Optimal high-bandwidth control of ball-screw drives with acceleration and jerk feedback

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Abstract: This paper presents an optimal non-collocated control strategy for flexible ball-screw feed drives. Within the non-collocated controller framework, all the feedback measurements are taken from table (load) side. The table acceleration and jerk feedback measurements are used to control both rigid body and the structural dynamics, which enables modal damping capability. Linear quadratic regulator (LQR) framework is then utilized to achieve optimal placement of the poles. State based LQR weights are mapped to frequency domain performance targets, i.e. crossover frequency and phase margin, and hence a novel frequency domain optimal tuning strategy is achieved. A kinematic state observer design is also presented to fuse analog accelerometer measurements with linear encoder feedback to realize high-fidelity state feedback and wide bandwidth motion control. Finally, robustness analysis of non-collocated control is carried out, and comparison against conventional full closed-loop collocated controllers is presented. Comprehensive experimental validations and performance benchmarks are conducted on an industrial scale precision ball-screw driven motion stage.

1. Introduction

Ball screw drives are widely used in modern machine tools to generate relative motion between tool and the workpiece [1]. Owing to their favorable torque/force transmission ratio, they provide larger driving forces in a compact mechanical design. However, dynamic accuracy of ball-screw drives is typically limited by structural resonances, i.e. flexibilities that are induced due to the finite stiffness of components such as coupling [2], bearings [3] and the ball-screw shaft itself [1], [4]. These structural resonances limit the achievable dynamic performance in two major ways. Firstly, they lower the phase and gain margins [5] of feedback control, and thereby pose an upper limit on the achievable control bandwidth. On the other hand, lightly damped structural modes can be excited either by reference motion trajectories or simply from external disturbance forces. To deliver high dynamic performance on ball-screw drives, the ultimate goal of modern servo control is to effectively dampen and control the structural resonances and hence achieve higher control bandwidths [6], [7].

One way to circumvent adverse effects of structural resonances is “passive” approach. The idea is to avoid or alleviate excitation of resonances from aggressive motion commands. Reference trajectories are optimized or pre-filtered to yield favorable frequency content [8], [9], [10], [11], [12]. FIR filtering [8] and input shaping [9] are widely used to generate smooth reference commands. If system the dynamics is