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Procedia CIRP 46 (2016) 189 – 192

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7th HPC 2016 – CIRP Conference on High Performance Cutting

Kinematically Coupled Force Compensation – design principle and control concept for highly-dynamic machine tools

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Abstract

Today, the dynamics, especially acceleration and jerk, of machine tools are limited in order to reduce excitations of machine structure vibrations to an acceptable level. A novel approach - the Kinematically Coupled Force Compensation (KCFC) - combines the principles of redundant axes and force compensation to further increase machines' dynamics. In this paper, the new principle is introduced and possible control concepts are compared based on an analysis in frequency and time domain. Simulations, using a simple multi-body simulation model implemented in MATLAB/Simulink®, show, that machine structure vibrations can be reduced significantly by KCFC.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair
Prof. Matthias Putz

Keywords: Machine tool; Control; Compensation

1. Introduction

Motion guided machine systems (in particular machine tools, industrial robots and handling systems) build the basis of industrial production. They contribute significantly to value creation in the process of manufacture. In order to increase the productivity of motion guided machine systems, numerous approaches like parallelisation, process integration [1] and the reduction of non-productive time are already being implemented. Since those measures are often maxed out, only the increase of motion dynamics can help to achieve higher productivity. For this purpose electric direct drive technology is applied because it eliminates mechanical transmission elements and thereby opens up ranges of maximum motion dynamics [2]. However, an increase in motion dynamics leads, mainly in consequence of higher acceleration and acceleration forces, to a stronger vibrational excitation of machine structures. As a result, in many cases motion accuracy and product quality are reduced.

2. Methods for the reduction of vibrations and vibration excitation in highly-dynamic machine tools

A variety of methods are known to reduce vibrations and vibrational excitation of machine systems. Currently approaches of structural lightweight construction, in particular by using fiber-reinforced plastics, are increasingly pursued [3]. Methods for passive and active vibration reduction or reduction of vibrational excitation are also topics of current research [4]. With regard to the method of Kinematically Coupled Force Compensation (KCFC) the principles of reaction force compensation [5] as well as redundant axis configurations [6] are discussed below.

Force compensation cancels out reaction forces that are induced into the lower-level machine structure by the feed drive. In order to realise this strategy, a second, counteracting compensation drive is used.

In redundant axis configurations, the motion of the Tool Centre Point (TCP) is divided into the sluggish motion of a heavy basis axis and the dynamic motion of a lightweight additional axis. Basis axis and additional axis can be arranged in series (based on each other) or in parallel (both based on

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doi:10.1016/j.procir.2016.03.198

the underlying structural assembly). Redundant axis configurations usually provide a reduction of the drive’s reaction force, as the highly dynamic motion components are executed by the lightweight additional axis.

3. Kinematically Coupled Force Compensation

3.1. Basic concept and derivation of the principle

The method of Kinematically Coupled Force Compensation (KCFC) [7,8] can be interpreted as a combination of a parallel redundant axis configuration (with $x_{TCP} = x_1 - x_2$) and the principle of reaction force compensation (see Fig. 1). In order to achieve a complete cancellation of reaction forces, Eq. (1) must be fulfilled best possible (friction is neglected):

$$F_1 = m_1 \cdot a_1 \equiv m_2 \cdot a_2 = F_2 . \tag{1}$$

Thus, the kinematic constraint for the motion of the slides 1 and 2 is as follows:

$$K_m = \frac{m_2}{m_1} = \frac{x_1}{x_2} = \frac{v_1}{v_2} = \frac{a_1}{a_2} = \frac{j_1}{j_2} . \tag{2}$$

K_m is the mass ratio of the two slides. Considering Eq. (2), KCFC requires that the highly dynamic and lightweight axis has a larger traverse than the slower and heavier axis, in order to accomplish full cancellation of reaction forces.

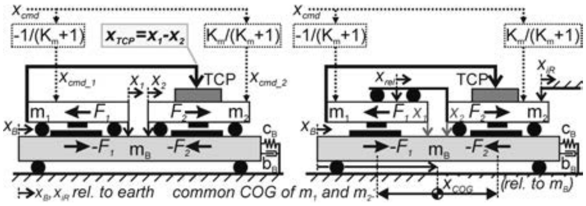

Fig. 1. Principle of KCFC (according to [7,8]): left – standard type; right: KCFC with relative linear guidance and relative measuring system x_{rel}

Since the parameterisation of the cascade control (P - position, PI - velocity and PI - current control) significantly influences the resulting force pulse, Eq. (1) must be extended to derive the correct controller configuration. Assuming a PI - speed controller in parallel arrangement and supposing identical values for position control gain ($K_{V\_1} = K_{V\_2}$) and force constants ($K_{Mot\_1} = K_{Mot\_2}$) of the linear motors, the equation for parameterisation of the velocity controller (current control idealised as gain = 1) is:

$$K_{P\_i} = K_{P\_0} \cdot \frac{m_i}{m_0} . \tag{3}$$

The index 0 stands for any axis of reference with the moving mass m_0.

3.2. Guiding and measuring systems for KCFC

For the parallel redundant axis configuration of the KCFC three alternative guiding arrangements can be derived: the guiding of both slides relative to the base (Fig. 1, left); the guiding of one slide relative to the base and the second slide relative to the first one (Fig. 1, right) and a combination of the aforementioned configurations. Below it is assumed that the guidance for each slide is arranged relative to the base. The other guidance configurations will be content of later investigations.

Three basic configurations can be used for the arrangement of position and speed measurement systems in KCFC-axis: the measurement between the slide and the base (e.g. x_1 in Fig. 1, left); the measurement relative between the two slides (e.g. x_{rel} in Fig. 1, right; indices *relP* and *relP&V* in Fig. 2) and the measurement relative towards an independent reference (e.g. x_{iR} in Fig. 1, right). This opens up 3•3 = 9 possible configurations for the position and velocity measurement system. The combinations with measurement relative towards an independent reference (e.g. x_{iR} in Fig. 1, right) are not considered because they are not technically feasible. In the following, the configurations with position and velocity measurement relative to the frame, with relative position measurement between the slides (index *relP* in Fig. 2) and with relative position and velocity measurement between the slides (index *relP&V* in Fig. 2) are considered. The configuration with relative velocity measurement (index *relV*) is excluded because it is unstable with regard to the analysis of the pole-zero map [9].

3.3. Alternative control concepts for KCFC

Similar to the arrangement of guiding or measuring systems relatively between both slides (Fig. 1, right) an overlaid controller cascade can be formed for the KCFC. In case of a separate cascaded control for each slide (*Single Axis Control* - A in Fig. 2) the relative movement x_{rel} is not fed back into the control loop. With a superimposed position control loop (*Superimposed Position Control* - SP in Fig. 2) or a superimposed position and velocity control loop (*Superimposed Position and Velocity Control* - SPV in Fig. 2) the relative movement x_{rel} is actually controlled. However, in the latter two configurations the common degree of freedom of both slides relative to the base (see x_{COG} in Fig. 1, right) is not bounded. In order to control x_{COG} an additional centring control (*Centring Control* - CC in Fig. 2) was supplemented for the superimposed position and velocity control (SPV).

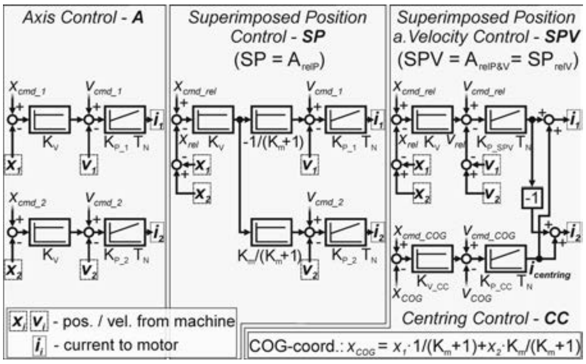

Fig. 2. Control concepts for KCFC (according to [7])