ACTA TECHNICA CORVINIENSIS
– Bulletin of Engineering
Tome X [2017]
Fascicule 2 [April – June]
ISSN: 2067 – 3809

1.Peter ZAHN, 2.Michael NEUBAUER, 3.Armin LECHLER

DIFFERENT APPROACHES TO IMPROVE THE DYNAMIC BEHAVIOR OF MACHINE TOOL FEED DRIVES

1-3.University of Stuttgart, Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), Seidenstraße 36, Stuttgart, GERMANY

Abstract: To increase productivity and efficiency of industrial machine tools, one important aspect is the dynamic behavior of their feed drives. At the Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW) of the University of Stuttgart, various approaches, based on constructive methods, control engineering or additional actuators were examined, which can influence the dynamic behavior in a positive way. In this paper, exemplary solutions are presented with their benefits and drawbacks to provide an overview on the currently ongoing research work. For validation and illustration of the different principles, simulative and experimental results are presented.
Keywords: machine tool feed drives, control, dynamic behavior

INTRODUCTION AND MOTIVATION

Feed drives in machine tools are needed to perform a relative movement between workpiece and tool as defined in a NC program. Nowadays, electromechanical servo drives are typically used for this purpose, which are configured either as direct drive or used with additional mechanical gear elements such as *ball screw drives* (see [1] as an overview).

Primary goals of dimensioning and control of feed drives are on the one hand the exact tracing of a given target contour with low latency. On the other hand, static and dynamic disturbances, for example process forces, shall be optimally compensated. The dynamic behavior not only influences machining accuracy and manufacturing time, it also has an impact on wear and damages of machine and tool.

For the feed drive system, which consists of mechanical, drive and control components these targets lead to two basic properties: high accuracy and good dynamic behavior, guaranteed under all predictable operating states. In the following text, an overview of different cross-domain approaches is given, which target on improvements in the dynamic behavior of feed drives. So they can help to expand the area of application or enhance the performance of machine tools.

The presented technologies for improved dynamical behavior can be subdivided into three main categories which are shown in Table 1. The following chapters show examples currently under research with their advantages and drawbacks, marked as advantageous (+), neutral (o) or unfavorable (-).

Table 1 – Comparison of different approaches for improved dynamics

	Construction-based	Control-based	Actuator-based
Effort/costs	-	+	o
Robustness	+	o	+
Upgrade capability	-	+	o
System Complexity	+	-	-

CONSTRUCTION-BASED APPROACHES

Construction-based approaches to achieve optimal dynamical behavior can be seen as the classical method. Here, the increased stiffness of all components which are involved in the feed motion is essential. However, a simple oversizing of those components is counterproductive regarding requirements like mass, material and cost reduction. For that reason, two detailed solutions are presented which offer significant improvement potential with moderate expenses.

Constant-level preload force in ball screw drives

Ball screw drives are one typical kind of components in machine tools to provide linear motion. Circulating rolling elements between a threaded spindle and nut transfer forces under rolling friction which leads to an efficient transmission from rotary to linear motion.

Typically preloaded double nuts are used to achieve a high stiffness and avoid backlash.

To provide the needed stiffness and guarantee the rolling contact under all operating conditions, it is important to choose an adequate preload. Simultaneous, the preload shall be chosen as small as possible to reduce friction induced heat generation and component wear. Furthermore, the reduction of the preload force over the lifetime of a ball screw drive due to wear has to be compensated by an initial oversizing.

To cope with these restrictions and achieve an optimal sized preload force over the lifetime, a novel adjustment mechanism is currently under research. It uses a spring-loaded, self-retaining adjustment wedge between both involved nuts as shown in Figure 1. The increased distance between the nuts result in a higher preload force without the need of an external active actuator. Because of the self-retention of the adjustment element, the preload force is only adapted as far as the preload is too small for a reliable operation.

As a result, the ball screw drive autonomously keeps an adequate preload force and ensures a constant stiffness and load capacity over the whole life cycle.

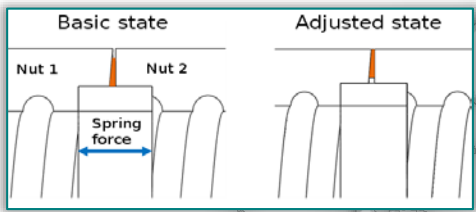

Figure 1 – Function principle of the self-adjusting ball screw double nut

Compliant bearing arrangement in feed drives

The first natural frequency of a feed drive is typically an axial vibration in feed direction and determined by the mechanical construction. This parameter limits the achievable control parameters of the drive so it is preferable to have the first natural frequency at a rather high value with moderate amplitude exaltation.

One construction-based method to deal with this limitation and increase the drive dynamics is an axial compliant bearing arrangement for the ball screw spindle which is enhanced by a strong axial damping element as specified in [2]. With an adequate sizing of the spring stiffness relative to the damping coefficient, the first natural frequency can be shifted significantly to a higher level while simultaneously reducing its amplitude. Figure 2 shows an appropriate frequency response of such a feed drive. The behavior of a typical conventional design with fixed bearing and its visible resonance exaltation is depicted in red. Shown in blue is a feed drive with compliant bearing and reduced exaltation as well as in green with optimal bearing and damping which results in a nearly flat amplitude curve. Based on this behavior, the amplification factor k_V of the position controller can be increased significantly, resulting in enhanced bandwidth of the feed drive.

Crucial for an effective application is certainly a damper with a sufficient high damping coefficient and also a high bandwidth. This aspect is currently a technical limitation of the method.

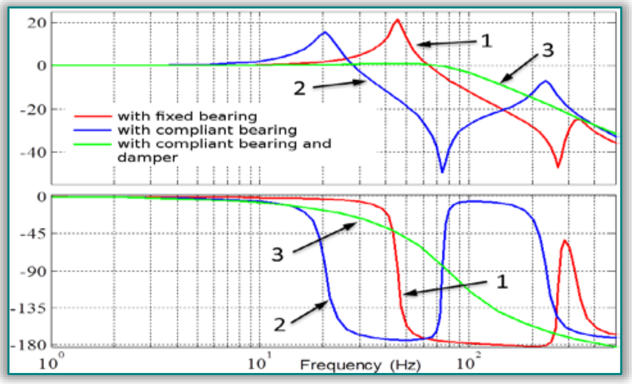

Figure 2 – Simulation-based comparison for a conventional feed drive (red) and optimal sized compliance and damping (green) [2]

CONTROL-BASED APPROACHES

In the field of the control theory, extended structures of the classical cascade control promise an improved dynamic behavior especially for high-dynamic drives. One important factor here is the availability of a linear position sensor on the output side which enables drive-based vibration damping. With the use of novel highly performant controller platforms, the parallel computation of individual system models, the feed-back of additional state variables (like acceleration) for the compensation of non-linear behavior or generally minimizing dead time become practicable. In the following section, two exemplary methods to increase the bandwidth are shown, which are currently under research.

Velocity control for minor gear ratio

To achieve high rapid traverse velocities in feed drives, increasingly smaller gear ratios are chosen in combination with low-inertia, high-dynamic motors. This however also reduces the ratio between the motor and the table related moment of inertia, resulting in a challenge for optimizing the parameters of the controller cascade.

One possible solution is to extend the controller cascade as shown in [3] and depicted in Figure 3. Here, a weakly parameterized rotation speed controller (which is closed with the actual motor speed) is strongly damping the mechanics in the area of the first natural frequency.

An additional linear velocity control loop (shown in red), based on a table-mounted position sensor compensates the damping and raises the phase response in the critical area. As a result, the amplification factor k_V of the position controller can be increased by a factor of two depending on the inertia ratio while maintaining comparable stability and robustness.

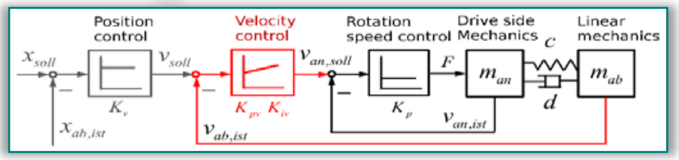

Figure 3 – Extended control loop
for high dynamic drives [3]

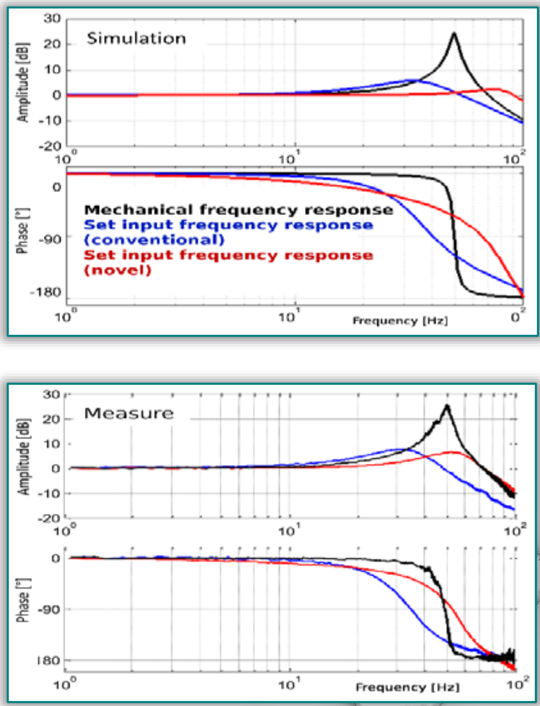

Figure 4 – Comparison of frequency response
(conventional to novel method) [3]

Figure 4 shows the corresponding frequency responses for mechanics (black) and set input for a conventional cascade controller (blue) and the novel, extended cascade (red). The plots are compared between simulation (left) and measurement (right). The higher bandwidth of the novel method and the correspondence between simulation and measurement is clearly visible.

Increased current control bandwidth by sliding mode control

Typically, the bandwidth of the current control with its small electrical time constant is much higher compared to the behavior of the mechanical components, so the current control is not limiting the overall performance of a feed drive. However, there are applications where a high dynamic torque control is demanded, for example to compensate high frequency process forces. One possible controller variant, which increases the bandwidth of the current control is the *direct sliding mode current control* as presented in [4].

The essential characteristic of this method is a modulation technique that minimizes switching processes in the power electronics which reduce bandwidth and energy efficiency. Figure 5 shows a measured comparison between a conventional current controller (red) and a direct sliding mode controller (blue), where the increased bandwidth can be seen from the frequency response.

Important aspects in realizing this controller are an adequate platform for high frequent computations and a current measurement system with sufficient bandwidth.

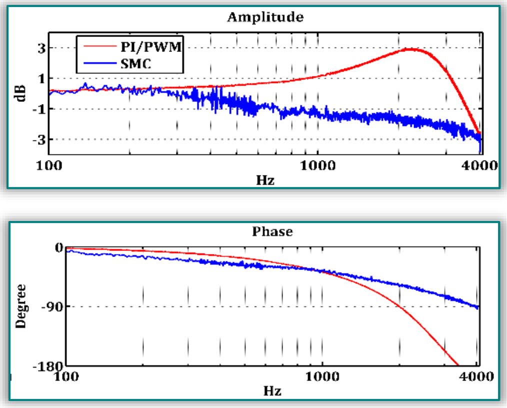

Figure 5 – Comparison of current control bandwidth for conventional (PI/PWM) method and direct sliding mode control (SMC) [4]

ACTUATOR-BASED APPROACHES

Actuator-based approaches for improved dynamic behavior typically request the installation of additional components which can be retrofitted. As a result, they provide new degrees of freedom due to their direct physical influence on the dynamic behavior of the mechanics. One challenge remains the implementation of the needed control logic, especially in commercial drive systems without open interfaces.

Semi-active damping

One exemplary application of an actuator-based approach is the semi-active damping of feed drives as shown in [5]. An additional mechanical friction-based damping actuator is used to reduce the amplitude exaltation at the first natural frequency by directed brake intervention. Subsequently, the choice of the controller parameter is less limited by the mechanics and the overall behavior can be improved.

The damping actuator is triggered in dependence of the difference between motor and linear velocity, so that the damping force is applied only when the table of the feed drive is overshooting. Figure 6 shows the needed extension of the controller cascade for this concept.

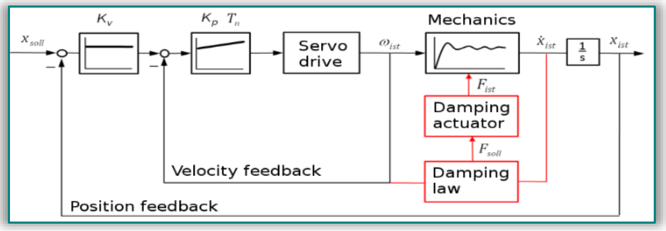

Figure 6 – Extended drive controller with semi-active damping [5]

The provided friction force, which acts between the linear bearing and the table, withdraws vibration energy from the feed drive. Due to the appropriate and short activation of only a few milliseconds, the normal operation is not influenced by the damping force.

Figure 7 shows the effect of the semi-active damping for a position setpoint and a disturbance force step. It is remarkable, that the setpoint step can tracked with significant less deviation and also position errors due to external forces are reduced. As a result, the amplification factor k_V of the position controller can be increased.

This approach creates some extra effort regarding mechanics, control and energy consumption, but the increased drive bandwidth overweigh this drawback.

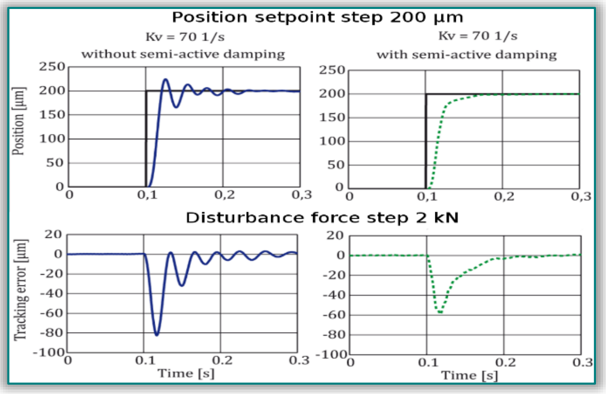

Figure 7 – Improvement potential for position and disturbance step [5]

Adaptive friction in glide bearings

The absolute value of the mechanical friction occurring in linear guides and bearings of a feed drive can also be seen as a damping effect that influences the choice of the maximum controller parameters. Nevertheless, the relationship between this friction force and the speed is non-linear and typically described by a *Stribeck curve.* Moreover, the excessive amount of static friction at low speeds leads to positioning errors.

At the ISW, a novel concept for glide bearing was developed, which uses a piezoactuator to induce ultrasonic vibrations on the contact areas as described in [6]. Depending on the chosen amplitude and frequency of the superimposed vibration, the friction characteristics can be linearized over the complete velocity range. This also improves the positioning accuracy in the field of precision manufacturing processes. By a variation of the ultrasonic vibration, also the damping in the guiding system can be adapted for different operating conditions.

For the implementation of this approach, novel guiding elements are needed which include the piezoactuators. Furthermore, it is necessary to integrate logic and power electronics in the machine if the friction coefficient shall be adapted appropriate to individual process phases.

CONCLUSION AND OUTLOOK

In the previous chapters, different approaches to improve the dynamical behavior of feed drives were presented with their characteristics. They can also be differentiated regarding the needed effort for their implementation, requiring additional hardware or specialized control structures. Construction and actuator-based methods are beneficial regarding robustness, because they are less prone to parameter errors.

Another important criteria regarding the use of such techniques is the availability of adequate open and performant platforms for the implementation of the algorithms. The conducted research has especially identified FPGA-based platforms like [7] as beneficial for such implementations.

Substantial scope of further research projects is currently the transfer of the presented concepts on rotary axis like they are often used in the context of industrial robots. Here, new processes and industrial applications can be exploited with the better dynamic behavior.

Acknowledgement: The authors would like to thank the Deutsche Forschungsgemeinschaft (DFG) for the funding of the research work, especially within the grants VE454/13-2 and LE2904/6-1.

Note: This paper is based on the paper presented at The International Conference Management of Technology – Step to Sustainable Production (MOTSP 2016), organized by the Faculty of Mechanical Engineering and Naval Architecture, Croatian Association for PLM and the University of North, in Porec/Parenzo, Istria, CROATIA, June 01–03, 2016.References

[1] Altintas, Y. et al.: Machine tool feed drives, CIRP Annals - Manufacturing Technology, 60(2011), 779-796.

[2] Pritschow, G. et al.: Ball screw drives with enhanced bandwidth by modification of the axial bearing, CIRP Annals - Manufacturing Technology, 62(2013)1, 383-386.

[3] Sun, Z. et al.: Bandbreite des Vorschubsystems erhöhen, MM Maschinenmarkt, (2015)43, 46-49.

[4] Laptev, I. et al.: Direct sliding mode current control of feed drives, CIRP Annals - Manufacturing Technology, 64(2015)1, 373-376.

[5] Frey, S.: Verbesserung des dynamischen Verhaltens von Vorschubantrieben durch semiaktive Dämpfung, Fraunhofer IRB Verlag, Stuttgart, 2013.

[6] Engel, T. et al.: Adaptive Friction Bearing for Reduction of Stick-Slip Effects, Advanced Material Research, 1018(2014), 351-356.

[7] Frick, F. et al.: Modular Design Approach for Model-Based Drive Control Systems on Reconfigurable Logic, Applied Mechanics and Materials, 704(2014), 380-384.