Journal of Machine Engineering, 2023, Vol. 23, No. 1, 123–132
ISSN 1895-7595 (Print)   ISSN 2391-8071 (Online)

Received: *31 January 2023* / *Accepted: 15 March 2023* / Published online: *16 March 2023*

machine dynamics,
wear effects, feed axes,
cyber-physical-system

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CYBER-PHYSICAL TEST ENVIRONMENT FOR THE IDENTIFICATION OF INTERACTING WEAR EFFECTS IN FEED AXES

For a comprehensive optimization and control of production processes, cyber-physical systems are necessary to include machines' time-dependent properties. These wear effects in machine tools, especially the feed axes, can significantly influence the process quality and are a steady research focus. However, the interaction of wear effects between different feed axes has received little attention. Especially models that represent the combined wear influence of different interacting feed axes on the control parameters and machine dynamics hold great potential. To close this knowledge gap, this paper proposes a cyber-physical test environment to identify the interaction of wear effects in feed axes. For this test environment, the relevant boundary conditions of different feed axes in machine tools and their systematic interaction are presented. Through these conditions, a physical test setup is derived and, analogous to this, a virtual model is created. This holistic approach represents the physical and virtual interaction between different components.

1. INTRODUCTION

For autonomous production plants, especially in Industry 4.0, knowledge about machine availability is becoming increasingly important. The effective utilization of all machines involved in the production is also relevant to increase economic efficiency. In addition to preventing machine downtimes due to not optimal planning of machine utilization, a primary focus is on reducing downtimes due to component wear or failure. This increase in Overall Equipment Efficiency (OEE) can be achieved by active planning of maintenance [1]. This involves maintenance interventions in the production line or the replacement of entire components at the end of their lifetime. These downtimes should be predicted and controlled through means of a digital twin and thus actively scheduled to create synergies with other possible downtimes or to reduce downtime. This planning of the life cycle time of machines and their components requires numerous data from sensors and models of the individual components, which are stored in a digital shadow. The trend in industrial applications today

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https://doi.org/10.36897/jme/162266

is to create digital twins to actively control the lifecycle of machines instead of passive monitoring [2].

In today's production, a wide variety of manufacturing processes are used. Machining tasks are mainly realized by machine tools [3]. Here, machine tool includes milling machines, lathes, or saws. They are, therefore, a fundamental part of the manufacturing of products [4]. Figure 1 shows on the left side the percentage distribution of the causes of machine tool downtime in the case of the known factor dominated by component wear. On the right side, it is shown which subsystems the wear occurs.

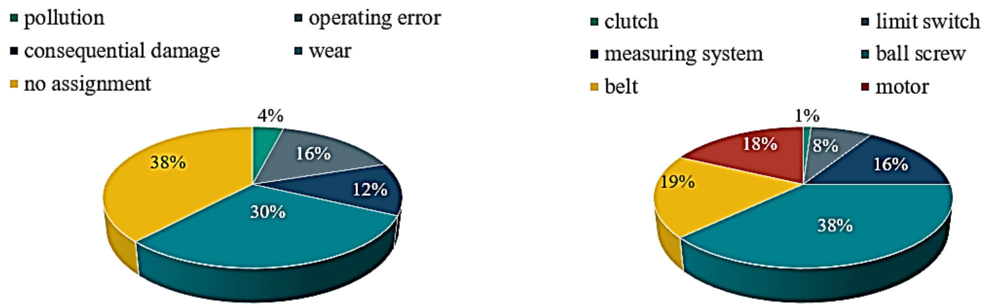

Fig. 1. Distribution of failure cause for feed axes (left) and breakdown of failures by feed axis components (right) [5]

The ball screw is particularly relevant here as an elementary part of feed axes due to an increased probability of failure. In a feed axis, they convert the rotational motion of a motor into a translational movement. Feed axes are predominantly used in industrial composition with more than one axe in a serial structure [3]. The wear of the rolling contact has a particular effect on the positioning accuracy and the stiffness of the feed axis [6]. The idealized load mainly used to investigate wear mechanisms in the current research simplifies complex interacting wear effects and load scenarios to one-dimensional problems and thus neglects corresponding interactions. This is also the case in the design process of ball screw drives and normative lifetime calculation, as these cases always use representative load scenarios and simplify the component strain [7]. This paper proposes an order-based wear concept that will systematically structure this interaction into four classes in relation to their theorized influence and derives a corresponding cyber-physical test environment to holistically investigate the interaction of wear effects and their influence on machine dynamics and control parameters.

2. STATE OF THE ART – WEAR EFFECTS

The changes in the properties of ball screws over their life cycle have been studied since the early 1990s. For this purpose, the focus has been on the various wear mechanisms, which can be divided into four tribological categories. The categories are adhesion, surface disruption, abrasion, and tribochemical reaction [8]. All are caused by relative motion between the balls and the nut or screw. In the ball screw, the effects of these wear mechanisms can be seen in the decrease of the ball diameter, which leads to a backlash within the system [9]. Furthermore, the decrease in the ball diameter in the nut leads to a loss of preload. This loss of preload in the system directly affects the stiffness of the ball screw [10]. Due to the loss of preload, the stiffness of the system is reduced and, in turn, the accuracy of the system under load. To maintain the position, the engine has to feed more due to the higher compliance to readjust the current position. Another phenomenon that occurs due to wear is the surface breakdown (pitting) in the ball orbit, which can lead to (spontaneous) failure of the component [11]. To get a better understanding of the ball screw, with its wear mechanisms and behaviour, various measurement systems have been used over time. Examples are sound microphones [12], acceleration [13, 14], temperature [15], tachometer [16], strain [17], vibration sensors [17, 18], and camera systems [11]. Various sensor principles have been used to characterize and, in some cases, predict the behaviour of ball screws. The developments in sensor technology have made it possible to collect data from which conclusions can be drawn. The trend in recent years is to generate a cyber-physical model of the machine from the sensor data collected from the physical product. This digital twin, or in the first instance, the digital shadow of a machine, opens up new possibilities in the lifecycle control of a machine [19]. Furthermore, digital twins enable machine manufacturers to save costly sensors based on this data and to predict and control the machine's lifetime based on the model with the minimum number of sensors [4]. These developments also offer potential in the area of retrofit of machine tools. Thus, old machine tools can be brought into the digital world without retrofitting additional sensors based on the existing sensor technology. Control parameters and encoder signals from position measurement offer considerable potential here as Data sources for the time-varying properties of these machines. For known relations between different wear effects and their influence on the control parameters, possible interactions between wear effects have to be analysed and classified first. The resulting classes can then be investigated in relation to the scale of their influence on the further wear process. The considerations of the ball screw were carried out exclusively on test benches intended to represent real application scenarios. However, these test environments are mostly limited to applying specific load situations. The effects of varying installation situations play a subordinate role here. Previous studies on this topic are limited, for example, to the impact of angular errors in the motor current of the drive axles [20, 21]. Wear mechanisms resulting from the interaction of two or more axes have not yet been considered in a structured way. However, knowledge about these interactions is particularly helpful in characterizing complex conditions in machine tools as mentioned above. This enables the holistic investigation of the relationship between component wear, especially the stiffness loss and the resulting drift in the machine dynamics in relation to a variation of the control parameters (control deviation).

3. ANALYSIS OF SYSTEM PROPERTIES – INFLUENCE OF WEAR EFFECTS

In all 1-axis tests to date, various factors that characterize the condition and behaviour of the ball screw are analysed. All conclusions were drawn based on a test bench in an idealized 1-axis configuration. There are essential factors, such as the accuracy and stiffness of a ball screw, that significantly influence its operation and the process parameters of the machine tool. This geometric accuracy becomes essential, especially for machines with only an indirect path-measuring system. Systems with direct measurement systems can compensate for these position errors. But this still leads to an influence on the occurrence and timing of process forces. A further influence on the system behaviour results from the wear-induced drift in the dynamic machine characteristics and the static control parameters. These would have to be adapted adaptively, with increasing wear, to the system to compensate for the advancing bias loss to enable optimal utilization of the machine tool. With series-connected axes, the ball screws are perpendicular to each other. The process force is transmitted to the machine bed via linear guides and ball screws. To withstand these loads, both components have a geometrically and materially dependent stiffness that opposes the forces. Using this simplification, it becomes clear that with serial axes, the force flow from the Tool Center Point (TCP) to the machine bed is an interaction of several axes. Thus, the accuracy and resistance of the TCP are also an interaction of the individual axes. Axes wear differently during the operation of machine tools because of different resulting forces and varying movements [22]. Thus, the wear is axis-dependent and not evenly distributed over the entire machine [12]. This axis-dependent wear leads to individual stiffness loss in the different axis [23]. The left part of Fig. 4 visualizes qualitatively this varying stiffness loss of two axes at different rates over the operation time of a machine tool. The loss of stiffness of the identical ball screws is visualized as an example for one location in the workspace.

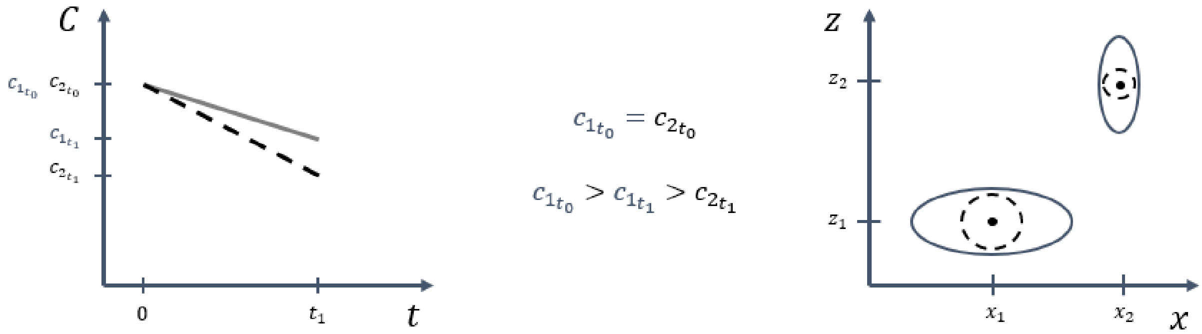

Fig. 2. Exemplary stiffness drift of a ball screw drive and the resulting dimensional-specific stiffness

If we transfer this knowledge to an *X*-*Z* coordinate system, as shown in the right part of Fig. 4, we see different compliance for the two points. Here, the dashed base circle indicates the initial suspension travel ($t = 0$) at the specific location of the coupling elements from Fig. 4 (left side) for a defined force. After a defined usage duration ($t = t_1$) the dominating stiffness loss of the feed axes in the dimension of the ball screw drive distorts the dashed circle in Fig. 4 (right side). This additional loss rate of the two axes is illustrated by forming an oval rather than a circle. Each coupling element shows a stiffness loss that axes dependent and characterizing for the individual dimension. Thus, a force at this point affects the axes differently than in $t = 0$, so the TCP moves differently in the *X*/*Z* direction with the same defined force. This means that micro deviations can occur in 2-dimensional traverse paths, for example, curves, which influence the roundness of the workpiece. These deviations can be compensated using a position measuring system and corresponding position control. For the workpiece in the machine tool, these deviations can manifest themselves as surface effects or in its dimensional accuracy as errors. These errors additionally influence positioning errors of the tool center point (TCP). Error estimation and compensation are broadly researched fields to increase the achievable positioning accuracy further to achieve higher production quality. [24, 25] use rigid bodies for the modelling of the relationship between axes and a rigid coupling of the elements. [26, 27] focus on modelling the stiffness between the machine components and the resulting influence on positioning errors. However, here the static stiffness is constant and will be calculated either initially via a FEM-Model or experimental at the beginning of the life cycle. But the stiffness of the ball screw drives, and through this, the stiffness of the feed axis changes over its lifetime.

4. ORDER-BASED WEAR EFFECT CONCEPT

Changes in the system mentioned above properties, in turn, can cause changes in the load profiles of the corresponding feed axes. A possible analogy can be drawn here to 0'th-order and 1nd-order errors due to the coupling of the axes. Here, the 0'th-order error influences the wear of feed axes resulting directly from the load of the axes. This load transfer to the individual elements is transferred via the individual force components, starting from the direction and proportion. Thus, the nominal case studied extensively in the idealized 1-axis configuration is shown in state of the art. 1st-order errors can influence the wear behaviour resulting from the displacement due to the upstream axis change in stiffness. These cause a variation in the displacement of the tool center point under force and, thus, in the next instance, a change in the load profile of the coupled feed axis. In machine tools, this displacement will be compensated through direct position control. This compensation links the state of wear represented through the static stiffness and the variation in the control difference (encoder signals).

The introduced analogy will be extended to include further possible interactions of wear mechanisms within the system. In addition to the introduced 0th and 1st-order errors, there can also exist 2nd and 3rd-order errors. The 2nd-order error represents a possible degradation of the expected coupling between the two serial axes. This degradation can be a "natural" prestressing loss of screws because of micro-movements between parts resulting from varying load profiles which further induces variations in the load profiles. 3rd-order errors can result from the delta between the considered and the appearing wear situation because of influence through the 0'th, 1st, and 2nd order. Because as shown in [23], there is a significant influence on the lifetime and further wear effects through optimal lubrication. Considering such relations between different stages of interacting wear effects, a comprehensive wear representation is proposed. The resulting axial force $F_{i_{KGT}}(t)$ is defined through the sum of the partial process force $F_i(t)$, the force influence through displacement $F_{i_{\Delta x \| \Delta z}}(t)$ and the force influence through degradation of the coupling between two axes $F_{i_{\Delta c_k}}(t)$. The Force related component wear can now be expressed through $W_{i_n}(t)$. $W_{i_m}(t)$ represents the induced wear influence because of variations in the expect force profile and corresponding lubrication delta to the expected (optimal) lubrication. The total wear of a point i on the screw over time can now be expressed through the cumulated wear $W_i(t)$.

The wear phenomena induced by the wear of the upstream axis (1st order), the degradation of the coupling element (2nd order), and the Lubrication induced wear influence (3rd order) can be investigated using the cyber-physical test environment described in this paper.

Furthermore, a second focus is an influence of interacting wear effects on the control parameters and machine dynamics which can also be investigated using the proposed cyber-physical system.

$$\underbrace{W_i\,(t)}_{\substack{\text{Total wear}\\ \text{of point } i}} = \underbrace{W_{i_n}\left(F_{i_{KGT}}(t)\right)(t)}_{\substack{\text{Axial force-induced}\\ \text{wear}}} + \underbrace{W_{i_m}(F_{i_{KGT}}(t))\,(t)}_{\substack{\text{Lubrication-induced}\\ \text{wear}}} \tag{1}$$

$$\underbrace{F_{i_{KGT}}(c_x(t), c_z(t), c_k(t), F_i)}_{\text{Axial Force}} = \underbrace{F_i(t)}_{\text{0'th order}} + \underbrace{F_{i_{\Delta x \| \Delta z}}\left(c_x(t), c_z(t)\right)(t)}_{\text{1'st order}} + \underbrace{F_{i_{\Delta c_k}}\left(c_k(t)\right)(t)}_{\text{2'nd order}} \tag{2}$$

5. CYBER-PHYSICAL TEST ENVIRONMENT

The Cyber-physical test environment needs to address the above-mentioned constraints, which are also seen in machine tools. Furthermore, a complete digital representation and static as the dynamic model are required to close the knowledge gap in the interaction of wear effects with control parameters and machine dynamics. The relevant constraints represent, on the top level, the most common occurrence of a machine type, the tower setup [3]. This setup has a serial connection of two feed axes in a modular design. With its standardized mounting, this modular design can accommodate a significant variance of ball screws. This possible variation addresses the need to investigate different kinds of ball screws for a necessary generalization of the investigated interaction of wear effects. In contrast to a typical machine tool, this test environment can especially consider this component variation. In addition, manufacturers have static or dynamic models for classical machine tools. Still, these are regarded as company property and thus motivate the need for an independently developed cyber-physical test environment. The development methodology of the corresponding test environment is a multi-stage approach, as shown in Fig. 6. Step 1 is the system analysis and target system definition. The technical configuration describes the defined axes configuration, which is influenced in its realization by defined parameters such as investigated process force range or the corresponding ball screw dimensions. The output of step 1 is a specified configuration for the feed axes and a realization concept. Step 2 addresses the model creation of the CAD and FEM models. The derived CAD model can be revised in an iterative process to respond to necessary adjustments because of results from steps 3 or 4. These two steps focus on the static and dynamic design of the physical test bench. These design steps characterize the virtual model and enable the manipulation of the system properties through the iterative revision of the CAD model. This manipulation focuses on the viable representation from the system properties of classical machine tools. Step 5 implements the virtual model on a modular basis to create a digital shadow of the test bench and complements the test setup to a cyber-physical test environment. The virtual model of the feed axes will be represented through the modular physics-based model of the feed axis and its components, as published in [29].

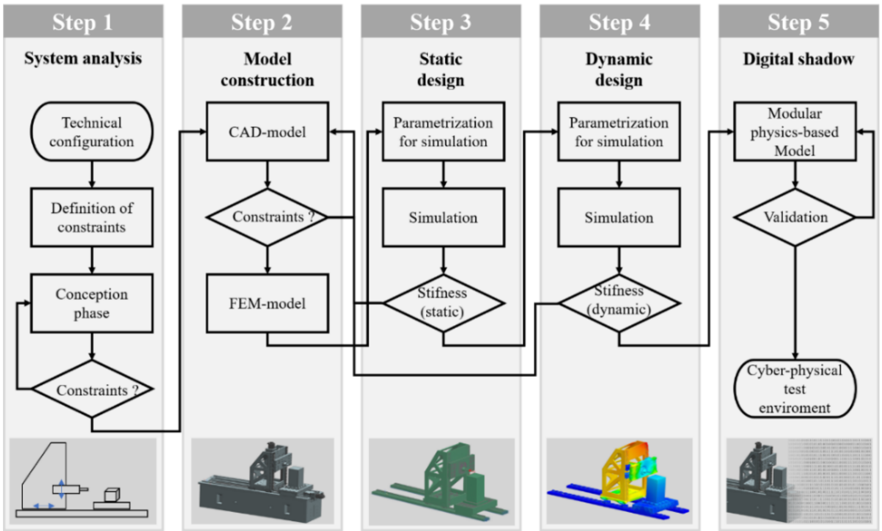

Fig. 3. Methodology for the development of the cyber-physical test environment

For the holistic investigation, especially of the relation between interacting wear effects and control parameters, the modular model proposed by [29] will be extended to include the position control, as shown in Fig. 7. The extracted torque and speed information from the test setup can be passed into the physics-based model of the feed axis components. This model also uses specified characteristics of the individual data sheets and the known physical relationship between components. Addionnaly to standard input parameters such as the rotational speed and torque generating current, the control parameters will also be used in this advanced model. Through the derived relation between current and speed, the resulting net torque can be calculated. This enables [29] the calculation of the resultant net force on the feed axis. The resulting axial force and the additional information on the control deviation will be used to investigate the stiffness loss in the ball screw.

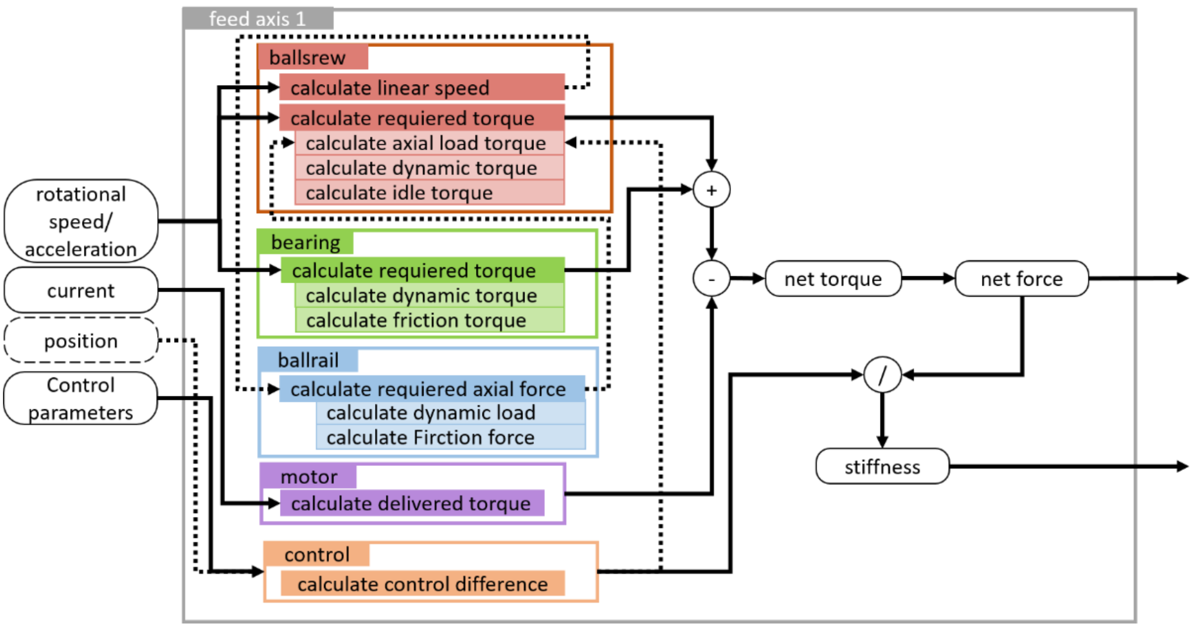

Fig. 4. Advanced Modular physics-based model of the feed axis and its components

The target test environment needs, as specified, a virtual representation in the form of at least an adaptive digital shadow. For a possible investigation of strategies for compensation or improved condition prediction, a digital twin is needed. This digital model with the option of bilateral communication would complement the proposed test environment. This possible additional step 6 would further increase the investigation possibilities of the proposed test environment but will be addressed in future research.

6. TEST SCENARIOS

The serial interconnection of the feed axes enables the investigation of the theorized wear effects or interactions of the different orders. In the first instance, the plausibility and scale of the expected effects of the thematized 1'st order is investigated. For this purpose, two ball screw drives will be integrated into the test environment. The axial force curves at the ball screw drive will be documented over X repetitions for a defined 2-axis load profile. By using 1-axis load profiles, the components will be worn down. At specified points of the nominal service life, tests are repeated with the 2-axis load profile. The time series thus obtained allows the influence of 1st order on the load profile to be quantified. The influence of 2nd order due to degradation in the coupling element can be achieved by selectively influencing the connecting elements (screws) or the joints. Here, the influence can be investigated for distinctive points using a design of experiments and repeated measurements of the axial load profiles at the ball screw drive. Combined with the existing FEM model and a corresponding variation in the modelling of the coupling elements, these results allow a more in-depth and minimal-influence investigation of the degradation effects on the load profile. In the next instance, the influences of the different orders on wear effects can be investigated.

Another main goal of the designed cyber-physical test environment is to investigate the correlation between the wear effects of ball screw drives and the control parameters or encoder signals from the position measurement. Here, the modular model of the feed axis and included control parameters shall enable the sensorless determination of the axis state. By realizing the test environment as a cyber-physical system, it is possible to follow the progressing development along the service life. Furthermore, the resolutions of the effects of the different introduced orders can be examined in relation to the control signals.

7. SUMMARY AND CONCLUSION

The state-of-the-art shows that a significant amount of machine tools have serial feed axes as a way to realize the necessary degrees of freedom. The analysis of the related system properties shows that the axial stiffness of the individual feed axes is coupled through process forces. This relation implies the interaction of wear effects in these feed axes, as modification or variation of the stiffness relates to different time-related force splits into the different dimensions. This variation in the force splits, and the resulting varying load profiles influence the component wear. This paper proposes, on the one hand, a systematic, comprehensive representation of interacting wear effects through an order-based classification. For the investigation of these different interacting wear effects, a cyber-physical test environment is developed. A test environment, as described in this paper, would enable in combination with the above-mentioned test scenarios a detailed research of the different orders of wear influences. For the investigation of these wear effects, especially in relation to control parameters, as a kind of soft sensor, the advanced physics-based modular model will be used. This enables the investigation of interacting wear effects in a holistic approach and creates the basis for further in-depth research.

However, the proposed test environment has to be validated in relation to machine tools to ensure the transfer of the experimental results. Also, the direct relationship between the control deviation and stiffness of feed axes through the axial force is hypothesized and will be addressed in future works.

In future works, the first planned step is the realization, initial characterization, and validation of the cyber-physical test environment. In addition, the system must be fitted with various sensors to ensure capability.

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