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Force sensing linear rolling guides

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Abstract
Force measurement capabilities in machine tools enable process monitoring and process control. Thus, force measurement is an essential enabler for industry 4.0 applications in cutting processes. Researchers have dealt with integrating force sensors into different machine tool components such as spindle slides, spindle units, clamping systems, and tool holders. This work aims to investigate the potential of expanding force measurement capabilities to linear rolling guides. The paper presents a force measurement approach based on strain gauge sensors applied on the guide carriages. The approach is investigated experimentally on a single carriage as well as on a linear-axis test rig. It is shown that measurement and distinction of two force directions at each carriage under the presence of disturbance torques is possible. The achievable sensitivity is sufficient to detect misalignment of the guide rails. However, force sensitivity is not sufficient for process monitoring yet. Moreover, disturbances such as time varying constraint forces, preload variation, and roller circulation lead to major challenges for force measurement by this component. Thus, sophisticated signal processing will be inevitable for reliable measurement of process forces.

Linear guides, force measurement, process monitoring, condition monitoring

1. Introduction

Analysis of forces in cutting processes is used for process monitoring and detection of undesired events such as tool breakage, chatter, process errors, and tool deflection [1]. Researchers have therefore dealt with the implementation of force sensing capabilities into different machine tool components such as tool holders or spindle units [1]. At the Institute of Production Engineering and Machine Tools (IFW) Hannover a force sensing spindle slide was developed for both, monitoring and compensation of tool deflection [2]. However, those components are unique to a certain machine tool type. Thus, considerable engineering effort is required for the adaptation to other machine tool types. Integrating force measurement into standardized linear rolling guides, in contrast, offers the possibility to expand force measurement to a wide range of machine tools. In addition to process monitoring, force sensing guides could enable condition monitoring applications such as detection of misalignments of the rails. Misalignment impairs accuracy of the feed axis and can increase wear of the guiding system [3]. Various approaches for force measurement on rolling guides are described in patents. They disclose measurement concepts such as measurement of deflection between carriage and rail [4] and strain measurement on the carriage [4] or rail [5]. Brecher et al. [6] showed that run-in frequencies of the rolling elements can be observed by strain measurement on carriages in order to support the detection of defects.

Force sensing linear guides promise to be beneficial to a number of applications such as process force measurement, condition monitoring and misalignment detection. However, the potential and limitations regarding the different applications are unknown. This paper presents an approach for enabling rolling guides for multiaxial force sensing based on strain measurement. The potential for force measurement and misalignment detection is evaluated experimentally.

2. Strain gauge positioning and prototype system structure

Due to the overconstrained structure of a guiding system, guide carriages are not only exposed to external forces (e.g. process forces) but also to constraint forces and moments (Figure 1). Since constraint forces can exceed process forces by an order of magnitude, high accuracy is required. Further sources of disturbances are preload variations and pulsations, which are caused by roller circulation.

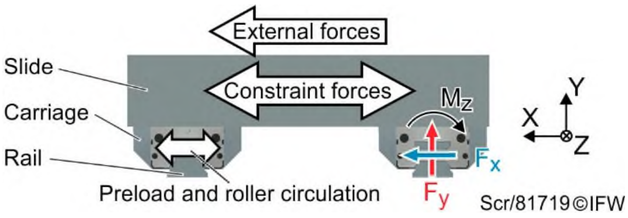

Figure 1. Guiding system and acting forces

In order to determine favorable positions for strain gauge sensors, a finite element analysis (FEA) of the roller guide carriages (Bosch Rexroth R1851, size 45) was done. The contact between carriage and rail was simplified with nonlinear spring elements (COMBIN39). The side faces of the carriages were chosen for sensor placement because of their accessibility. Normal strains on these faces remain below 1.0x10^{-7} m/m for forces of 100 N in X-direction (F_x) and below 0.3x10^{-7} m/m for forces in Y-direction (F_y). A moment M_z of 10 Nm around the Z-axis leads to strains of up to 1.1x10^{-7} m/m and therefore requires consideration as well.

Based on the FEA, strain gauge sensors (Vishay N2A-06-S1449) were placed on the guide carriages (Figure 2). Four sensors were placed such that forces in X- and Y-direction can be differentiated as well as M_z moments. Strains resulting from moments around the X- and Y-axis can be neglected at the chosen position due to their low value. A processing board converts the analogue strain gauge voltage with a 24 bit ADconverter (Texas Instruments ADS1256). The signal is transmitted via CAN-Bus to an industrial-PC. The prototype carriage was integrated into a linear axis test rig (Figure 2). The test rig comprises a ball screw driven slide mounted on four roller carriages.

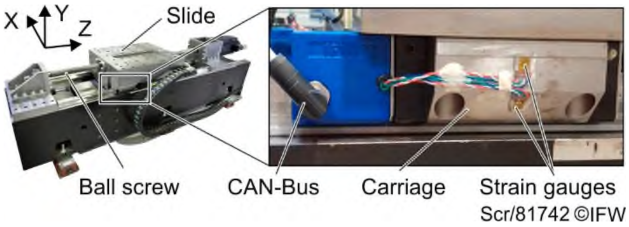

Figure 2. Linear axis test rig and prototype of force sensing guide carriage

3. Experimental investigation

3.1 Two-axial force measurement with a non-moving carriage

In order to derive the forces F_x and F_y from the strain gauge voltages $\mathbf{u_{sg}}$ the following equation is used:

$$\begin{pmatrix}F_x\\F_y\end{pmatrix} = \mathbf{K}\cdot\mathbf{u_{sg}} \qquad (3\text{-}1)$$

Firstly, the coefficient matrix $\mathbf{K}$ has to be identified empirically. In order to generate data to identify $\mathbf{K}$, forces between ca. 300 N and 500 N were applied sequentially on different positions in in Y-direction (1 to 3) and X-direction (4 to 6) on an adapter plate on the carriage (Figure 3). The applied reference force was measured with a force measurement probe (HBM C9B) and $\mathbf{K}$ was calculated with the least squares method subsequently. The different positions are chosen to produce different values of M_z. Figure 3 shows the calculated forces F_x and F_y in comparison to the reference force. Due to the low strain amplitudes, the strain gauge signal was low-pass filtered at a cut-off frequency of 6 Hz. It can be seen that force measurement in the two directions is possible on a non-moving carriage. However, in accordance with the simulation results, sensitivity in Y-direction is considerably lower compared to the X-direction. The noise level and a remaining signal drift reduce the goodness of the identification especially in Y-direction significantly. In Y-direction, the difference to the reference force is 29% at peak (3).

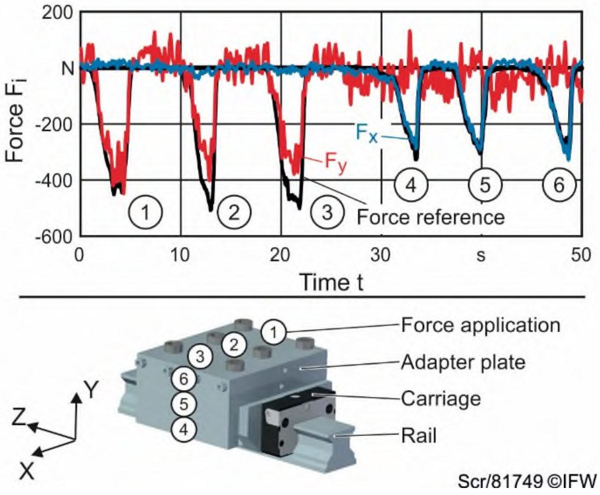

Figure 3. System identification on a single guide carriage

3.2 Investigation of a moving carriage and misalignment detection

After identification of the coefficient matrix, the force sensing carriage was integrated into the linear axis test rig in order to evaluate the effect of disturbances during motion and to evaluate the potential of detecting misalignment errors of the rail. Figure 4 shows the horizontal force $F_x(z)$ as a function of the position in Z-direction during a reverse motion between $z = 500\ \mathrm{mm}$ and $z = 0\ \mathrm{mm}$ with a feed velocity of $v_f = 1{,}000\ \mathrm{mm/min}$. The force signal is subjected to roller circulation (period 10 mm) and a significant hysteresis following the motion reversal. Moreover, force variations of several kilonewton can be identified. Those are likely caused by mounting inaccuracies of the rail.

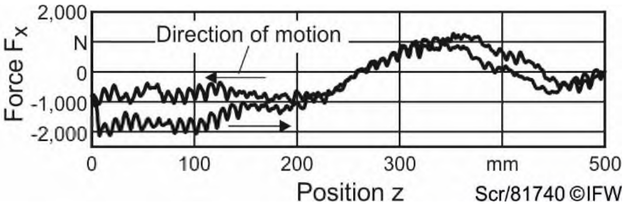

Figure 4. Horizontal force $F_x(z)$ during reverse motion

In order to evaluate the potential for the detection of misalignment errors of the rails, a misalignment was set deliberately. To this end, mounting screws of the rail were loosened in the first half ($z = 0$ to $250\ \mathrm{mm}$) of the carriage's travel path. The rail was then deviated in X-direction such that a deviation of d_x at $z = 0\ \mathrm{mm}$ and $d_x/2$ at $z = 125\ \mathrm{mm}$ was measured with a dial gauge. For $z > 250\ \mathrm{mm}$, the alignment remained unchanged. The deviation d_x was set to 6, 9, and 16 µm successively. For each setting of d_x, the mounting screws were fixed and $F_x(z, d_x)$ was measured during a reverse motion. The difference between the initial and deviated state was calculated as $\Delta F_x(z, d_x) = \bar{F}_x(z, d_x) - \bar{F}_x(z, d_x = 0)$. Whereas $\bar{F}_x(z, d_x)$ is the mean value of $F_x(z, d_x)$ of both moving directions. Figure 5 shows that even a deviation of 6 µm, which is below the manufacturer's mounting tolerance of 9 µm, can be detected and leads to a ΔF_x of 1,215 N at $z = 0$.

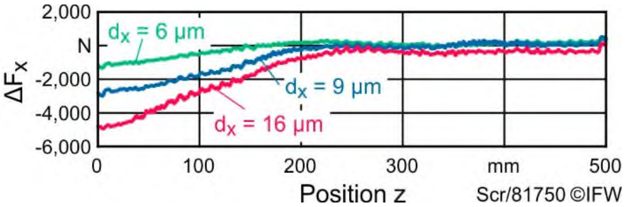

Figure 5. Force deviation $\Delta F_x(z, d_x)$ for different deviations d_x

4. Summary and conclusion

In this paper, an approach for sensing of forces on linear guide carriages based on strain gauge sensors was presented. The approach allows the measurement of forces perpendicular to the rail. Experimental evaluation showed that the force sensitivity is sufficient to detect misalignment errors of the rails. However, sensitivity requires improvement in order to be used for process monitoring. Further work will improve force sensitivity using semi-conductor strain gauges. Furthermore, it will be investigated how model-based signal processing and fusion with machine control signals (position, velocity, drive currents) can be applied to differentiate between external forces and disturbances from roller circulation and other sources.

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