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Mechanically coupled high dynamic linear motors – A new design approach and its control strategy

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ABSTRACT

Improved drive dynamics decisively boost productivity and accuracy of machine tools. Linear motors have advantages to overcome drawbacks of electromechanical drives, but are limited by their power density. Reaction forces of linear motors cause undesired excitation of the machine structure. Current research approaches focus on impulse decoupling and compensation as well as on force reduction. The paper presents a new design approach, characterised by two mechanically coupled and opposite driving linear motors. This arrangement improves the static and dynamic properties by force distribution which leads to an impulse-free feedback system. In order to have an effective use of the gained dynamics various control structures for coupled drives are investigated. Tuning methods as well as simulation and experimental results are discussed.

1. Introduction

Enhanced dynamics of machine tools is of contemporary interest due to multiple reasons: first, higher dynamics results in a shorter machining time, which makes it a key to energy efficiency [1]. On the other hand, new manufacturing processes, for example non-circular machining, are only possible through higher feed dynamics. Current research activities associated with the design of machine tools include structural concepts such as use of parallel kinematics [2], lightweight design, for example with the use of CFRP [3]; and specifically damped [4,5] and effective feed drive systems [6,7]. Feed drives, consisting of an elastic drive train that represents a multi-mass system, have acquired a key role in literature. In particular, their dynamics have a decisive impact on the productivity and quality of machined components [8]. An analysis of the operating drive systems suggests that a majority of systems use mechanical transmission elements. Direct drives generally find a wide application in the case of rotatory axes [8,9], but due to their limited power density and economic factors translatory direct drives are often not used in production systems.

2. Design concept

2.1. State-of-the-art of feed drives

The advantage of drive systems that use mechanical transmission elements (Fig. 1I) lies in their easy adaptability to different applications. The moving masses and the combined stiffness of the transmission elements are factors that contribute towards limiting the dynamics of these drives, as depicted in Fig. 2 for the typical feed drives used in a machining centre. These result in a weakly damped low first eigenfrequency of the drive system. Furthermore, the classical cascaded servo control of feed drives limits the potential for improvement of the control performance with regard to the set point and disturbance behaviour. From a technical perspective, it has long been confirmed that linear direct drives (Fig. 1II) have the potential to overcome the above described mechanical limitations. However, in order to effectively implement linear direct drives, it is required to minimize vibrations and excitation forces of the machine base, to realize a compact design solution to increase feed force, as well as integrate an efficient counterbalance mechanism. The effective utilisation of linear drive technology will also open up new economic prospects. The available literature offers various solutions, in particular in a range of topics related to power increase (Fig. 1III), vibration minimization and prevention (Fig. 1IV). An overview of the existing research approaches is presented in Fig. 2(A). The existing available approaches lack strategies that completely compensate

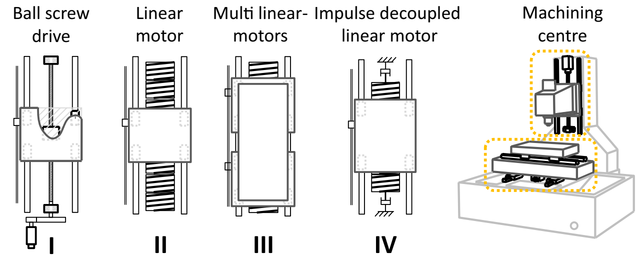

Fig. 1. Typical feed drives of a machining centre.

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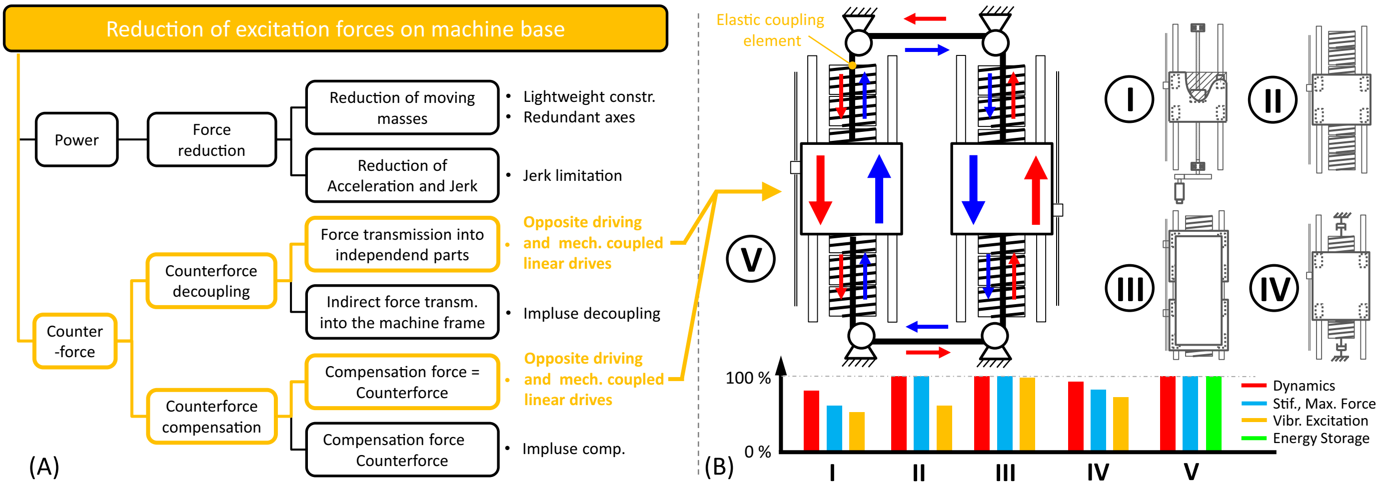

Fig. 2. Research approaches for reduction of excitation forces into machine base (A). New structure of opposed driving, mechanically coupled linear motors and its properties in comparison with other typical feed drives (B).

the counterforces or allow them to be transmitted into frame independent components.

2.2. New design approach

A novel approach to reduce counterforces can be derived by a holistic approach on the mechanical and servo control structure based on a highly dynamic, force decoupled feed drive system, as schematically illustrated in Fig. 2(B and V), characterised by two mechanically coupled linear motors that move in opposite directions relative to each other. A fundamental advantage of this structure is its ability to distribute the drive force between the two motors by the coupling of an elastic movable element (e.g., tooth belt with steel reinforcement), as a result of which both drives can be downsized and the force remains in the complete frame in the form of a circulating force. Besides this new approach of force decoupling (Fig. 2(A), orange), this drive structure allows a complete compensation of the reactive forces so that the dynamics can be improved, which facilitates further investigation into the still open research area of force compensation. This mechanical structure has also a high relevance for vertical applications, since in case of error (malfunction, failure), both forcers can balance and compensate each other, which can lead to deduction of new application fields as well as cost savings for linear motors in production systems. Besides the effect of minimizing the reactive forces, the presented drive structure also allows the storage of energy in the mechanical coupling elements which can be specifically used to cover power peaks. Due to the low mechanical need for action, an effective control strategy is inevitable, including both drives and their interaction. For best possible utilisation of the gained dynamics, the following section discusses a selection of the various control structures for coupled drives and the necessary parameterisation.

3. Control structures

The main features of all following control concepts and structures are based on an industrial servo control. These concepts have been established as an industry standard due to their good parameterisation and extensibility, its good dynamic characteristics as well as possibilities of implementation of safety related features on different control levels. Since pure servo control is limited in its degrees of freedom, different extensible control concepts have been investigated. They also include additional feedback and feedforward control paths with controls and filters. All these concepts have a good parameterised control cascade, thus, first of all their parameters should be selected as discussed in Section 3.1.

3.1. Parameterisation of a servo control

The innermost control loop of a servo control consists of a PI-current controller with current set point filters and a cascade current control loop. Its dynamic behaviour can be represented by a first order transfer function with dead time in the following form:

$$G_{\mathrm{sub,i}}(s) = \frac{e^{-T_{\mathrm{dead,i}} \cdot s}}{T_{\mathrm{sub,i}} \cdot s} + 1 \tag{1}$$

The dead time $T_{\mathrm{dead,i}}$ and the substituted time constant $T_{\mathrm{sub,i}}$ of the current control loop depend upon the electrical characteristics of the motor as well as the power and processing speed of the power electronics and control. The PI-current controller is usually set according to the optimum amount as in [10] since further optimisation approaches offer only slight improvement. Next, the PI-speed controller with its gain K_p and its integral time $T_{\mathrm{N,v}}$ has to be tuned. For this purpose, the open speed control loop can be represented as an $\mathrm{IT_1PDT}$-model:

$$G_{\mathrm{o,v}}(s) = K_{\mathrm{p}} \cdot \left(\frac{T_{\mathrm{N,v}} \cdot s + 1}{T_{\mathrm{N,v}} \cdot s}\right) \cdot \frac{1}{J_{\mathrm{sum}}} \cdot \frac{e^{-T_{\mathrm{dead,i}} \cdot s}}{T_{\mathrm{sum,v}} \cdot s} \tag{2}$$

Once the total inertia J_{sum} as well as the substituted time of the speed control loop $T_{\mathrm{sum,v}}$ has been determined, a suitable parameter for this model type can be chosen on the basis of a variety of rules [11] for parameter selection. It was found that the adjustment rules of the symmetrical optimum, Shinsky I as well as Samal allow for good system dynamics. Their parameters can be found in Table 1.

As the last control loop, the P-position controller with the feed forward control K_{pc} and the symmetry filter T_{vtc} is parameterized. The transfer function of this closed loop is represented as:

$$G_{\mathrm{c,x}}(s) = \frac{K_{\mathrm{V}}}{T_{\mathrm{sub,v}} \cdot s^2 + s + K_{\mathrm{V}}} \tag{3}$$

After the determination of the equivalent time constant $T_{\mathrm{sub,v}}$ of the underlaid velocity control loop, a suitable parameter for the

Table 1
Tuning parameters for PI velocity controller [11].

	K_{P} [$N_{\mathrm{s/m}}$]	$T_{\mathrm{N,v}}$ [ms]
Symmetrical optimum	$\frac{0.5 \cdot J_{\mathrm{sum}}}{T_{\mathrm{sum,v}} + T_{\mathrm{dead,i}}}$	$4 \cdot (T_{\mathrm{sum,v}} + T_{\mathrm{dead,i}})$
Shinskey I	$\frac{0.556 \cdot J_{\mathrm{sum}}}{T_{\mathrm{sum,v}} + T_{\mathrm{dead,i}}}$	$3.7 \cdot (T_{\mathrm{sum,v}} + T_{\mathrm{dead,i}})$
Samal	$\frac{\pi}{4} \cdot \frac{J_{\mathrm{sum}}}{T_{\mathrm{sum,v}} + T_{\mathrm{dead,i}}}$	$3.3 \cdot (T_{\mathrm{sum,v}} + T_{\mathrm{dead,i}})$