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Error propagation in two-axis feed drives using physical error injection and multibody simulation

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Abstract
Linear and rotational motions in machine tools are generated by feed-drive systems, which are critical subsystems of precision machinery. Small geometric errors within these systems can propagate through the structural loop and result in table-positioning deviations. This study investigates error propagation in a redundantly constrained, dual-rail feed drive system integrated in a testbed. Controlled guideway rail deformation was introduced via pusher bolts, and linear positioning tests were performed using laser interferometer. A physics-based multibody simulation model was used to replicate the same positioning tests and evaluate the positioning deviation induced by the injected guideway straightness error. The results demonstrate that the simulation replicates the spatial characteristics of the guideway straightness error and its corresponding scaling effect on positioning accuracy, validating the physics-based mapping between rail deformation and table displacement. The observed deviation profile confirms that localized guideway geometry directly influences the structural-loop response in overconstrained configurations. Thus, this study establishes a validated multibody modelling approach for analyzing geometric error propagation in overconstrained feed-drive systems.

Feed-drive system, Geometric error propagation, Multibody simulation, Validation, Accuracy

1. Introduction

Linear feed drive systems in machine tools convert rotary motor motion into translational table movement and directly determine positioning accuracy [1,2]. The motion transmission path comprises the motor, ball screw-nut assembly, carriage supported table and linear guideways, which together define the structural loop of the axis. The axial and torsional stiffness of these elements determine the static deformation of the loop under load and influence positioning performance [3]. Beyond elastic deformation, linear axes exhibit geometric component errors, including positioning, straightness and angular deviations, which propagate through the machine kinematic chain and affect overall volumetric positioning accuracy [4].

While geometric errors of linear axes can be characterized individually [5], their propagation depends on the guideway constraint topology. In dual-rail configurations employing multiple carriages, the guideway assembly becomes overconstrained. Small geometric inconsistencies between parallel rails can induce internal load redistribution among carriages, altering the effective stiffness distribution of the structural loop and introducing nonlinear sensitivity to localized rail straightness error.

Despite extensive stiffness and dynamic modelling of feed drive systems [3], experimental validation of geometric error propagation in overconstrained guideway configurations remains limited. In particular, the capability of physics-based simulation to reproduce positioning deviations induced by controlled geometric error injection has not been systematically assessed. This study addresses this gap by introducing controlled rail deformation into a dual-rail feed drive testbed and evaluating a multibody simulation model against interferometric measurements.

2. Methodology

2.1. Multibody model of the feed-drive testbed

The physical two-axis feed-drive testbed and its corresponding virtual model are shown in Figure 1. The model was implemented in MATLAB®/Simulink® R2024b using Simscape™ Multibody toolbox, with the top-level modeling architecture illustrated in Figure 2. The modeling implementation follows the detailed formulation reported in [6].

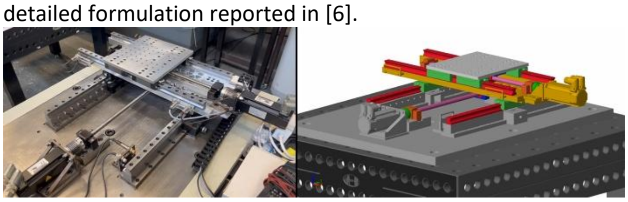

Figure 1. Physical two-axis feed-drive testbed in a stacked-axis configuration (left) and its corresponding virtual model (right).

The model represents the structural loop of the testbed from motor torque input to translational displacement at the center reference point. The structure comprises an X-axis stage and a stacked Y-axis stage, each featuring dual linear guides and a screw-nut transmission. Guideway geometry is represented by a spline-based profile, allowing rail deformation to be introduced as a geometric disturbance input. Shaft rotation is converted into linear displacement through a lead screw joint in parallel with linear guides, reflecting the overconstrained configuration.

Friction at the carriage-rail interface is modelled using externally applied Coulomb and viscous components based on carriage velocity. The mechanical model is coupled with cascaded P-PI control loops to generate torque inputs. In the X axis stage block, rails are fixed to the base using weld joints, and carriage-to-plate connections are represented by 6-DoF joints to allow limited compliance under rail deformation.

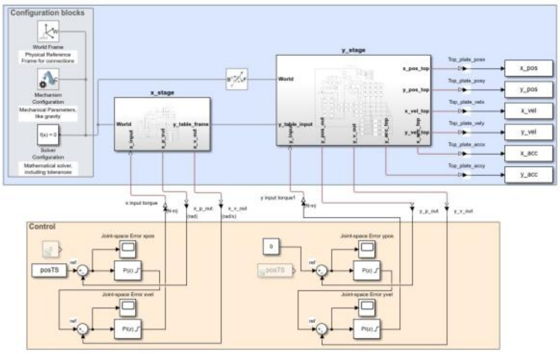

Figure 2. Top-level architecture of the two-axis feed-drive testbed model implemented in MATLAB®/Simulink® R2024b using Simscape™ Multibody toolbox.

2.2. Error injection and validation procedure

Controlled rail deformation was introduced via pusher bolts tightened to defined torque levels (Figure 3), generating vertical rail displacement in the physical testbed. The measured deformation profile was reconstructed as a continuous rail curve and implemented in the simulation by modifying the spline used in the point-on-curve constraints, enabling direct injection into the structural loop without altering other model parameters.

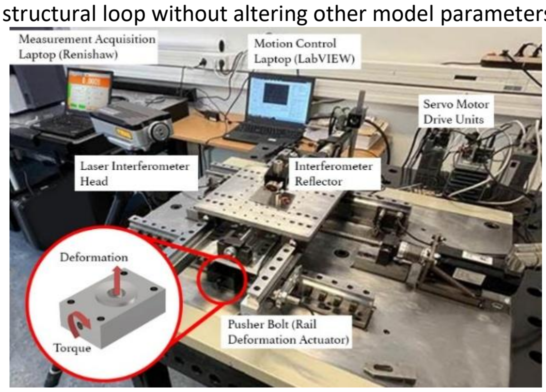

Figure 3. Experimental setup for interferometric linear positioning measurement with controlled rail deformation.

Linear positioning tests were conducted along the X axis from 30 mm to 240 mm and back in 30 mm increments. At each target position, stationary samples were extracted to eliminate dynamic transients. A laser interferometer reflector was mounted at the center of the moving table, corresponding to the defined measurement reference point.

Positioning deviation was calculated as the difference between the stationary displacement and the commanded reference position issued by motion controller to the servo drives. Simulation results were compared with interferometer measurements along the stationary line at $y = 0$ mm.

3. Results

Linear positioning tests were performed under undeformed and two controlled deformation levels (τ = 10 Nm， 15 Nm). Under the undeformed condition, physical measurements exhibited a systematic position-dependent deviation (Figure 4(a)), while the simulation predicted negligible deviation under ideal alignment (Figure 4(b)).

With deformation applied, measurements followed the baseline trend but increased in magnitude, scaling with the torque level. By defining the deformation-induced deviation as the difference between deformed and undeformed conditions, both experiment and simulation revealed a localized mid-travel feature. The spatial profile of this feature reflected the injected guideway straightness error, and its magnitude scaled consistently with the applied deformation level.

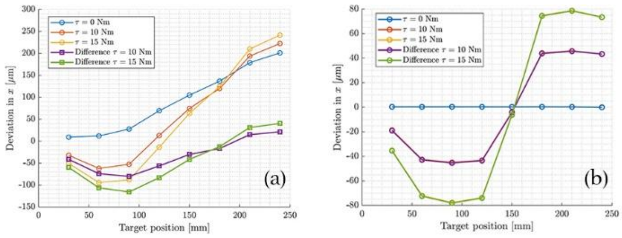

Figure 4. Positioning deviation along the x-axis under controlled rail deformation: (a) interferometer measurements, (b) simulation. Curves show undeformed (τ = 0), deformed (τ = 10 Nm, τ = 15 Nm), and deformation-induced deviation (deformed − undeformed).

The simulation captures the spatial characteristics and scaling of the deformation-induced deviation. Quantitative agreement is assessed via Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) (Table 1), reflecting average residuals and sensitivity to larger deviations, respectively. The slight decrease in agreement at higher deformation may reflect increased sensitivity to unmodeled carriage–rail contact and assembly effects.

Table 1 Simulated MAE and RMSE metrics for deformation-induced positioning deviation.

Deformation torque τ (Nm)	MAE (μm)	RMSE (μm)
10	9.9	13.1
15	15.9	22.1

4. Discussion and Conclusions

The experimental results indicate that localized guideway deformation is a dominant contributor to the positioning deviation at the structural-loop output. A mid-travel deviation feature was observed near the location of maximum rail deformation point, consistent with error propagation through the overconstrained structural loop. With the measured rail deformation profile as input, the multibody model predicts the positioning-deviation profile and its scaling with deformation level, supporting its use for error-propagation analysis in such systems.

Future work will incorporate experimentally identified assembly parameters and improve carriage-rail contact compliance to enhance accuracy. The approach will further be extended to synchronized X–Y axis motion to analyze error propagation and positioning deviation under coupled multi-axis operation, accompanied by a comprehensive uncertainty budget.

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