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MACHINE TOOL

Novel moving-magnet electrodynamic feed units for small machine tools

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Abstract Small feed motions in the mm and cm range today are mostly realised with miniaturised leadscrew motor systems, piezo stages and moving-coil actuators. A short survey on typical properties of those existing feed units for small machine tools is given first. A simple yet powerful complement or alternative to the above-mentioned small drives are single-phase linear direct drives with moving magnets. Especially motor designs with slotted stator winding offer high force densities and good dynamics. Combination of those short-stroke motors with ball or flexure guides and with embedded position or force control resp. leads to particular compact feed units. Such modules are currently being developed at Technische Universität Dresden for applications in future small machine tools and in automation. Two different prototypes of those feed modules are presented in this paper. With travel ranges of 11 and 14 mm, resp., peak forces of 39 and 112 N resp., linear force characteristics and speeds up to 1.6 m/s they feature attractive properties. A first module with ball-guided slide already contains an integrated low-cost position sensor and embedded state space position control. A second module with flexure-guided mover is currently being extended with latter embedded control components. Due to their high compactness, force density, dynamics and modularity, the developed feed units can widely be used in future small machine tools and in automation.

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1 Introduction

Small working spaces of future small machine tools of only a few cm^3 enable unique technical solutions for feed drives that are not just derived by downsizing of conventional machine tools [1, 2]. In large machine tools, three-phase linear motors have been used for many years by now as highly dynamic direct feed drives [3]. In contrast, small maximum travel ranges of appr. 25 mm are sufficient for many feed units of future miniature machine tools. Furthermore, motor forces of small electrodynamic direct drives and typical maximum process forces of small machine tools (appr. 20 N) match very well. The limited stroke and the force requirements allow for simple and cost-efficient motor designs with only one magnetic and electrical phase per axis. Motors with moving permanent magnet(s) and a slotted single-phase stator winding offer a high compactness, good dynamic behaviour and a large volume-based actuator constant (see Sect. 5). Furthermore, the limited stroke allows for nearly stick-slip-free flexure guides. Due to their simplicity all subsystems of those feed units, i. e. magnetic circuit, guide system, position sensor and control hard- and software can be combined to very compact modules. Two different prototypes of such feed units are presented in Sects. 3 and 4. Prior to this, a short survey on typical existing linear stages for small strokes is given in the following section.

2 Feed units for small strokes

Miniaturized leadscrew systems driven by a DC or stepper motor with reduction gear can be used for miniaturized machine tools. Due to the gear and typical screw pitches between 0.4 and 1 mm, feed rates of only a few mm/s are achievable. Self-locking in de-energized state and a high stiffness are advantageously for most applications, whereas a backlash of a few µm is a disadvantage.

Linear short-stroke direct drives are utilized in several machine tools, especially for fast servo tools [4]. Piezo stack actuators are applied in precision grinding and conventional CNC turning [5, 6]. In these applications, strokes are typically in the range of 40 µm and the actuators are combined with large monolithic flexure guides.

For larger travel ranges up to appr. 20 mm, piezo stepping motors provide high forces up to 800 N and velocities of a few mm/s [7]. As a low-cost alternative, piezo inertia motors reach forces of appr. 10 N at low speeds (5 mm/s). For higher dynamic requirements, ultrasonic piezo actuators represent an additional solution. As the force is transmitted via friction, theoretically unlimited travel ranges at high velocities (up to 400 mm/s) are possible. However, the achievable push and pull forces are low (appr. 5 N) [7].

For micro-EDM as well as for diamond turning processes, voice-coil motors with strokes up to 1 mm are used [8, 9]. Due to the small electrical time constant and small moving masses, voice-coil motors are suitable for highly dynamic applications. However, heat removal from the coil is rather poor, air gaps are large, and winding cross-sectional areas are limited. Compared to moving-magnet actuators, the volume-based actuator constant is two to three times smaller (see Sect. 5). In contrary to the above-mentioned feed units, moving-magnet actuators offer high dynamics, large force densities, and large strokes at the same time.

3 Cube-shaped feed unit with embedded control

Figures 1, 2 and 3 show the structure and mechanical design of a first realised single-phase feed unit with moving permanent magnets and embedded control [10]

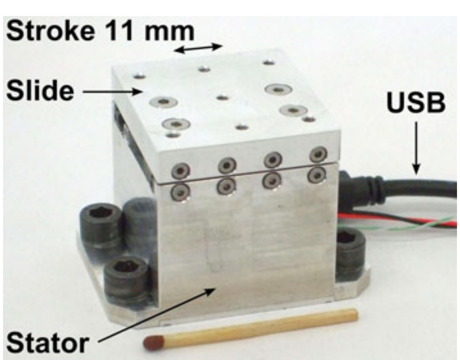

Fig. 1 *Cube-shaped* feed unit with ball-guided slide and embedded position control

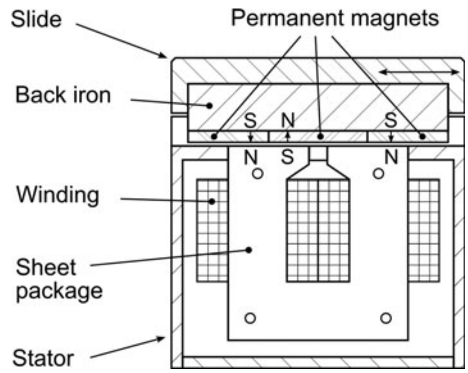

Fig. 2 Schematic cross-sectional view of the *cube-shaped* feed unit

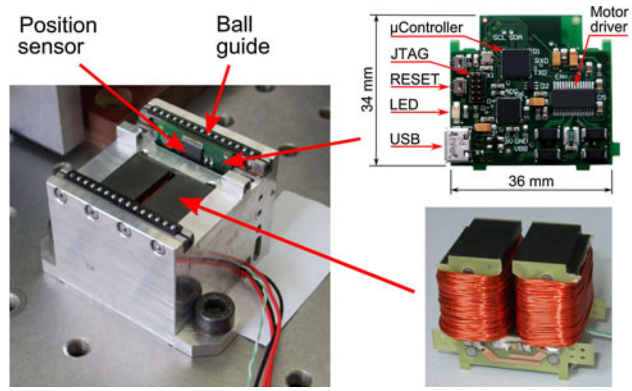

Fig. 3 Stator components of the *cube-shaped* feed unit

The stator consists of a U-shaped laminated sheet package with a single-phase winding and an embedded control electronics for state space control of the mover position. A low-cost magnetic incremental position sensor with an interpolated resolution of 0.488 µm is placed on the electronics board. The slide acts as tool or workpiece holder. It contains permanent magnets on a back iron and a magnetic scale for the position sensor.

Unlike in most short-stroke linear stages with preloaded closed ball guides, the guide rails are arranged as a simple open ball guide (Fig. 3), utilizing lateral magnetic forces between slide and stator (170 N without current) as preload [11]. This results in a compact design and facilitates assembling.

Magnetic design of this single-phase moving-magnet motor by means of a lumped magnetic network model and FEA is outlined in [12]. The arrangement with three permanent magnets chosen for this motor leads to moderate reluctance forces between the two outer permanent magnets and the stator sheet package, causing in turn centering forces acting on the mover without current (as of a mechanical spring with stiffness of appr. 1 N/mm, see negative slope of curves in Fig. 4). Those centering forces can be avoided with different arrangements of the permanent magnets, if needed [13].

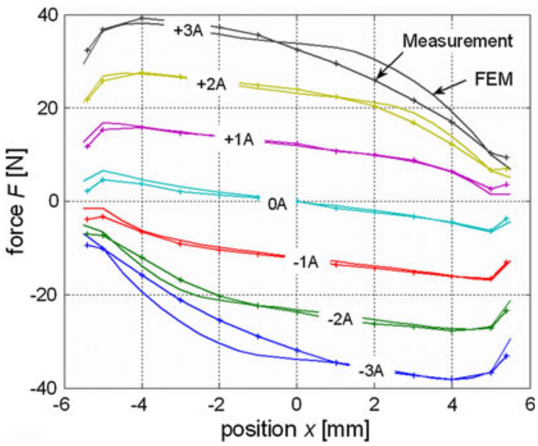

Fig. 4 Force–position–current characteristic of the *cube-shaped* feed unit

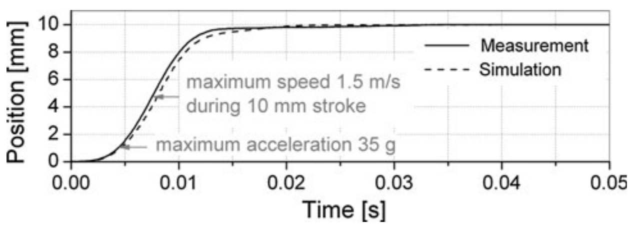

Fig. 5 Set point response of the position control embedded into the *cube-shaped* feed unit

The embedded control electronics shown in Fig. 3 realises state space control of the mover position in conjunction with an outer integral control loop and a state observer. Both voltage feed and current feed of the motor winding by the state space controller as well as state observers of different order have been evaluated with respect to control performance and hardware requirements [11].

The step response shown in Fig. 5 was obtained with voltage feed of the motor winding and a reduced observer for velocity and current. In the present configuration, the sample frequency of the position control loop is 5 kHz, and the measured bandwidth (−3 dB) of the closed loop position control is 38 Hz. An increase of both values is to be expected from a redesign of the embedded control hardware and from implementation of flatness-based control currently underway.

Set positions and simple trajectories (e.g. harmonic motion or constant velocity) are easily transferred to the feed module via USB. Control through common field busses can be realised with future work. Force control can be realised too with the flatness-based control currently being implemented.

Preliminary technical data of the developed cube-shaped feed module are (see also Table 1):

- travel range 11 mm,
- continuous force acc. to force curves for ±1 A in Fig. 4 (12.3 N in mid position $x = 0$ of mover),
- peak force up to 39 N (reduced force drop in end positions to be expected with optimised magnetic design),
- resolution of position sensor 0.488 µm,
- measured two-sided repeatability of positioning 3.0 µm (DIN ISO 230, confidence interval 4σ),
- measured positioning accuracy 5 µm,
- set positions via USB e.g. with any terminal program from a computer.

4 Cylindrical feed unit with flexure guide

Lateral magnetic forces as present in the cube-shaped feed unit described above can be avoided with an axisymmetric magnetic design as shown in Figs. 6 and 7.

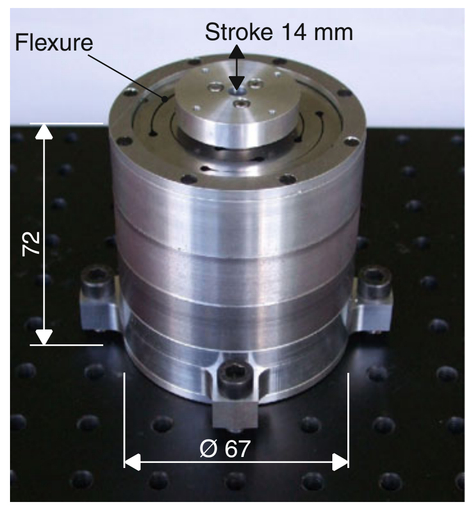

Fig. 6 *Cylindrical* feed unit with integrated flexure guide

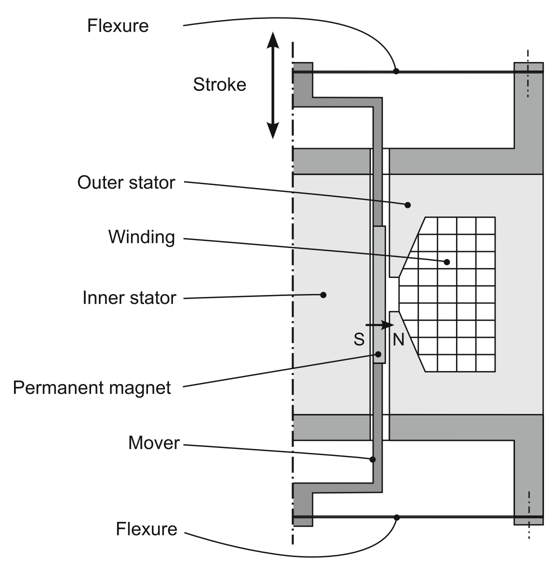

Fig. 7 Schematic cross-sectional view of the *cylindrical* feed unit

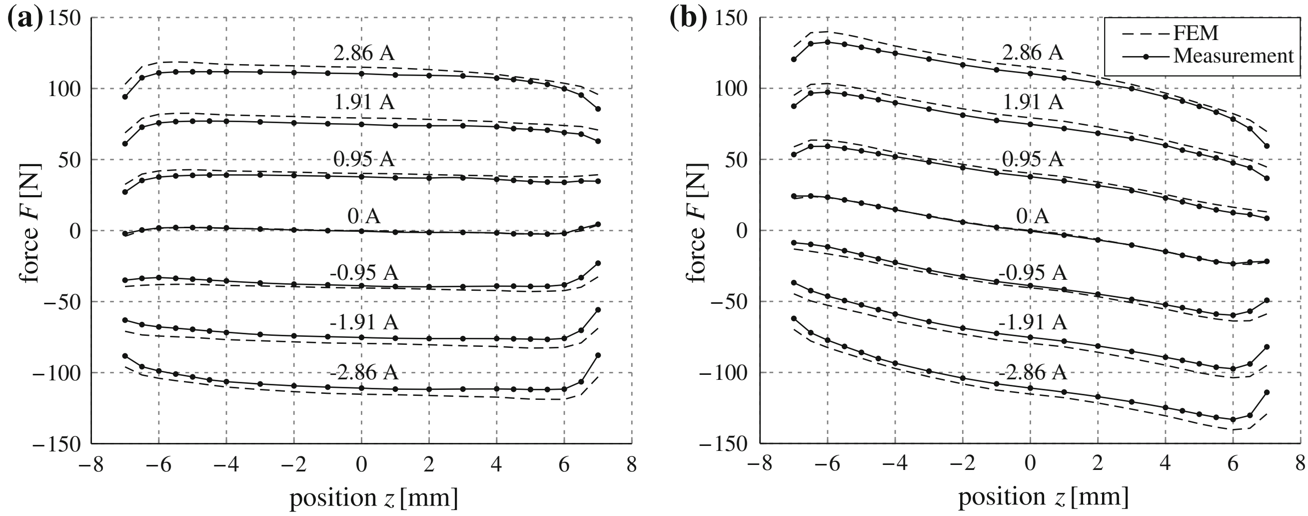

Fig. 8 Simulated and measured force–position–current characteristic of the *cylindrical* feed unit **a** without and **b** with the restoring force of the flexure guide

A tubular mover with radially polarized NdFeB permanent magnets moves translatory in axial direction between two ferromagnetic stator components. The outer stator contains a single-phase winding concentrically wound around the mover magnets and the inner stator. Modelling the ring of permanent magnets on the mover as a circular equivalent current on each of the two end faces of that ring, this actuator can be thought of as a Lorentz force actuator with the excitation field in the two airgaps between inner and outer stator being imposed by the stator winding [13].

In order to minimise eddy currents during dynamic operation, the stator components are made of a soft-magnetic composite material rather than of radially stacked electric sheets [14]. A simple axial lamination as common in rotating electrical machines is not possible here due to the direction of the magnetic flux. Various other magnetic designs differing in geometry and placement of mover, stator and winding are possible for those axisymmetric moving-magnet actuators too [13, 15].

The feed unit provides a continuous force of 44.2 N nearly independent on the mover position (at 105 °C winding temperature) and a peak force of 110.3 N (Fig. 8a). With a mover mass of 0.085 kg, peak accelerations of appr. 34 g are to be expected during position-controlled operation with 48 VDC supply voltage.

Due to the small stroke, a flexure guide free of stick-slip, backlash and lubricants (suitability for clean room applications) is realised in this actuator. With circular, concentrically profiled diaphragm flexures a large stroke of ±7 mm at an outer flexure diameter of only 59 mm could be realized. In contrast to the commonly used spirally profiled flexures, parasitic rotation of the mover at deflection is avoided by a symmetrical design. With an intentionally low axial stiffness of the flexure guide of 3.55 N/mm (Fig. 8b), ohmic losses due to holding of the mover in either of its both end positions are 4.5 W only. Since the quality factor of the spring-mass oscillator formed by the mover and its flexure guide is low, a good control performance in a closed-loop operation is to be expected. The radial stiffness of the flexure guide in zero position is greater than 2 N/µm at the flange, which is sufficient for many applications in small machine tools.

5 Volume-based actuator constant

The volume-based actuator constant

$$E' = \frac{F^2}{P_{Cu} \cdot V} = \frac{k^2}{R_{Cu} \cdot V} \qquad (1)$$

Table 1 Comparison of the feed units with an exemplarily chosen commercial voice-coil actuator

	VCM[a]	Cube-shaped feed unit	Cylindrical feed unit
Stroke (mm)	25	11	14
Envelope volume (cm^3)	391.4	73.9	253.8
Continuous force[b] (N)	75.6	12.5	44.16
Peak force[b] (N/A)	266.9	39	110.3
Volume-based actuator constant[c] ($N^2/(W \cdot cm^3)$)	**0.315**	**0.44**	**0.62**

Bold values indicate volume-based actuator constant

[a] Commercial voice-coil actuator LA28-43-001A from BEI Kimco, semi-housed with integrated slide guide [16]

[b] In mid-position

[c] Averaged over travel range

(F thrust force at fixed mover, P_{Cu} winding losses, V envelope volume, k force sensitivity, R_{Cu} winding resistance) is a useful parameter for evaluation of the energetic performance of positioning actuators. In contrast to the efficiency, it can be used at standstill of the mover. As can be seen in Table 1, the volume-based actuator constant E' of the presented moving-magnet actuators is up to two times higher than that of a similar voice-coil actuator. If only the magnetically active volume is considered, E' is up to three times higher compared to unhoused voice-coil actuators. These differences are mostly due to smaller air gaps and larger cross-sections of windings (and hence larger magnetomotive forces) possible with single-phase moving-magnet actuators compared to those with moving coils [13].

6 Conclusions and outlook

Although these first two demonstrators of novel low-cost electrodynamic feed units for small travel ranges represent an early design stage, they illustrate the modular character and the attractive performance data of the feed modules under development. Differing from most other linear stages and feed units with external controller, a position control is already embedded into the cube-shaped feed unit described in Sect. 3. The measured two-sided repeatability of 3 μm and positioning accuracy of 5 μm are achieved with a low-cost magnetic incremental position sensor. A redesigned version of this control electronics is currently being integrated into the cylindrical feed unit presented in Sect. 4. In conjunction with a low-cost optical incremental position sensor currently being integrated into latter feed unit, a positioning accuracy of appr. 1 μm or better is to be expected.

Because of their compactness, their relatively high force and their good dynamics, the developed single-phase moving-magnet feed modules could become a cost-efficient complement or alternative to other feed drives for small strokes, e.g. to miniaturized leadscrew motor systems, piezo stages and moving-coil actuators. Potential fields of application are not only feed units for small machine tools, but also automation and assembling.

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