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Investigations on a torque-compensating adjustment drive for mechanically sensitive devices

Martin Wittke[1], Matthias Wolf[1], Florian Weigert[1], Maximilian Darnieder[1], Erik Gerlach[2], Klaus Zimmermann[2], René Theska[1]

Technische Universität Ilmenau, Department of Mechanical Engineering,
[1]Insitute for Design and Precision Engineering, Precision Engineering Group
[2]Technical Mechanics Group

E-Mail: martin.wittke@tu-ilmenau.de

Abstract
To satisfy the increasing demands for adjusting sensitive precision engineering devices, a torque-compensating adjustment drive was developed in previous work. A counter torque compensates the applied torque through an appropriate coupling of the adjustment drive to the device. Within this work, a prototype of the adjustment drive was fabricated and put into operation. Investigations focused on determining the prototype's specifications and reducing undesirable influences. Primarily, the mechanical model of the drive was derived from its simplified working principle for adjustment. The overload protection that intervenes when the drive and the device are incompletely coupled, and also the torque-compensated adjustment are discussed theoretically and then investigated experimentally. Thus, the maximum transmitted parasitic torque is determined and lateral forces are detected. In an iterative process, the adjustment drive is optimized to minimize the transmitted parasitic torque and lateral forces impacting on the mechanically sensitive device. Further investigations include determining the specifications of the drive such as the nominal adjustment torque, the angular resolution at the output shaft and the backlash to be considered for precise adjustments.

Keywords: torque compensation, adjustment, mechanical model, torque measurement

1. Introduction

The increasing demands for adjusting sensitive precision engineering devices such as mass comparators or nano-positioning and nano-measuring machines led to the development of a torque-compensating adjustment drive [1]. The drive uses a counter torque to compensate for the transmitted torque of the adjustment motion. Within this work, the mechanical relations of the overload protection and the torque compensation are considered. Then, a prototype of the adjustment drive is optimized, commissioned, and tested. Investigations include determining the adjustment parameters and measuring the transmitted parasitic torque and lateral forces impacting on the mechanically sensitive device (MSD).

2. Theoretical considerations

To derive the interrelationships during adjustment, the system is analyzed using the simplified working principle shown in Fig. 1, in which the coupling mechanism is omitted. The compensation forces (F_{comp}), the friction torques of screw gear ($M_{f,sg}$) and bearing ($M_{f,b}$), the resisting torque of the electrical connections ($M_{r,c}$), the torque of the drive unit (M_{dr}), and the transmitted parasitic torque (M_t) were added. During adjustment, two phases differ: complete coupling with intervening overload protection, and torque compensated adjustment.

2.1. Complete coupling with intervening overload protection

The coupling mechanism extends the drive and positions the tool and the reaction arms to transmit a torque-compensated rotary motion to the adjustment gear of the device. Due to dissimilar clearance of several form-fit couplings, drive and device coupling is incomplete over a small angular range. The rotary adjustment motion would be transmitted non-torque-compensated, but the overload protection intervenes [2].

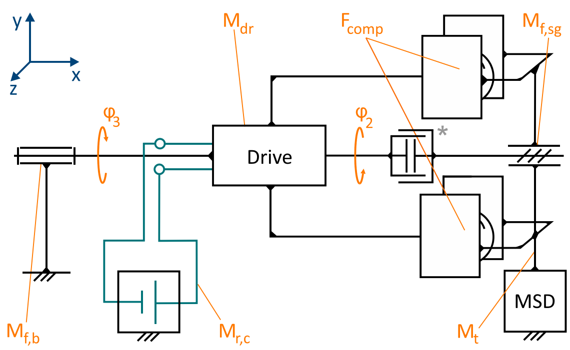

Figure 1. Simplified working principle. (*shiftable form-fit coupling)

To determine the parasitic torque transmitted to the device during that period, the mechanical models of the system's components were developed. They are shown in Fig. 2. In case the sphere-plane contact pairs of the torque compensation are not engaged ($F_{comp} = 0$), the equilibrium of moments for the x-direction of the stator (1) and the rotor (2) of the drive and the device (3) is derived.

$$- J_S \cdot \ddot{\varphi}_3 = - M_{dr} + M_{f,b} + M_{r,c} \quad (1)$$

$$(J_R + J_{sg}) \cdot \ddot{\varphi}_2 = M_{dr} - M_{f,sg} \quad (2)$$

$$0 = M_{f,b} - M_t \quad (3)$$

Since the friction in the bearing is significantly lower than the friction in the screw gear, the rotor of the drive can be considered fixed ($\varphi_2 = 0$). That results in equation (4) for the rotor side.

$$0 = M_{dr} - M_t \qquad (4)$$

After substituting equation (4) into equation (1) and converting, equation (5) is derived for the transmitted parasitic torque.

$$M_t = M_{f,b} + M_{r,c} + J_S \cdot \ddot{\varphi}_3 \qquad (5)$$

2.2. Torque compensated adjustment

After the drive and device coupling is completed by rotation of the whole drive unit, the precision engineering device is adjusted torque-compensated [3].

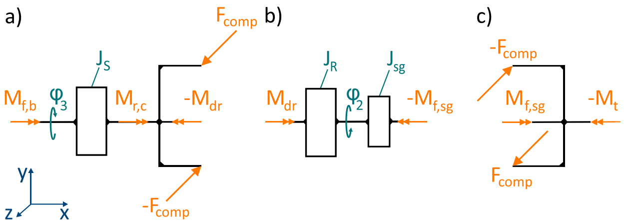

Figure 2. Mechanical model of a) stator. b) rotor. c) MSD.

To determine the parasitic torque transmitted during adjustment, the mechanical models from Fig. 2 are used to derive the equilibrium of moments for the x-direction of the stator (6) and the rotor (7) of the drive and the device (8). For clarity, M_{comp} summarizes the torques caused by F_{comp} and $-F_{comp}$.

$$-J_S \cdot \ddot{\varphi}_3 = -M_{dr} + M_{f,b} + M_{r,c} + M_{comp} \qquad (6)$$

$$(J_R + J_{sg}) \cdot \ddot{\varphi}_2 = M_{dr} - M_{f,sg} \qquad (7)$$

$$0 = M_{f,b} - M_t - M_{comp} \qquad (8)$$

Due to the complete coupling of the drive and the device, the torque compensation supports the stator ($\varphi_3 = 0$). Equation (6) is thus simplified to equation (9).

$$0 = M_{dr} - M_{comp} \qquad (9)$$

Substituting equations (7) and (9) into equation (8) provides the parasitic torque transmitted to the device during adjustment.

$$M_t = (J_R + J_{sg}) \cdot \ddot{\varphi}_2 \qquad (10)$$

3. Commisioning and initial optimization

A prototype of the torque-compensating adjustment drive was fabricated and after commissioning, the overall operating principle was validated. To use the drive to adjust precision engineering devices, initial optimizations were carried out. Thus, the transmitted parasitic torque could be minimized according to equations (5) and (10). The pre-tension of the drive's fixed bearing was decreased after statically balancing the drive by subsequently added balancing mechanisms. Replacing the original motor cable with 50 µm copper wires minimized the resisting torque given by the mechanical stiffness of the electrical connections. A suited acceleration start-up curve reduced the dynamic torque caused by inertias close to zero. Combining tool and tool holder led to a strongly reduced run-out error, which resulted in decreased lateral forces.

4. Specifications of the prototype

A motor-gear combination allows a nominal torque of 1796.27 N mm and an angular resolution of 9.69''. For an environmental pressure of up to 0.01 bar, the usage for vacuum applications is granted. The design space of the whole drive unit amounts to (243x99x95) mm^3.

To determine the transmitted torque, the impact of lateral forces, and the backlash contributing to the adjustment uncertainty, the measuring setup shown in Fig 3. was used. A specially designed coupling point (1), which represents the MSD, is mounted to a 3-component force sensor (2) and a fixed torque sensor (3) via adapters. A pre-tensioned screw (4) simulates the adjustment gear to be moved. The tool (5) and the reaction arms (6) of the drive are coupled for the initial state. To check the phase described in chapter 2.1, the reaction arms were removed for several measurements.

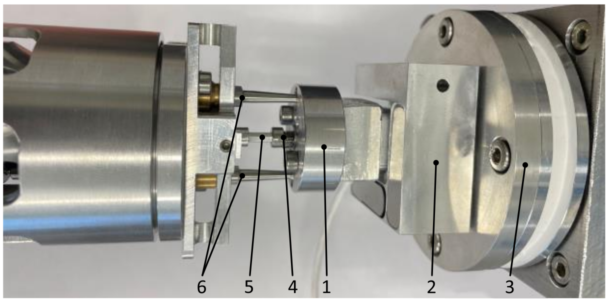

Figure 3. Measuring setup.

The maximum measured values for the impact on the device are below 1.5 N mm for the transmitted parasitic torque and 1 N for lateral forces. By reversing the motion and determining the encoder steps until the torque sensor detects a peak in the measurement signal, a highly reproducible backlash of 330.95° ± 4.2' could be calculated.

5. Conclusion and Outlook

After developing a torque-compensating adjustment drive for precision engineering applications in previous work, a prototype was fabricated and its adjustment parameters were determined. To minimize impacts on the device, theoretical considerations were carried out to identify the major contributions to the transmitted parasitic torque. Based on these considerations, the adjustment drive was optimized after commissioning. Prototype investigations revealed the real adjustment parameters. Minor parasitic impacts such as the transmitted parasitic torque and lateral forces confirm the proper applicability of the drive for mechanically sensitive devices.

Ongoing optimization of the adjustment drive allows further minimization of the transmitted parasitic torque and lateral forces. The electrical connection can be replaced by wireless power and signal transmission and inertias can be reduced by lightweight design. To minimize lateral forces, two universal joints between the drive unit and the tool could be integrated. The design as flexure hinges with concentrated compliance enables precise angular transmission of the adjustment motion while minimizing the lateral stiffness of the component.

The system's applications will be extended by using it as a low-impact fastening system for screws in sensitive precision engineering applications.

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