LOAD FORCE COMPENSATION FOR DIRECT DRIVES IN MACHINE TOOLS

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INTRODUCTION

The feed axis servo drive is the key component for the performance (e.g. stiffness, precision, path velocity) of a numerically controlled production machine. Replacing flexible transmission devices (e.g. ball screws, belts) by direct drives can improve the productivity. Although claimed by manufacturers of linear and torque motors, the performance of one axis test benches cannot be transferred to real multi axis machine tools.

The small masses and inertia required for linear and torque motors result in a higher disturbance sensibility of direct driven machine tools. Friction as well as gravity loads can be minimized mechanically or can be compensated in most servo controllers. Coupling forces, as discussed in the next Chapter, disturb the dynamic performance especially for high accelerations and velocities and cannot be compensated on the servo axis level.

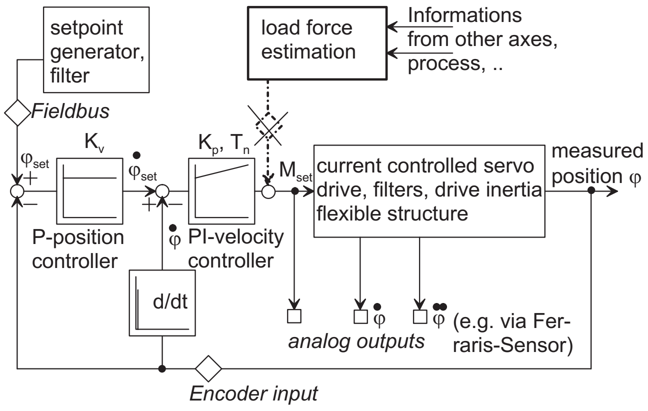

FIGURE 1. Standard machine tool control structure and interfaces.

While most robot control systems compensate the dynamic coupling forces on the numerical control level, machine tool control hardware has no such options. As shown in Figure 1 the standard machine tool control system has several analog outputs and one setpoint- and one or two encoder inputs. Closed loop force inputs are not available.

DYNAMIC COUPLING FORCES FOR DIRECT DRIVES

Figure 2 shows a typical serial machine tool manipulator with 3 direct driven degrees of freedom (DOF). The relevant system parameters are given in Table 1.

The general dynamic robot model following [2] includes centrifugal-, coriolis- and acceleration forces. For machine tools, the acceleration forces are by far the dominating coupling forces. In the example discussed here, also the excentricity of the C-axis is negligible (a=0 in figure 3). Thus the simplified dynamic model yields the coupling force F_{kX} for the X-axis and torque M_{kB} for the B-Axis:

$$F_{kX} = -(m_2 + m_3) \cdot d \cdot \cos(B) \cdot \ddot{B} \qquad (1)$$

$$M_{kB} = -(m_2 + m_3) \cdot d \cdot \cos(B) \cdot \ddot{X} \qquad (2)$$

with m_2 - B-axis mass (body 2 in Figure 3)
m_3 - C-axis mass (body 3 in Figure 3)
d - excentricity of the common gravity center

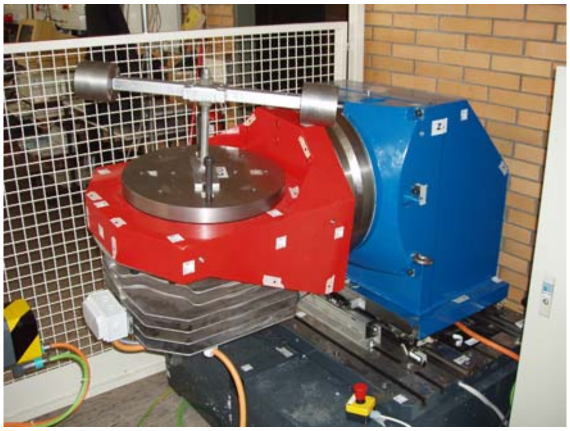

FIGURE 2. Exemplary machine tool manipulator with 3 direct driven DOF [1]

TABLE 1. Parameters for the machine tool manipulator in Figure 2

X-Axis	
Mass	$m_1 = 285$ kg
Linear Motor	Fischer Motoren GmbH
Current Converter	Simodrive 611 U
Maximum Force	$F_{Xmax} = 2500$ N
B-Axis	
Inertia	$J_2 = 13{,}7$ kgm^2
Mass	$m_2 = 285$ kg
Excentricity	$d = 0{,}05$ m
Torque Motor	Technai SA
Current Converter	Simodrive 611 U
Maximum Torque	$M_{Bmax} = 1000$ Nm
C-Axis	
Inertia	$J_3 = 1{,}3$ kgm^2
Mass	$m_3 = 138$ kg
Torque Motor	IDAM GmbH
Current Converter	Simodrive 611 U
Maximum Torque	$M_{Cmax} = 750$ Nm

The effect of the coupling forces is shown in Figure 4 for a fast 5°-positioning of the B-axis. Acceleration and braking produce heavy coupling forces for the X-axis. They lead to significant position deviations in the range of 30 µm.

The measurements in Figure 4 and Figure 5 were sampled by the current converters. The simulations in Figure 4 and Figure 5 result from a MATLAB/Simulink-model of the 3 DOF-manipulator in Figure 2 [2]. They depict the fact that the simplified dynamic model in Eqs. (1) and (2) is precise enough for the representation of the dominating coupling forces.

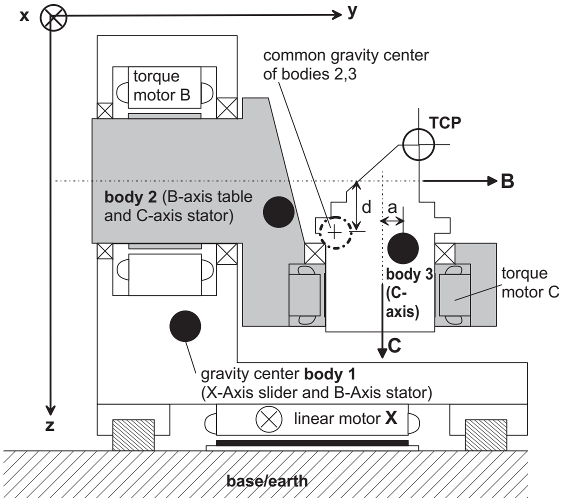

FIGURE 3. Rigid body model of the 3 DOF machine tool manipulator in Figure 2

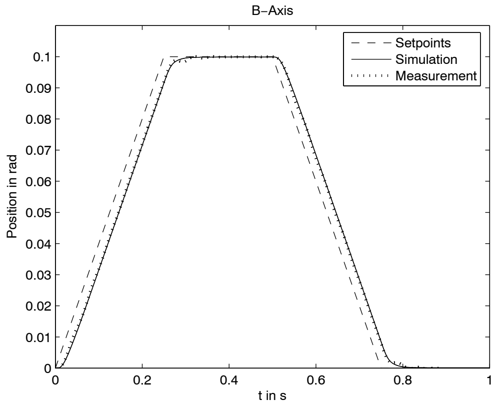

FIGURE 4. B-axis positioning trajectory.

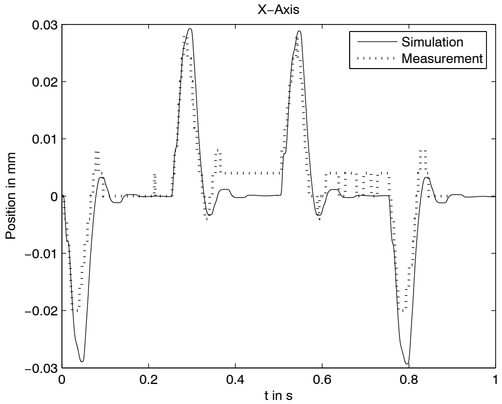

FIGURE 5. X-axis position deviation while positioning the B-axis.

As machine tool axis acceleration duration is in the range of 50..200 ms, the resulting deviation can be estimated using the static drive stiffness following [1]:

$$\Delta x \approx \frac{F_{kX}}{K_v \cdot K_p} \tag{3}$$

with K_v - position control gain

K_p - velocity control gain

HARDWARE EXTENSION

Although standard servo controllers have no additional force input (see Figure 1), they all have two position encoder inputs for a motor encoder (velocity measurement) and a second encoder (e.g. for position measurement at the slider). Direct drives have just one encoder for position and velocity measurement. Modification of the encoder signal for the motor encoder input opens the required coupling force input for direct drives [3]. Figure 6 shows the realization of the compensation based on the universal interpolator of Hübner AG, Berlin [4]. This so called “Blackbox” branches the measured axis position and modifies the motor position input.

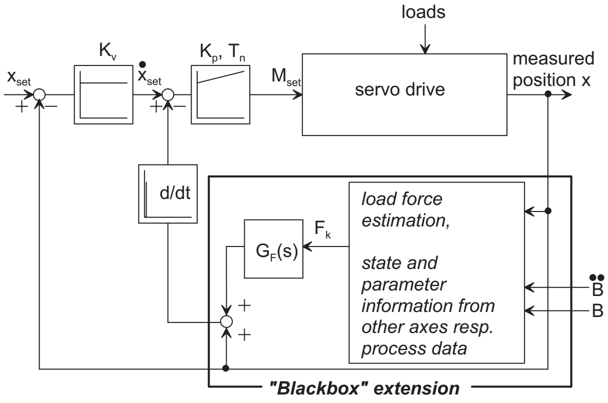

FIGURE 6. Standard machine tool control structure with a force input extension (“Blackbox”)

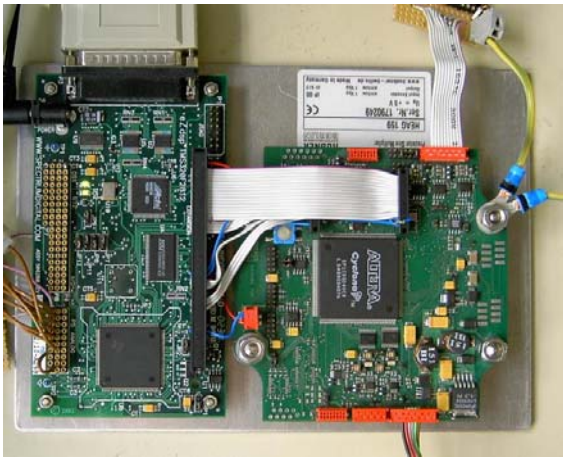

FIGURE 7. Blackbox based on the universal interpolator (courtesy Huebner AG, Berlin).

The inverse filter *$G_F(s)$* compensates the motor position signal processing in the PI-velocity control loop and “mixes” the coupling force compensation to the cascade controller:

$$G_F(s) = \frac{K}{K_p \cdot \left(s + 1/T_n\right)} \tag{4}$$

with K – compensation weighting factor (0 .. 1)

T_n – integral time constant

PRACTICAL APPLICATION

Using Eq. (1) to compensate the effect of the B-axis movement on the X-axis by considering the B-axis motor current as equivalent for the B-axis acceleration decreases the deviation significantly (see Figure 8). The complete compensation is prohibited by the delayed force generation in the current control loop as well as by friction and model uncertainities.

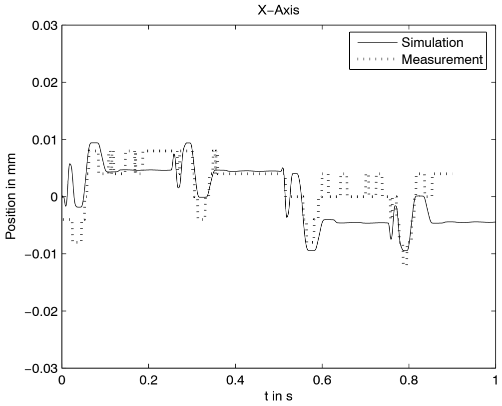

FIGURE 8. X-axis position deviation while positioning the B-axis.with load force compensation via “Blackbox”

CONCLUSIONS

This paper studied the compensation of load forces for direct drives to achieve better accuracy for machine tools and robots. A proposal for the realization on standard control hardware is worked out. The practical benefit is demonstrated by an industrial application and shows that the position resp. path deviations caused by dynamic coupling forces can be suppressed effectively.

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