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Concept and control strategy for active jerk-decoupling of feed-drives

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Abstract
In high speed machining linear direct drives (LDD) enable high dynamics. However, the jerk excites vibration of the machine tool structure and affects the achievable machine accuracy. Therefore, the jerk is limited by the numeric control. One method to avoid excitation of frame vibrations and to increase the dynamics of the feed drive axis is passive jerk-decoupling (JDC) by the means of a mechanical low-pass filter. Nevertheless, passive JDC comes at the price of an additional resonance due to the added mass-spring-damper system. In order to overcome this disadvantage this paper presents a hybrid concept for active JDC. The extension of the passive JDC offers the potential to damp both, the machine structure vibration and the additional JDC-resonance. This paper describes a full state feedback control strategy for damping the critical eigenmodes based on a multi-body model of the feed drive axis. Simulations show that an active JDC reduces the amplitude of the frame- and JDC resonances.

Active jerk-decoupling, linear direct feed-drives, state space controller

1. Introduction

Dynamics of machine tool feed drives are limited by the acceptable excitation of vibrations by reaction forces of the feed-drives [1]. As a result, the performance of linear direct drives (LDD) is not fully exploited.

One solution is damping the peak forces with a passive jerk-decoupling (JDC) by placing a mechanical low-pass (mass, spring and damper) between the LDD and the machine tool frame structure [2, 3]. Another approach is to compensate the reaction-force of a LDD. In this approach, a second slide is accelerated in the opposite direction (on the same guide) [4].

Different optimisation strategies for the JDC parameters were analysed in academia. One approach is to optimise the spring-damper-parameters with the goal of low energy-effort [3]. Another approach is to determine the parameters together with the gain factors of axis-control [5]. However, it was shown that a further resonance (JDC-resonance) is added due to the additional elements of the JDC [4, 6]. Secondly, for structures with low resonance frequencies the low-pass-effect cannot be fully exploited, if the frame-resonance is only slightly above the realizable JDC-resonance [6]. In this case, the displacement of the JDC-mass (counter-motion) will exceed an acceptable workspace.

For this reasons, the approach is to extend the JDC with active elements to damp both, the machine structure vibration and the additional JDC-resonance. In the following, the concept for active JDC of a feed-drive is presented and a mechanical model of the feed-axis is introduced. The mechanical model is based on a vertical cross-table test-rig. The parameters of the full state feedback are chosen such that the disturbance frequency response is minimal. To compare the passive JDC with the active JDC the simulation results are presented.

2. Principle of active jerk-decoupling

Figure 1 shows the active concept. As a reaction of a steep increase of the main LDD-force F_M the reaction-force excites vibrations of the machine frame and of the JDC-carriage. To reduce these vibrations, the force F_{JDC} of the jerk-LDD manipulates the JDC-carriage and simultaneously the machine frame. The dynamic deflection of the JDC-carriage is limited and damped by the JDC-elements to obtain small deflections of the counter-motion.

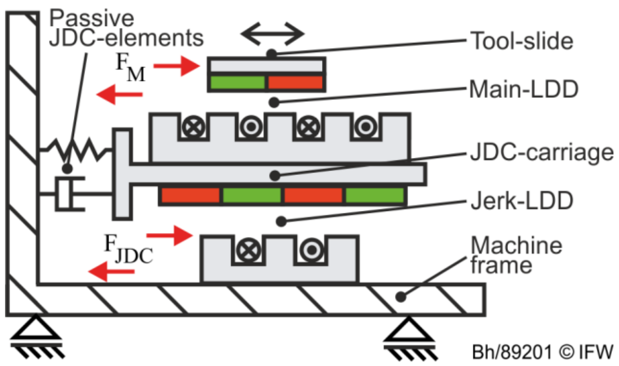

Figure 1. Principle of active jerk-decoupling

3. Mechanical model and controller design

The state space controller is based on a mechanical model of the feed-drive of the test-rig. The system is simplified as a two degree of freedom (2DOF)-multibody-model, which is shown in figure 2. Where m_F describes the equivalent mass of the machine frame and c_F and d_F the stiffness and damping ratio of the machine-frame-structure. The mass of the JDC-carriage is represented through m_{JDC} and the stiffness and damping ratio of the spring/damper elements (cp. "passive JDC-elements" in figure 1) are symbolized as c_{JDC} and d_{JDC}.

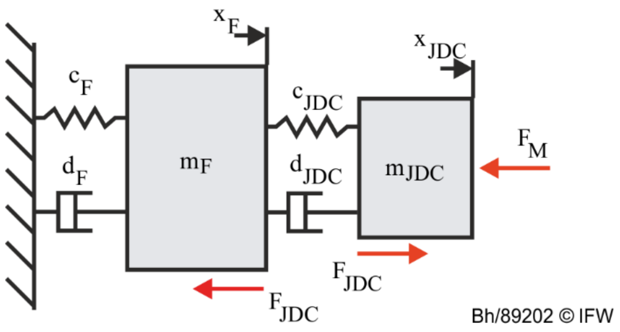

Figure 2. Mechanical model of the feed-drive

The mechanical model is represented with $\underline{q} = [x_{JDC} \quad x_F]^T$ to:

$$\begin{pmatrix} \mathrm{m}_{JDC} & 0 \\ 0 & \mathrm{m}_F \end{pmatrix} \ddot{q} + \begin{pmatrix} \mathrm{d}_{JDC} & -\mathrm{d}_{JDC} \\ -\mathrm{d}_{JDC} & \mathrm{d}_F + \mathrm{d}_{JDC} \end{pmatrix} \dot{q} + \cdots$$

$$\begin{pmatrix} \mathrm{c}_{JDC} & -\mathrm{c}_{JDC} \\ -\mathrm{c}_{JDC} & \mathrm{c}_F + \mathrm{c}_{JDC} \end{pmatrix} q = \begin{pmatrix} -1 & 1 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \mathrm{F}_M \\ \mathrm{F}_{JDC} \end{pmatrix} \qquad (1)$$

Where x_{JDC} and x_F represent the displacements of the JDC-carriage resp. of the machine frame. For using a full state feedback strategy, the equation (1) has to be transformed into the state-space-model where the state-space-vector is:

$$\underline{x} = [x_{JDC} \quad x_F \quad \dot{x}_{JDC} \quad \dot{x}_F]^T \qquad (2)$$

The approach of the controller design is to minimize the amplitude of the disturbance frequency responses. The disturbance is represented by the force F_M resulting in the displacements x_F resp. x_{JDC}. To realise a high damping for a wide range of frequencies without a resonance amplitude, the eigenvalues of the closed-loop are selected in such a way, that the DOF have first-order system properties. The corresponding cut-off frequency is set to 40 Hz. The product of the resulting feedback vector K and the state-space-vector $\underline{x}$ defines the force F_{JDC} of the jerk-LDD.

4. Simulation results

In this section, the results of the simulation are presented and discussed. The system without passive JDC is compared to the passive JDC and the active JDC. The main focus is on analysing the disturbance frequency response. The parameter of the mechanical model are based on the test-rig and listed in table 1. The values of the JDC-spring-damper-elements are varied in the simulation.

Table 1 Parameter values of the test rig

Parameter	Value
m_F	3.8×10^3 kg
c_F	6.9×10^8 N/m
d_F	1×10^5 N/s
m_{JDC}	150 kg

Figure 3 illustrates the frequency response of the machine frame excited by the reaction-force F_M of the main-LDD. It can be seen, that the passive JDC (blue) damps the resonance peak of the frame (red dashed). However, a further resonance is added. The further JDC-resonance varies in amplitude and resonance frequency depending on the stiffness of the JDC-spring-element. The JDC-resonances can be seen at 10 respectively 30 Hz. Furthermore, figure 3 shows that the active-JDC is able to reduce the amplitude of the frame- and JDC-resonances. The frequency-response of the active JDC is independent (with a new setting of the K vector) of a spring-stiffness variation. Figure 4 shows the frequency response of the JDC-carriage x_{JDC} excited by the reaction force. It can be seen, that a lower JDC-stiffness results in a higher amplitude of the JDC-carriage (the counter-motion). In comparision to the passive-JDC, the active JDC reduces the amplitude to a lower level independend of the JDC-stiffness.

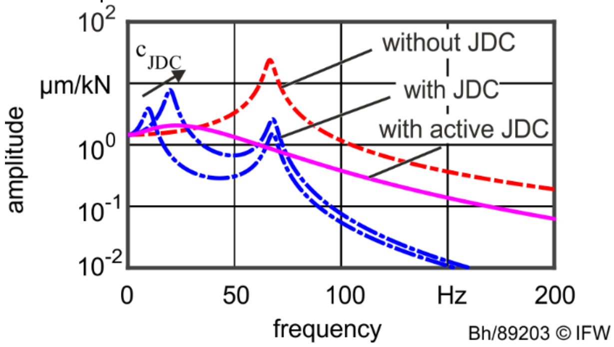

Figure 3. Disturbance frequency response x_F/F_M

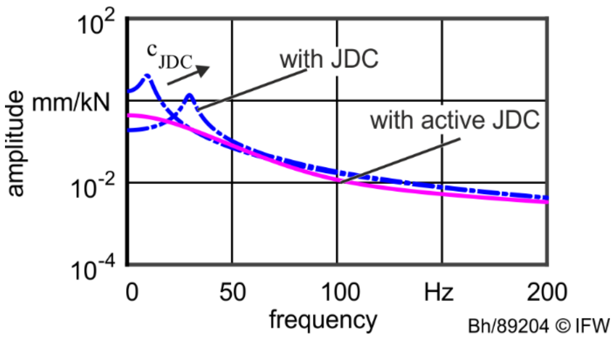

Figure 4. Disturbance frequency response x_{JDC}/F_M

5. Summary and conclusion

A hybrid concept for active JDC is presented and a full state feedback control strategy is introduced. The comparison of the simulation results of passive JDC and active JDC shows that an active jerk decoupling reduces the amplitude of the frame- and jerk decoupling resonances.

An active JDC achieves the same advantages as a passive JDC without adding a further resonance to the system. Not acceptable large displacements of the JDC-carriage (counter motions) due to the JDC-resonance can be prevented.

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