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Adaptive preloading for rack-and-pinion drive systems

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ABSTRACT

In the field of machine tools, rack-and-pinion drive systems are one of the commonly used feed drive systems. In order to achieve the high accuracy specifications of modern production facilities, these drives are electrically preloaded to reduce backlash in the drive train. In most cases, the preload is fixed, even though the method of electrical preloading allows adjustment during operation.

This paper describes a novel approach – called adaptive preloading – to adjust preload during operation. The objective is to increase the drive system's energy efficiency by continuously adapting the preload, which is minimally required for maintaining the drive system's accuracy.

1. Introduction

The manufacturing quality and dynamics of modern production facilities are mainly influenced by the used electromechanical feed drive system. The drive system defines the attainable drive force and acceleration, positioning and path accuracy and the static and dynamic rigidity of the machine axis [1]. The most common drive systems are ball-screw drives (BSD), rack-and-pinion drives (RPD) and linear direct drives (LDD). The choice mainly depends on the application and the associated costs.

1.1. Rack-and-pinion drive systems

For use in large machine tools, RPD are particularly characterized by the fact that their stiffness, unlike the otherwise established BSD [2], is independent of the traveling distance, as the feed force is directly transmitted from the motor, stocked with a gearbox, to the contacting teeth of the rack and the pinion [3,4]. The stiffness of BSD depends on traveling distance, spindle diameter and current position of the machine table [5]. In order to ensure sufficient stiffness with increasing traveling distance, the spindle diameter has to be increased. This leads to a reduction of the drive dynamics due to the increasing spindle moment of inertia. Thus, BSD cannot be operated efficiently for traveling distances larger than 5 m [6]. LDD are also applicable in large machine tools. However, the high energy consumption as well as the secondary parts required over the entire traveling distance have a negative effect on costs compared to RPD [1].

1.2. Method of electrical preloading

A central problem of electromechanical feed drive systems is the backlash in the drive train. In the case of RPD, the backlash is caused by the gearing and bearing in the gearbox as well as by the rack-and-pinion coupling. It influences the attainable positioning and path accuracy and the control quality of the drive system due to its non-linearity transfer behavior. In order to meet the requirements of modern production facilities, additional measures to reduce backlash are necessary. The backlash in the drive train can be reduced by preloading two pinions arranged in parallel. Various mechanical and electrical methods for preload generation are mentioned in literature [1–3,7–10].

This paper focuses on the method of electrical preloading, as it is the only method, which allows preload adjustment during operation. The preload torque

$$\tau_p = K_{w,1}\tau_{ref,1} - K_{w,2}\tau_{ref,2} \tag{1}$$

is defined as the weighted difference between the motor's reference torques $\tau_{ref,1}$ and $\tau_{ref,2}$. Commonly, the weightings $K_{w,1}$ and $K_{w,2}$ are set to 0.5. They can be adjusted, if different motor types or transmission ratios are used. Three control structures for preload generation are listed in literature and summarized in Ref. [6]. This paper focuses on the industrially used torque balancing controller, shown in Fig. 1. The preload torque τ_p is controlled by a P-controller, which generates a velocity value v_{add}. This value is added, respectively subtracted, to the reference velocity v_{ref} for each drive train to maintain preload. The controller gain K_b is used to set the dynamic behavior of the torque balancing controller. According to Ref. [11], the controller can be experimentally designed by velocity step responses.

The motor reference torques $\tau_{ref,1}$ and $\tau_{ref,2}$ and the feed torque τ_{feed}, which is the sum of $\tau_{ref,1}$ and $\tau_{ref,2}$ and identical with the overall reference torque τ_{ref}, are shown in Fig. 2 as a function of τ_{ref}. In case of constant preloading (left graph) with the preload torque $\tau_{p,c}$, the curves of $\tau_{ref,1}$ and $\tau_{ref,2}$ are parallel. If $\tau_{ref,1}$ reaches the maximum motor torque τ_{max}, $\tau_{ref,2}$ is still lower than τ_{max}. This

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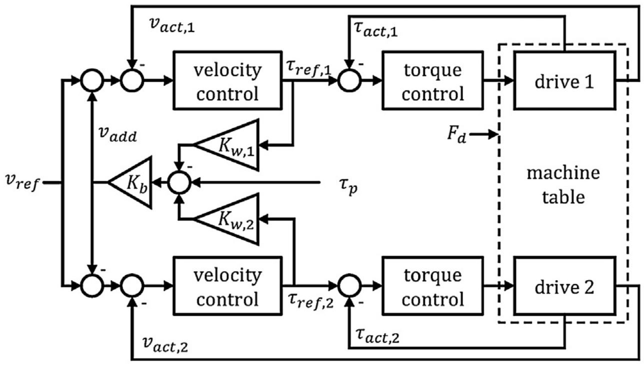

Fig. 1. Torque balancing control structure [based on Ref. [12]].

leads to a reduced and preload depending maximum feed torque

$$\tau_{\text{feed,max,a}} = 2(\tau_{\max} - \tau_{\text{p,c}}). \tag{2}$$

To avoid this dependency, it is possible to decrease the preload proportionally to the quantity of τ_{ref} (right graph). This in commercially available control systems [13] already applied method is called motion adaptive control. It leads to a preload independent maximum feed torque

$$\tau_{\text{feed,max,b}} = 2\tau_{\max}. \tag{3}$$

Despite preloading, backlash still occurs. In static state, which means standstill of the machine table, backlash occurs during sign change of the torque of one motor. Details are given in Ref. [6]. In dynamic state, which means acceleration of the system, the occurrence of backlash depends on the relationship between the accelerated moments of inertia and masses. Details of the occurrence of backlash are discussed in Section 2.2.

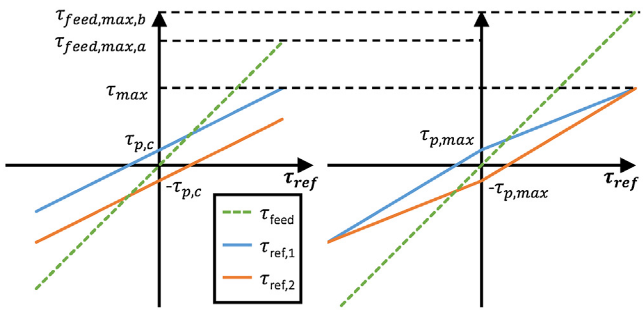

Fig. 2. Characteristic curves for constant preloading (left) and motion adaptive control (right).

2. Concept of adaptive preloading

The method described as motion adaptive control in Section 1.2 is a first approach of adaptive preloading. It solves the problem of reduction of the maximum total torque. However, it is not the optimal adaptive preloading strategy, as preload is still generated in operating conditions, in which it is not necessary to maintain the accuracy reached by constant preloading. For efficient machine operation, it is essential that preload only is generated in operating conditions, in which a reduction of preload torque would cause a degradation of accuracy. Thus, a concept of minimum preloading during operation is desired. To develop this concept, three criteria are defined in Section 2.1. Based on these criteria, an optimization of the characteristic curve is developed in Section 2.2.

In general, preloading is only necessary in operation modes, in which the maximum drive system's accuracy is required. Otherwise it can be deactivated. The detection of these modes is not subject of the presented concept. It is assumed that the maximum accuracy has to be maintained.

2.1. Criteria for efficient operation

To reach the objective of efficient machine operation three essential criteria were identified during the development of the novel concept of adaptive preloading. These criteria are:

1. No reduction of maximum feed torque caused by preloading.
2. No preloading, if it is not necessary to maintain the accuracy reached by constant preload torque.
3. Minimum preloading during operation to maintain the accuracy reached by constant preload torque.

Criterion 1 is already satisfied by the method of motion adaptive control. Criterion 2 is defined for the operating conditions, in which backlash cannot occur. Thus, within these conditions, preloading is not required. Criterion 3 is defined for the operating conditions, in which backlash might occur. Within these conditions, the minimal required preload torque has to be defined.

2.2. Design of characteristic curve

The defined criteria demand a minimization of the area A_p enclosed by the curves of $\tau_{ref,1}$ and $\tau_{ref,2}$. This area is related to the energy, which is consumed by preloading. In a first step, A_p is reduced by defining a minimally required preload torque $\tau_{p,0}$ at $\tau_{ref} = 0$. For this, the friction within the system has to be considered. Especially stiction prevents movement. In detail, a pinion is not rotated until the driving motor overcomes the stiction torque of its drive train $\tau_{s,1}$ respectively $\tau_{s,2}$. To reach contact between the rack and the pinions and thus, a defined position of the machine table, it has to be fulfilled that

$$\tau_{p,0} > \max(\tau_{s,1}; \tau_{s,2}). \tag{4}$$

In a second step, A_p is minimized by defining a limit value, at which preload can be deactivated. For this, the stiction of the machine table has also to be considered, as $\tau_{p,0}$ is not sufficient to move the machine table, since the stiction torque $\tau_{s,t}$ of the machine table must also be overcome. Thus, during movement, it has to be ensured that the system is preloaded until the motor torques $\tau_{ref,1/2}$ reach the summed stiction torque $\tau_{s,1/2} + \tau_{s,t}$. This issue leads to the definition of a limit torque value

$$\tau_{\text{off}} > \max(\tau_{s,1}; \tau_{s,2}) + \tau_{s,t}, \tag{5}$$

at which preload can be deactivated. The definitions (4) and (5) in combination with the requirement of monotonically increasing torque values result in the characteristic curve, shown in Fig. 3. The torque values have to be monotonically increasing, as a reduction of one motor torque during increasing τ_{ref} would result in an excessive load on the other motor. Summarized, the preload torque τ_p is minimized and thus, criterion 3 is achieved. It is calculated as a function of τ_{ref} by

$$\tau_p(\tau_{ref}) = \begin{cases} \tau_{p,0}, |\tau_{ref}| \leq |2(\tau_{off} - \tau_{p,0})| \\ \tau_{off} - \frac{1}{2}|\tau_{ref}|, |2(\tau_{off} - \tau_{p,0})| < |\tau_{ref}| < |2\tau_{off}| \\ 0, |2\tau_{off}| \leq |\tau_{ref}| \end{cases}. \tag{6}$$

Fig. 3 shows that preloading is deactivated in sectors 1 and 3. Thus, it has to be proved that backlash cannot occur within a torque range higher than $2\tau_{off}$. In order to identify the torque range, in which backlash can occur, the relationship of forces, respectively torques and accelerations, in the system is investigated. All relevant quantities are outlined in Fig. 4. There are both translational and rotational quantities. The quantities can be converted into each other by means of the gear ratio and the pinion diameter.

Backlash occurs, because the contacting flanks of rack and pinion change from one side to the other. For positive feed torques the flank change arises, if

$$\varphi_{1+t} \equiv \varphi_2 \tag{7}$$