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MACHINE TOOL

Experimental derivation of a condition monitoring test cycle for machine tool feed drives

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Abstract

Due to their critical influence on manufacturing accuracy, machine tool feed drives and the monitoring of their condition has been a research field of increasing interest for several years already. Accurate and reliable estimates of the current condition of the machine tool feed drive's components ball screw drive (BSD) and linear guide shoes (LGSs) are expected to significantly enhance the maintainability of machine tools, which finally leads to economic benefits and smoother production. Therefore, many authors performed extensive experiments with different sensor signals, features and components. Most of those experiments were performed on simplified test benches in order to gain genuine and distinct insights into the correlations between the recorded sensor signals and the investigated fault modes. However, in order to build the bridge between real use cases and scientific findings, those investigations have to be transferred and performed on a more complex test bench, which is close to machine tools in operation. In this paper, a condition monitoring test cycle is developed for such a test bench. The developed test cycle enables the recording of a re-producible data basis, on which models for the condition monitoring of BSDs and LGSs can be based upon.

Keywords Machine tool · Feed drive · Condition monitoring · Test cycle

1 Introduction

Machine tool feed drives perform the relative positioning of the tool and the work piece. Hence, their positioning accuracy has a significant influence on the quality of the machining process. In addition, their speed determines the productivity of a machine tool. Due to advances in design and the resulting efficiency and high service life, ball screw feed drives are still the most common feed drive type applied today [1, 2]. In order to assure high positioning accuracy and advantageous dynamics (i.e. high stiffness), the feed drive's ball screw and linear guide shoes are pre-loaded. However, over time and usage a loss in pre-load and a successive loss in manufacturing accuracy can be observed [3]. Therefore, monitoring the feed drive's condition enables improved maintenance, which leads to a more efficient operation of machine tools and can further improve the competitiveness of a machine tool user [4]. Due to that, investigations on the degradation and the condition monitoring of feed drives were subject of extensive research in the past years [5, 6]. However, a majority of those investigations were conducted on simplified test benches, which raises the question how transferable the approaches are to a real machine tool. This work aims at an experimental derivation of a condition monitoring test cycle, which can be applied not only to a simplified test bench but to a real machine tool, and which ensures re-producible and reliable measurements that allow to assess the current condition of a machine tool feed drive. In short, the following contributions are made:

- It is shown how different disturbing factors for condition monitoring test cycles can influence the recorded signals and how they can be controlled such that changes in the signals can actually be correlated with changes in preload conditions.
- A condition monitoring test cycle is derived on a complex test bench, which is similar to a real machine tool.

Therefore, the structure of the paper is as follows: In Sect. 2, related work for feed drive condition monitoring is reviewed

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with a special focus on the utilized test benches. The experimental setup utilized in this work for the derivation of the condition monitoring test cycle is presented in Sect. 3. In Sect. 4, potential factors of disturbance for the assessment of the condition of a feed drive are discussed and it is shown how to control these. The final test cycle and its resulting measurements are shown in Sect. 5. The presented work is summarized and concluded in Sect. 6.

2 Related work

A direct strategy to monitor the condition of machine tool feed drives is the design of new components with embedded sensors near the location where wear is expected to appear. Moehring and Bertram developed a sensory ball screw double nut system equipped with strain gauges that can measure the preload directly inside the ball screw nut [5]. The necessary electronics for recording, amplifying and transmitting the signals were mounted onto the flange of the nut. The results showed, that with ongoing wear a loss in preload can be measured. However, the force measurements at the measurement location were sensitive to thermally induced preload differences and the integration of sensors into the ball screw assembly can be costly. Another example for embedded sensors was presented by Feng and Pan, who integrated a temperature sensor and an accelerometer into the ball screw nut and used the recorded signals to classify the preload level of a given ball screw [7]. Again, the approach showed good results at the cost of a new ball screw design being necessary for the integration of the sensors. Furthermore, both mentioned approaches cannot detect a change in preload condition of the linear guide shoes.

In contrast to the costly design of new components, large portions of the sources reflecting the state of the art used already available signals from machine controls or signals from external sensors, which can easily be placed at the component investigated and whose signals can then be correlated with wear. Verl et al. used a simplified test bench and recorded angular and linear velocities from the motor encoder and linear encoder respectively [8]. The signals were provided by the machine control and the wear process was accelerated by contaminating the lubricant. By monitoring manually designed features from time and frequency domain, wear could be detected. Walther further enhanced the approach by Verl et al. by using the same test bench and investigating additional feature extraction techniques, such as a Hilbert-Huang-transformation [9]. Schopp designed a feed drive test bench, which enables the investigation of five ball screw drives at once [10]. On that test bench, Schopp was able to show that with a defined test cycle and emerging pitting damage the amplitude of the acceleration measured at the ball screw nut is increasing. It has to be noted, that Schopp was able to show the effect on a machine tool in operation, too. The prognosis of failure based on those observations was investigated and validated on the simplified test bench, however. Lee et al. also designed a simplified, single axis feed drive, approximately one tenth of the dimensions of a common machine tool feed drive, and placed an external accelerometer at the ball screw nut [11]. The recorded signals were analyzed in frequency and time-frequency domain and could be correlated with ball screw degradation. In [12], Tsai et al. also used a single axis feed drive, mounted an accelerometer onto the nut flange of the ball screw drive, and recorded the acceleration before they constructed a novel ball passing frequency feature, that they were able to relate with a loss in preload of the ball screw. Another example of a simplified single axis feed drive test bench with external sensors placed at the ball screw nut can be found in [13]. Here, Li et al. conducted extensive run-to-failure experiments, after which they extracted a large number of features and later reduced this number of features to a few relevant and informative ones. The relevant features were used in machine learning models to estimate not only the current wear condition but also the remaining useful life of a ball screw drive. Nguyen et al. also used a simplified single axis feed drive. But instead of measuring and correlating signals from external accelerometers, they built a mechanical model of the feed drive, which allowed them to re-construct the current preload level of a ball screw by only measuring the feed drive table position and the motor current [4, 14]. In [15], Tsai et al. monitored the preload levels of linear guide shoes on a simplified single axis feed drive by placing external accelerometers on the work table and conducting an operational modal analysis. Due to the extensive research, that has been conducted in the recent years, even industry solutions, which promise accurate condition monitoring of machine tool feed drives have been presented in the past. However, since they are proprietary and the details are not published, it is hard to evaluate and compare their scientific approaches.

All the above mentioned contributions, except the work presented by Schopp, who made some limited experiments on a machine tool in production, developed systems to monitor the feed drive condition on a simplified, single axis feed drive. In fact, many more investigations performed on a simplified test bench can be found in the literature [16–20]. Transfers to a more realistic test bench, resembling a real machine tool, are rare, however. Ellinger et al. conducted such an investigation for the detection of loss in preload in BSDs and LGSs by applying an external inertial actor to excite a machine tool structure and identify modal parameters from the recorded signals and the constructed frequency response functions [21]. Although the results were promising, further investigations with signals which are already available in the machine tool's computerized numeric control (CNC) and thus potentially assessing the feed drive's condition without external sensors, are yet to be performed. Furthermore, many of the presented approaches performed their investigations and validation with the exact same components, thus a transferability cannot be shown. Therefore, a condition monitoring system, which has proven to be effective and transferable to other components of a realistic machine tool has yet to be presented. In this work, the first step to such a condition monitoring system, i.e. the test cycle for data acquisition on a test bench, which is similar to a real machine tool, is experimentally derived.

3 Experimental setup

The experiments were conducted on a DMG DMC duo Block 55H five-axis milling machine without housing, without spindle and with only the three linear axes assembled. The machine was equipped with a Heidenhain iTNC530 CNC. Only the motion of the machine's X-axis was investigated. The Heidenhain CNC also enabled the excitation of a single feed drive within a defined frequency range by passing a linear sine sweep to the motor current of the feed drive's X-axis.

3.1 Components

For designing the test cycle, the investigated components (ball screw drives (BSDs) and linear guide shoes (LGSs)) were assembled on the X-axis of the machine. The components under investigation were Bosch Rexroth FEM-E-C 40x16Rx6-4 ball screws and R185143910 profile guiding shoes with different preload levels (see Table 1). It is assumed that the BSD with higher preload corresponds to a healthy component which is suitable to fulfill the manufacturing tolerances, whereas the BSD with lower preload corresponds to a degraded component. The same was assumed for the LGSs. In real use cases, the machine tool user has to define a preload class that is suitable for his or her manufacturing requirements. Degradation of the components and a loss of the pre-defined preload were simulated for this paper by the application of components with less pre-defined preload.

3.2 Sensors

All signals were acquired either by the Heidenhain iTNC 530 itself by using both the internal oscilloscope TNCScope and the Heidenhain software tool TNCOpt, or by external Kistler 8762A10 piezo-eletric accelerometers, which were placed at the ball screw nut and next to the LGSs. The signals provided by TNCOpt are velocity time series recorded at the rotary encoder at the motor of the X-axis and velocity time series recorded at the linear encoder (e.g. glass scale) of the X-axis. The external sensor signals were acquired with a National Instruments (NI) cDAQ-9198 data acquisition box. The measurements of the accelerometers were sampled with a sampling frequency of 20 kHz. The data from the internal oscilloscope TNCScope is sampled with 333 Hz. Therefore, the TNCSope signals were only analyzed in the time domain. The experimental setup is shown in Fig. 1. Exemplary data from the different sensors and different excitations can be found in Fig. 2.

3.3 Excitations

Three different excitations were applied to the machine tool's X-axis. They are described in the following subsections and are summarized in Table 2.

3.3.1 Sine sweep

For the sine sweep excitation, the motor of the X-axis-slide was fed with a current signal in a defined frequency range from 1 Hz to 500 Hz. The excitation was realized as a speed set point of the motor. In TNCOpt, the actual speed of the motor encoder and the glass scale was recorded. For successive feature extraction, a transfer function was constructed, treating the signal recorded at the motor encoder as the system's input and the signal recorded at the glass scale as the system's response. The resulting transfer function represents the dynamic behavior of the machine tool (see Fig. 2a). The analysis of the changes of the dynamic behaviour along with wear has been found to be a promising strategy when assessing the condition of machine tool feed drives in previous investigations [21, 22]. At the same time, vibrations were recorded with the external Kistler accelerometers at different measurement positions (see Fig. 2b for exemplary data). The Heidenhain CNC does not support simultaneous recording with TNCScope and TNCOpt. Therefore, no signals from the internal oscilloscope could be recorded during the sine sweep excitation measurements.

3.3.2 Constant speed

This excitation involved the X-axis-slide moving back and forth with a defined speed along the entire axis length. During the experiments, control signals were recorded via TNCScope and acceleration signals were recorded via the external Kistler accelerometers. The sequence of motion is defined by a CNC program. The spatial length of the constant speed sequence, where no acceleration or deceleration of the X-axis-slide is present, was maximized in order to cover the longest possible measuring distance with a constant speed being present. The speed was set to the maximum speed of 24000 mm/min in order to maximize the

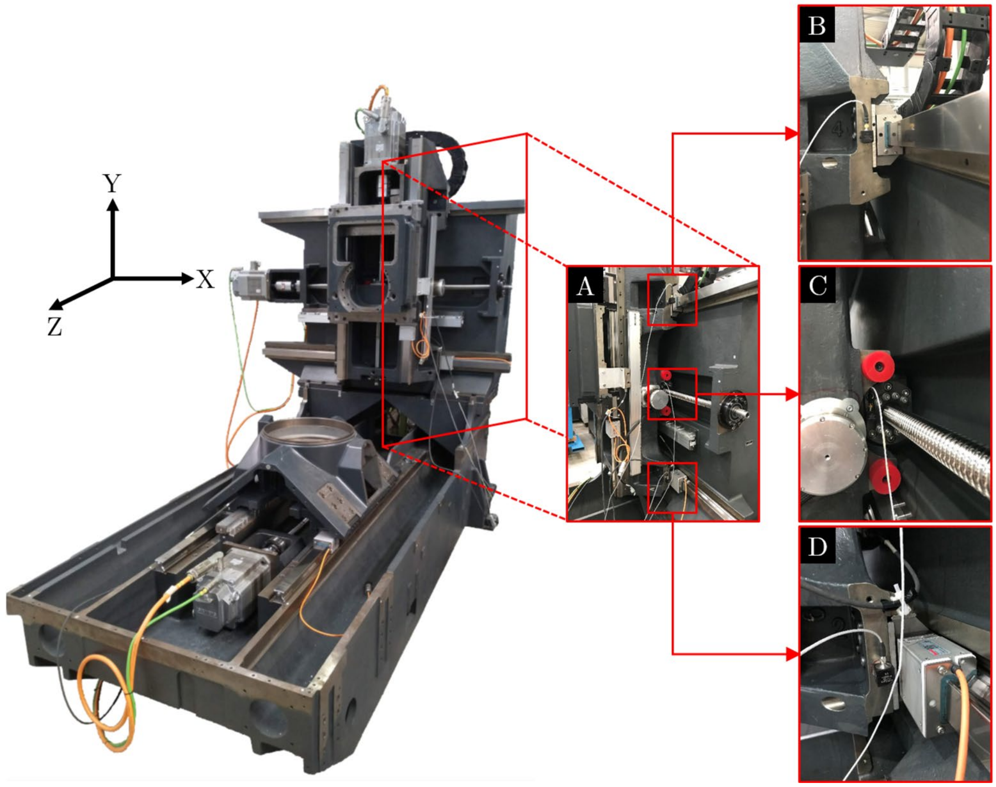

Fig. 1 Experimental setup. On the left hand side the investigated DMG DMC duo Block 55H is shown. **A** shows a side-view of the investigated machine's X-axis including the three Kistler accelerometers placed at the upper LGS (**B**), the BSD nut (**C**) and the lower LGS (**D**)

Table 1 Available components for the experiments

no.	component	name	preload in N	class
1	BSD	G2	2390	C3
2	BSD	G3	950	C1
3	LGS	D3	12840	C3
4	LGS	F3	4430	C1

Table 2 Overview of the available measurements. Possible combinations are marked as ✓, others are marked as ×

	Sensors		
Excitation	TNCOpt	TNCScope	Kistler
Sine sweep	✓	×	✓
Constant speed	×	✓	✓
Directional change	×	✓	✓

initiated energy input and thus the excitation. In Fig. 2c, exemplary data recorded with TNCScope is shown.

3.3.3 Direction change

At a defined machine position, fast and short direction changes were specified via a CNC program. During the experiments, control signals were recorded via TNCScope and acceleration signals were acquired with the external Kistler accelerometers. The speed was set to the maximum speed of 24000 mm/min and the spatial length between the direction changes was set to be 1 mm. Due to the small spatial length, acceleration and deceleration sequences alternated rapidly. This was done with the intention to stimulate wear in the recorded signals for highly dynamic operations. Experimental investigations suggested, that for the direction change excitation, no position dependencies need to be considered. In other words: The machine tool's X-axis position had no influence on the signal in this case and therefore could be set freely for the direction change excitation. In Fig. 2d, exemplary data recorded with TNCScope is shown.

4 Factors of disturbance

In order to ensure the comparability of different condition monitoring measurements over time, potential factors of disturbance, that might change the signal but are not related

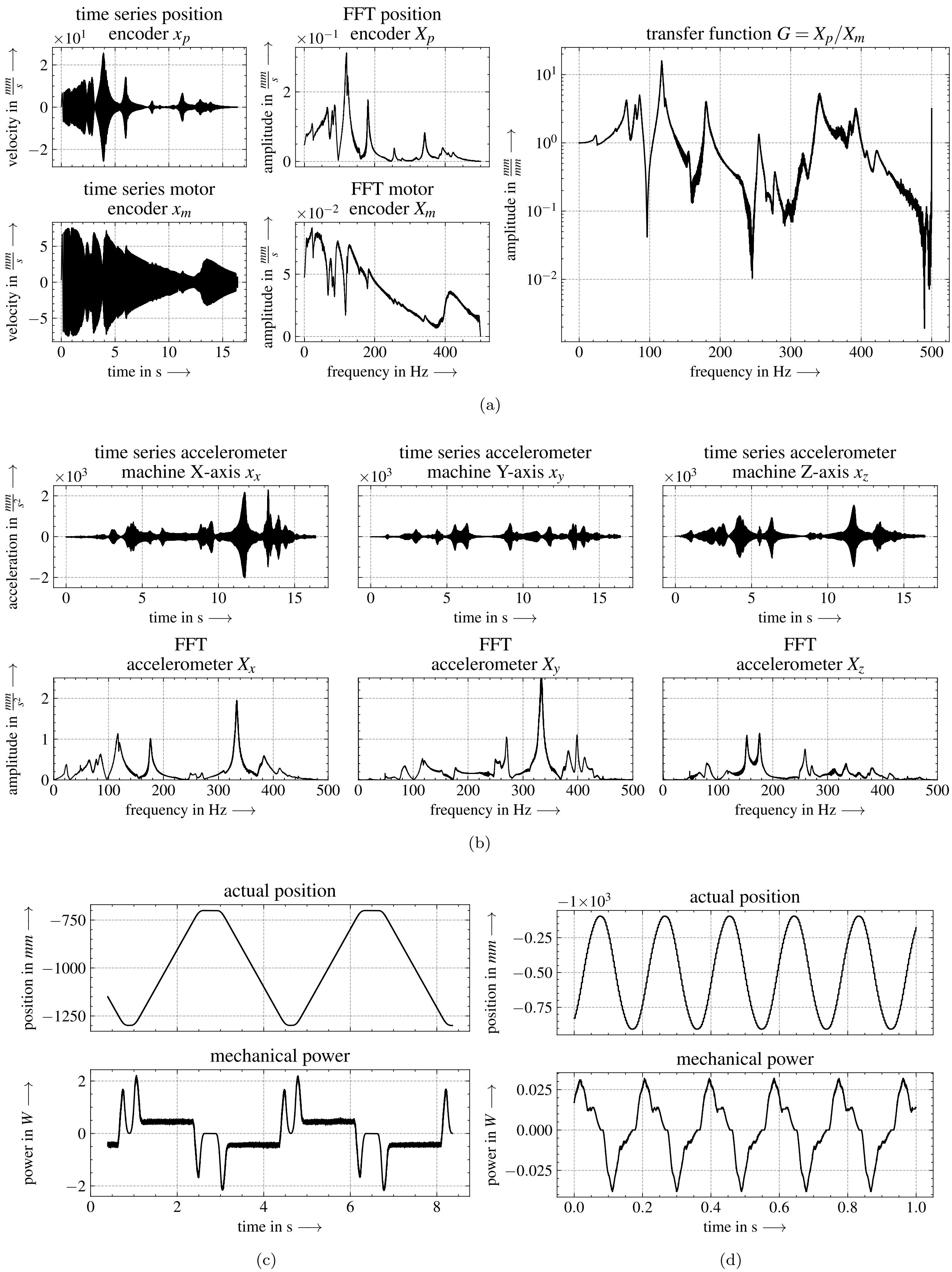

Fig. 2 Exemplary data collected with the available sensors and excitations. **a** Exemplary TNCOpt data for sine sweep excitations. **b** Exemplary Kistler data for sine sweep excitations measured at the BSD nut. **c** Exemplary TNCScope data for constant speed excitations. **d** Exemplary TNCScope data for directional change excitations

to wear, need to be controlled. Three critical factors of disturbance, that are investigated in further detail are the axis position, the temperature and the assembly variances.

4.1 Axis position

Different axis positions lead to different mass distributions and thus different machine tool dynamics. Subsequently, the signals for the sine sweep excitations are expected to change when changing the X-axis position. Hence, the axis position has to be controlled and set to a fixed value for sine sweep excitations in a condition monitoring test cycle. In Fig. 3a, b, this effect can be observed in the TNCOpt and Kistler signals respectively. In both cases it can be observed, that different X-axis positions lead to different frequency responses. In order to control this disturbance, a condition monitoring test cycle has to perform measurements at a defined X-axis position.

4.2 Temperature

Numerous investigations of other authors have shown that temperature is a factor of disturbance in machine tools [23]. Classic investigations of the influence of temperature on machine tool feed drives deal with its influence on manufacturing accuracy [24]. However, there are also investigations about the influence of temperature on the machine tool dynamic behaviour as well. For example, Lee and Donmez showed that with higher temperatures, the natural frequencies of the tool-holder-spindel change [25]. Therefore, the influence of temperature on the investigated machine tool feed drive axis has to be taken into account when defining a condition monitoring test cycle. In order to investigate the influence of temperature on the recorded signals, the measurements were conducted as follows: First, the axis was moved along the entire axis length back and forth with a feed rate of 24000 mm/min. In parallel, the temperature at the surface of the ball screw nut was measured. This was done for approximately 90 min until the temperature converged to 36 °C. After this warm up, measurements were conducted every ten minutes. Hence, with each measurement, the machine cooled down. The last measurement was conducted with a recorded temperature on the ball screw nut of 23 °C. In Fig. 3a, b, it can be observed, that in the temperature range from 23 °C to 36 °C, the deviations in the signals are very small. Hence, when controlling the temperature in a condition monitoring test cycle, for example by a defined warm-up cycle, the changes in the recorded signals due to temperature are negligible, as long as the experiments are conducted in the named temperature range.

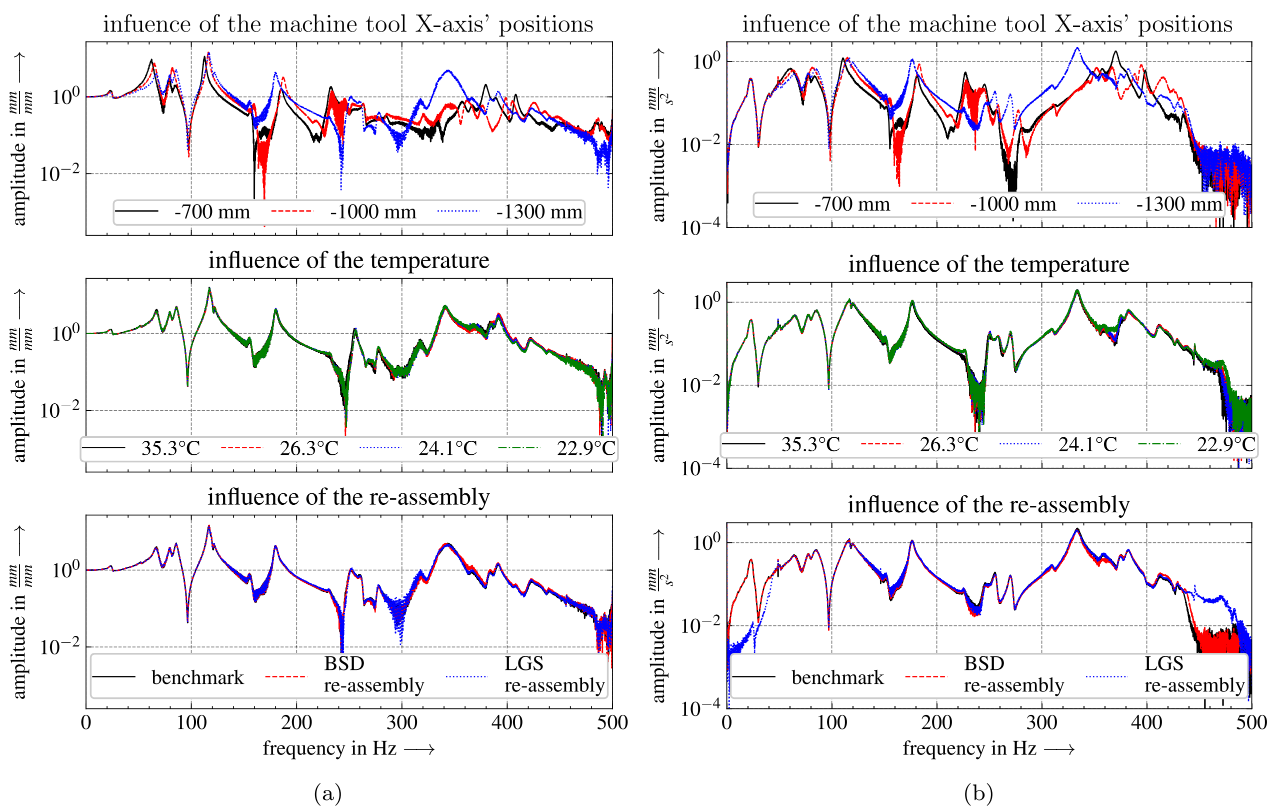

Fig. 3 Influence of disturbing factors on TNCOpt and Kistler data for sine sweep excitations. **a** TNCOpt data. **b** Kistler data

4.3 Assembly variances

The authors' ongoing investigations into condition monitoring of feed drives involve the re-assembly of different components in different wear conditions on the machine tool test bench in order to simulate wear. Variances in the assembly potentially lead to changes in the recorded signals and therefore, the assembly itself is another major influence factor, which has to be controlled. In order to identify potential assembly variances, three measurements with sine sweep excitation were conducted. The first measurement was conducted before any re-assembly. The second measurement was conducted after a re-assembly of the BSD and the third measurement was conducted after a re-assembly of the LGS. All measurements were done immediately after the re-assembly without any preliminary warm-up of the machine or the axis.

In Fig. 3a, it becomes clear, that neither the re-assembly of the BSD nor the re-assembly of the LGS have a significant influence on the signals recorded with TNCOpt. The three transfer functions are almost identical and exhibit no noticeable deviations. This is different for the signals acquired with the external Kistler accelerometers. In Fig. 3b it can be seen, that the influence of the BSD re-assembly is negligible, since the signals are quasi-identical. However, the signals change after the LGS re-assembly. Especially in the frequency ranges 0 Hz to 50 Hz and 420 Hz to 500 Hz, significant deviations can be observed. Furthermore, it can be observed, that the mode at around 25 Hz can be recorded by the external accelerometers but is hardly recorded by the linear and rotary encoder signals which are provided by TNCOpt. This is due to the fact that this first mode is one of the machine tool's rigid body modes, at which the entire machine tool is moving without any internal deformation [26]. Therefore, the linear and rotary encoder, which measure relative movements between the axis parts, naturally cannot record this mode shape. The fact, that this rigid body mode of the entire machine tool cannot always be recorded by the external Kistler accelerometers can be explained by the complex friction state within the ball screw nut and the linear guide shoes [27, 28]: In some cases the rolling elements inside these components can move almost friction-less. In those cases, the force introduced by the motor leads to a counter-phase movement of the X-axis and the machine bed such that the X-axis-movement is fixed in absolute space. Therefore, no signal is recorded by the Kistler accelerometers. Sometimes, however, the rolling elements are in a state of higher stiction. In this case, the force introduced by the motor results in an in-phase movement of the X-axis and the machine bed, resulting in a non-zero signal recorded by the Kistler accelerometer. The occurrence of the one or the other case was observed to be quasi-stochastic and hence could not be controlled by the authors with the chosen excitation via TNCOpt. Therefore, the frequency ranges 0 Hz to 50 Hz and 420 Hz to 500 Hz in the external Kistler accelerometer signals have to be excluded from further investigations.

5 Derivation of a condition monitoring test cycle and results

The final condition monitoring test cycle aims at collecting data that is, on the one hand, robust against the factors of disturbance presented in Sect. 4, and, on the other hand, can identify different wear conditions of the machine tool feed drive's components BSD and LGS.

Since the transfer functions derived from the sweep measurements depend on the absolute X-axis' position (see Sect. 4.1), the position at which the sweep measurements are recorded must be defined. The end position of the X-axis at the motor side was selected due to the following reasoning: At this position the free length of the screw between motor and nut is minimized and thus the axial stiffness of the system is mainly dependent on the ball screw nut's stiffness. Preliminary tests, where the end points of the X-axis, as well as the center position of the X-axis were compared with regard to condition information, confirmed this.

As shown in Sect. 4.2, the influence of the temperature is negligible if the machine is sufficiently warmed up. In order to reliably bring the machine into this condition, an initial warm-up of 60 min of constant speed excitation with maximum feed of 24000 mm/min has to be conducted.

In accordance with the results from Sect. 4.3, the assemblies of different components in different wear conditions were standardized such that the signals were unaffected by assembly variances.

The final test cycle was defined to be a combination of a warm-up cycle and the three different excitations. After the warm-up, the excitations defined in Sect. 3.3 are applied in the following sequence: First, the constant speed excitation is measured. Second, the direction change excitation is recorded. Finally, the sine sweep excitation is measured. This sequence is executed ten times for averaging the measurements and to account for statistical randomness. A reheating procedure of 2 min after one measurement sequence prevents the machine from drifting out of the specified temperature range. The final test cycle is shown in Fig. 4.

For the validation of the derived test cycle, BSDs and LGSs in different preload conditions were mounted and the test cycle was executed. Two different preload classes were used for the BSD and LGS assemblies each (see Table 1). Visual examination of the recorded data showed that the signals produced by the condition monitoring test cycle contain individual characteristics for the respective preload conditions of both, BSDs and LGSs. Figure 5 exemplarily illustrates the visual distinguishability between preload

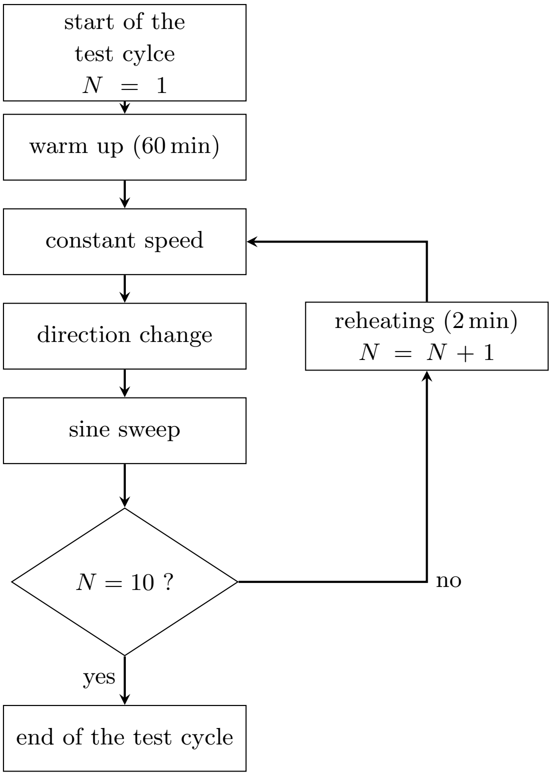

Fig. 4 Flow chart of the developed test cycle

conditions for BSDs and LGSs. There, TNCOpt data is shown for sine sweep excitations. It becomes visible, that for differently preloaded BSDs, shifts in frequency and amplitude occur for the modes around 117 Hz, 190 Hz, 340 and 400 Hz. For differently preloaded LGSs, additional mode changes around 90 Hz, 320 Hz and 350 Hz were found to be characteristic. Thus, in general, the data recorded with the derived condition monitoring test cycle contains information, which is usable to identify the investigated components' conditions. This is necessary for further steps in building models, which can help to estimate the exact condition of BSDs and LGSs based on the recorded data.

At this point it has to be critically noted, that there exist other forms of wear, as well. However, with correct design and dimension of the components, abrasion and adhesion are the dominant wear mechanisms in feed drives, which lead to a loss in preload and pitting damage respectively [29]. Even though pitting damage was not explicitly investigated in the presented work, Schopp has already shown that pitting damage can be detected in acceleration signals from sensors mounted at the ball screw nut [10]. As the presented test cycle also applies accelerometers mounted to the ball screw nut, it is assumed, that pitting damage can be detected, as well.

The presented test cylce lasts for roughly 88 min (including warm-up, ten repetitions and nine re-heating steps), which is very high with regard to time being a scarce resource in the industry. In order to increase its acceptance in the industry, two changes can be made in the future: First, the test cylce could be conducted in times of downtime, such as at the end of a shift, for example. This would not influence productivity. Second, the long duration is mainly due to the warm up and the ten repetitions. At the one hand, performing the test cycle at the end of a shift, could make the warm up phase negligible. At the other hand, the repetitions could be reduced, of course. Investigations about the loss of information with less repetitions should be conducted first, however.

6 Conclusions

This paper presented an experimental derivation of a condition monitoring test cycle for machine tool feed drives on a complex test bench, which is similar to machine tools in operation. After giving an introduction and a review of the related literature, the test bench along with the available sensors and excitations was presented. Due to the nature of the signals that were available for monitoring the condition of the feed drives, factors of disturbance were introduced, that can distort the process of condition monitoring. The identified factors of disturbance were the machine tool's axis positions, temperature and assembly variances. It was shown how those factors can influence condition monitoring signals and how one can control those disturbing factors. Finally, three types of excitations, which are intended to reveal characteristics of the machine for different preload conditions, were combined into a condition monitoring test cycle. The developed test cycle enables reliable and, in terms of disturbing factors, re-producible recordings of condition data. This was shown by an exemplary application of the test cycle to BSDs and LGSs in different preload conditions. The industrial applicability of the developed condition monitoring test cycle was ensured by the use of a realistic test bench. Therefore, this work is a starting base for the further development of a suitable condition monitoring database, which, in turn, can serve for the generation and optimization of reliable models for the diagnosis and prediction of wear in BSDs and LGSs. Extensive experiments and data recording with several components in different wear conditions will be conducted with the presented test cycle in the future. Based on the recorded data, condition monitoring algorithms will be developed and applied.

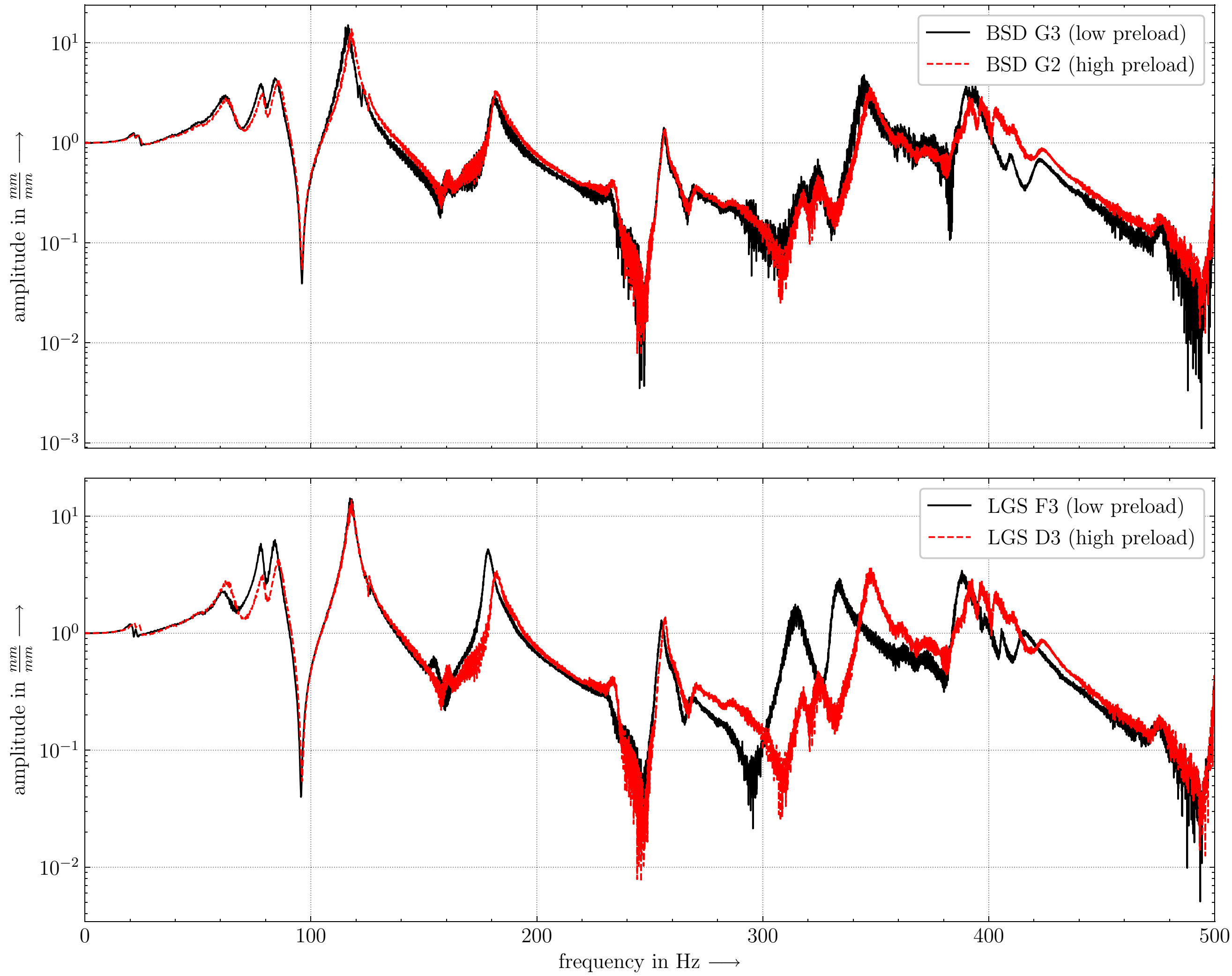

Fig. 5 Influence of different preload conditions of the BSDs (upper figure) and the LGSs (bottom figure) on the transfer function measured with TNCOpt

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