with an outer diameter of 120 mm and an inner diameter of 72 mm. The ideal nozzle diameter in terms of high thrust forces was determined based on experimental data.

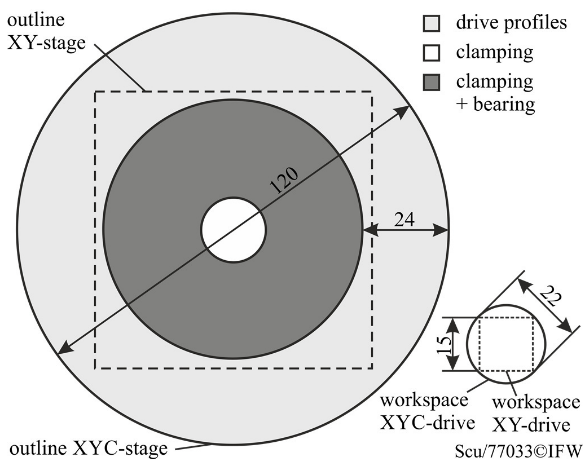

Fig. 2. Areas on the slide and workspace of the XYC-drive

2.2. Arrangement of profiles and nozzles:

To allow for continuous rotation of the slide, a radial arrangement of the triangle profiles is the most promising approach. An example is shown in Fig. 3 (a). The two opposite flanks of each triangular profile are marked either as positive (green) or negative (red) flank. The gap width between two triangles has great effect on the flow-off behavior and force generation. It is therefore chosen to be constant. The optimal gap width of s = 1 mm was determined experimentally by thrust force measurements at variable gap widths. For maximum force generation the inclination of the flanks has to be 45° [9]. With these parameters given, a profile arrangement is defined only by the angular pitch τ_P of the profiles.

The circular nozzles are arranged circularly in four groups (actuator units), consisting of three nozzles each (Fig. 3 (a)). The diameter r_D of the pitch circle equals the mean diameter of the profile area. Therefore, the nozzle positions are defined by the number of nozzles per group and the angle τ_D between the nozzles within a group.

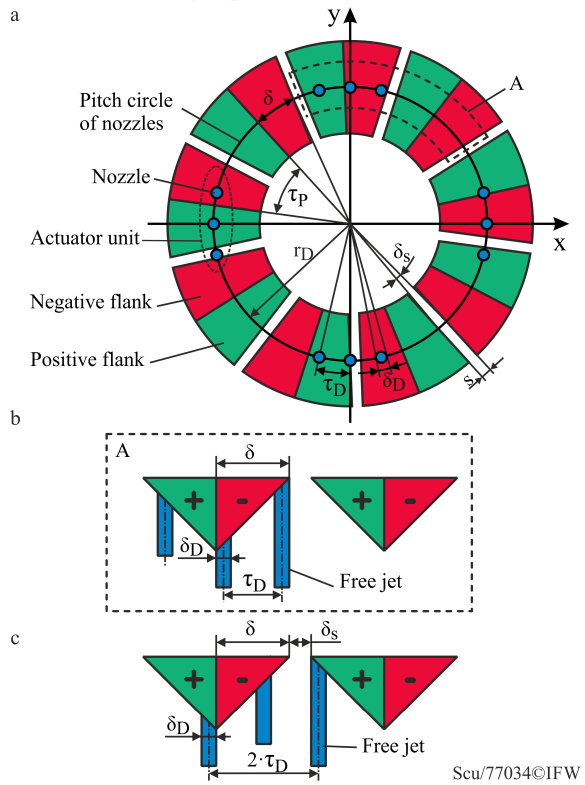

Fig. 3. (a) Arrangement of triangular profiles and nozzles in plan view; (b) first limiting case in side view; (c) second limiting case in side view

2.3. Geometrical constraints

For the functionality of the drive, every actuator unit has to provide drive forces in two directions, regardless of the position and orientation of the slide. In other words: for each actuator one positive and one negative flank need to be covered by at least one nozzle. For a given profile arrangement, this condition can be formulated mathematically in two inequalities for the angular pitch of the nozzles. This becomes obvious in the two limiting cases depicted in Fig. 3. The first (Fig. 3 (b)) defines the upper boundary for the angular pitch of the nozzles. The second (Fig. 3 (c)) represents the lower boundary. For a pure rotation of the slide in the center position, the inequalities can easily be stated. Assuming three nozzles per actuator unit, the angle τ_D has to comply with condition (1).

$$\frac{\delta+\delta_s+\delta_D}{2} < \tau_D < \delta - \delta_D \qquad (1)$$

A nozzle pitch meeting this condition for every arbitrary positon and orientation of the slide can be calculated based on a geometrical model and a brute force algorithm. This calculation was carried out automatically for different numbers of profiles.

It turned out, that for the given parameters a configuration with 3 nozzles per actuator can only be realized for a maximum number of 7 profiles as seen in Fig. 4. Because of the 45° flank inclination, the height of the profiles depends directly on the angular pitch τ_P and therefore on the number of profiles. In the depicted example the height measures 29.5 mm. Great heights of the slide result in increasing design space and mass. Furthermore, the maximum flow lengths of the free jets increase, which leads to minor force generation in the edge zones of the flanks, due to the expansion of the jet.

On the other hand, a design with more profiles has disadvantages as well. For arrangements with eight or more profiles, a total number of 16 nozzles are necessary. This in turn would lead to higher costs, a higher need for design space for the valves and a more complex control system.

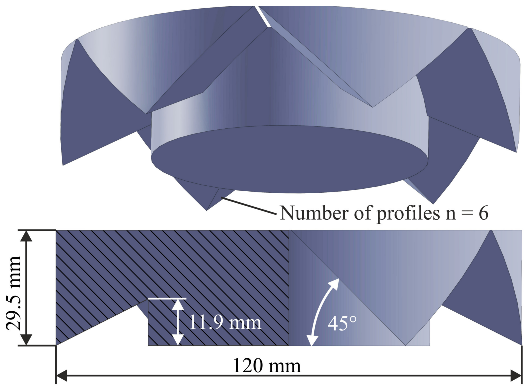

Fig. 4. Configuration with 6 triangular profiles for 12 nozzles

3. Modified drive principle

To overcome the mentioned problems and to solve the conflict of goals between the height of the slide and the number of nozzles, a modification of the drive principle is proposed. The basic idea is to replace the positive and negative flanks of the triangles by flow grids with opposite directions of deflection. As shown in Fig. 5, the modified concept can be derived from the previous in three steps:

- Segmenting the flanks of a triangular profile
- Optimizing the resulting grid of blades
- Transferring the blade grid to the XYC-slide

Since the angular pitch τ_P and the height of the slide are decoupled by means of the flow grid, τ_P can be increased further without affecting the height. The shown configuration of blade grids in Fig. 5 corresponds to an arrangement of only four triangular profiles. Given an angular pitch of $\tau_P = 90°$, the actor units are decomposed and, instead of being arranged in groups, the nozzles can be evenly distributed on the pitch circle (Fig. 5).

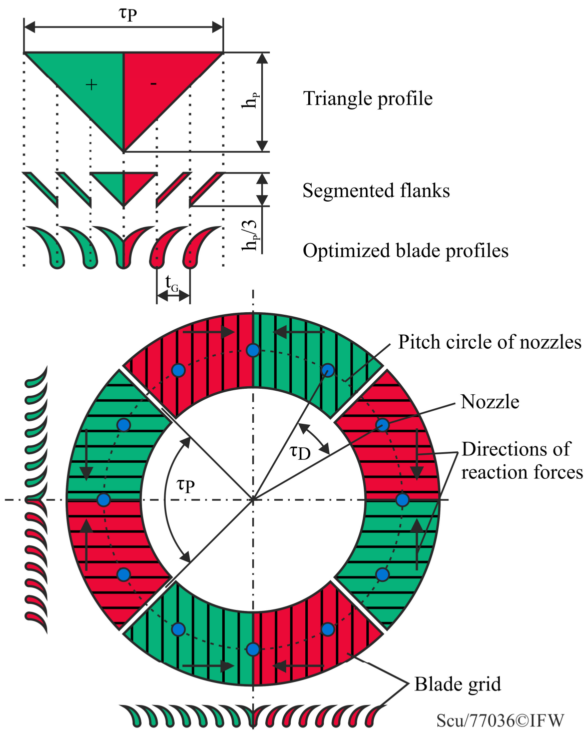

Fig. 5. Derivation of the flow grids from triangular profiles

The ability to generate thrust forces and torque in every required direction can be ensured by the condition that every "flank" has to cover at least one nozzle in every position of the slide. This results in a configuration with 12 nozzles and τ_D=30°. To control the drive, thrust forces and torques of the single nozzles are linearly combined, forming the total force and torque. A set of input signals for the 12 proportional valves can be derived. Since the directions of thrust forces generated by the nozzles vary with the position of the slide, they have to be recalculated within every control cycle.

4. Optimization of the flow grid

The flow grids on the slide have to meet two key criteria. First, they have to deflect the vertical jet from the nozzle in such a way that the greatest possible thrust force is generated. Secondly, the generated thrust force has to show little dependence on the relative position between nozzle and grid. Otherwise, force ripple effects can compromise the controllability of the drive.

The flow grid and the geometry of the single grid profiles or blades have been optimized in regard to these criteria. Different geometries have been investigated in numerical flow simulations, using the software ANSYS CFX. Air has been taken as an ideal gas and the thrust forces were calculated from the pressure force and viscous force components acting on the blades in the horizontal direction. Position dependence has been taken into account by simulating the flow in six different nozzle positions for every flow grid. This way the computing effort was limited. Fig. 6 shows cut-outs of velocity fields, originating from these simulations. The normalized nozzle position x* is given as multiple of the grid spacing. The mass flow is let in through the tube from below and exits the fluid domain through distant openings.

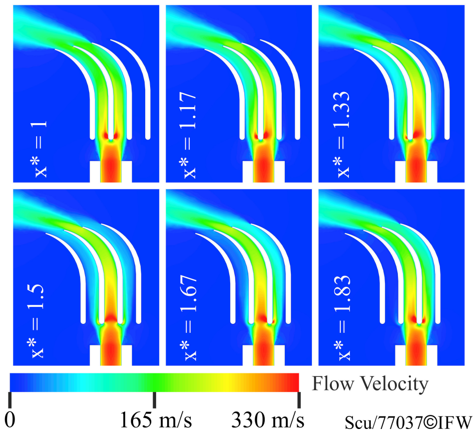

Fig. 6. Velocity fields for different nozzle positions

The results show, that force ripple is primarily influenced by the grid spacing. The maximum magnitude of thrust force depends mainly on the deflection angle of the jet and the flow cross-section between two blades. The optimal configuration would be a great flow cross-section combined with little grid pitch. However, a minimum thickness of the blades is necessary for reasons of feasible production and mechanical durability. By arranging the blades staggered with slightly increasing height, the angle of deflection can be increased further without minimizing the flow cross-section between two adjacent blades. The final grid design can be seen in Fig. 7.

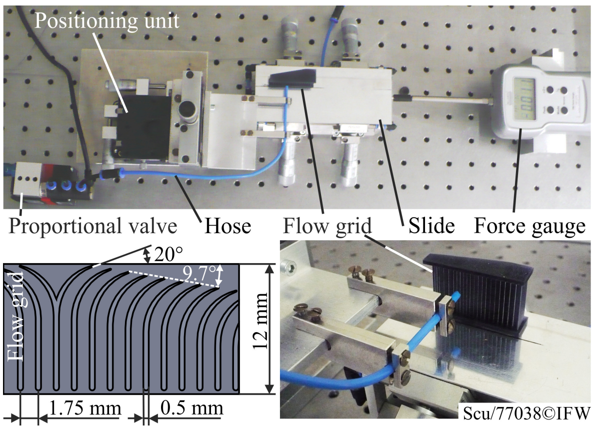

Fig. 7. Experimental setup and final flow grid design

The results of the flow simulations for the final grid design have been evaluated experimentally using a simple setup (Fig. 7). The flow grid was 3D-printed and mounted on a single-axis slide, running nearly frictionless on aerostatic bearings. A high resolution force gauge coupled to the slide locked its motion and measured the thrust force. The end of a hose with an inner diameter of 2 mm was used as a nozzle. It was positioned relative to the blades by means of a three axis positioning unit. The supply pressure was controlled by a proportional valve.

Force-path curves were recorded for different supply pressures. As Fig. 8 shows, the simulation results at 1.91 bar that correspond to the velocity fields in Fig. 6, match the experimental results. The highest change in force, with respect to the maximum value of the force curve, occurs at a pressure of 3 bar and is 8.4 %. The highest absolute difference between maximum and minimum force was 0.039 N. It was measured at a pressure of 4 bar. For reference, experiments with a single triangular profile and 45° flank inclination were carried out on the same setup. It turned out that the thrust forces of the flow grid exceed the forces of the triangle profile by up to 75 %.

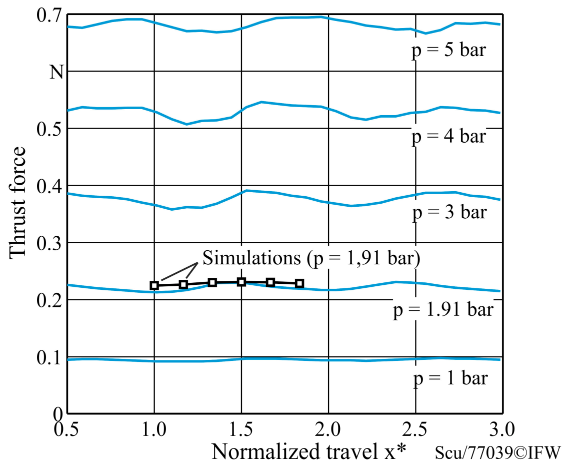

Fig. 8. Experimental validation

5. Design of the XYC-stage

The assembly of the new XYC-stage is shown in Fig. 9. As in the XY-drive, the two main components are the slide and the stationary frame. A micro-nozzle air bearing pad is used to guide the slide. To increase the stiffness, it is pre-stressed by means of a permanent magnet that is embedded in the center of the pad. The nozzle bores are directly integrated into the frame. To reduce the signal propagation time, the proportional valves are attached directly to the frame with minimal distance to the nozzles. All valves are supplied with pressurized air via an annular groove in the bottom of the frame. The inner part ("core") of the slide is made of steel, to allow for magnetic attraction forces. Its bottom side is ground to supply a planar counter surface with high quality for the air bearing. The flow grids are integrated in one monolithic part that is produced by Multi-Jet-Printing. This 3D printing process deposits photo-curable plastic resin layer by layer. Support structures are printed from a different wax material that can be removed from the work piece by melting. This way the delicate features of the flow grid are not damaged by a mechanical cleaning process.

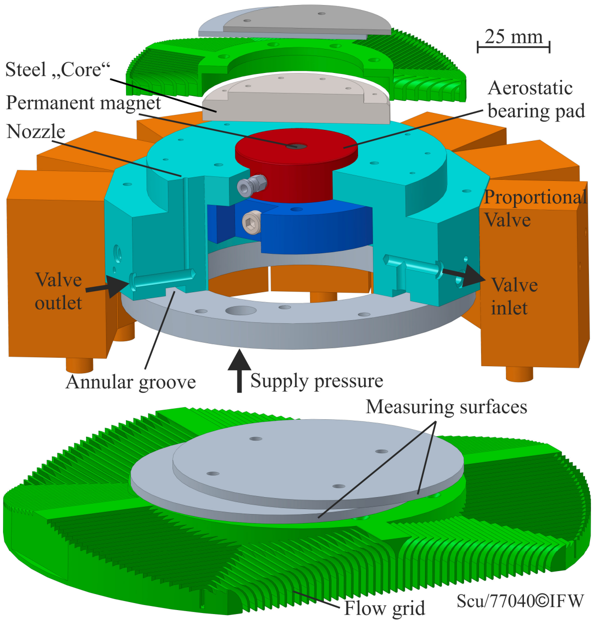

Fig. 9. Design of the XYC-stage

To allow for a full rotation of the slide, a new measurement system is required. A simple approach that has been implemented for first function tests of the XYC-stage is shown in Fig. 10. Two circular disks of defined diameter are attached eccentrically to the slide. The lateral surface of each disk is scanned by two sensors of perpendicular orientation which are fixed to the frame. The centre location of each disk can be calculated from the data of the two corresponding sensors. With the centre location of both discs and the distance in between, centre and orientation of the slide can be calculated. In contrast to polygonal measurement geometries the circular disks can be scanned uninterruptedly and regardless of the orientation of the slide. On the downside, the accuracy is limited by the resolution of the used triangulation sensors (60 µm) and the varying incidence angles of the laser-beams on the convex surfaces. Angular resolution is further limited by the small eccentricity of the disks.

Fig. 11 shows the first real-world prototype of the XYC-stage. It will be used for further investigation of the proposed drive and measurement system.

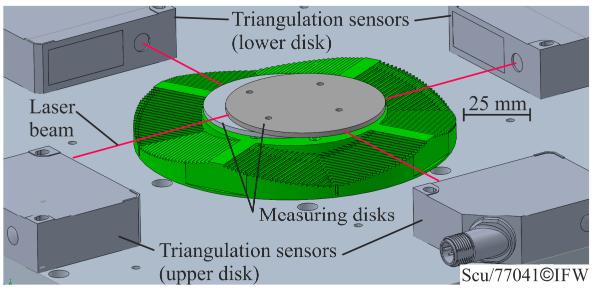

Fig. 10. Measuring system

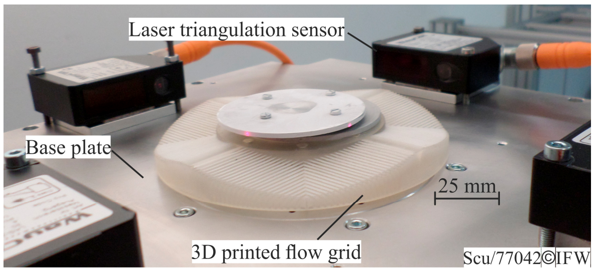

Fig. 11. XYC-stage prototype

6. Conclusion and outlook

Originating from an existing fluiddynamic XY-stage, an extended design was presented which enables rotations of 360°. Due to modifications of the drive principle and optimized drive profiles, the new drive allows higher thrust forces and a very compact design while maintaining the number of drive nozzles and valves. A simple measurement system for preliminary tests of the XYC-stage was designed. This system limits the accuracy of the drive in closed loop control.

Further studies will concern the optimization of the measuring system as well as the control and testing of the new stage. The investigations will also be extended to operation with liquid media. Finally, the system will be used with other modules in reconfigurable desktop machine tools.

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