Sensorless Condition Monitoring of Feed Axis Components in Production Systems by Applying Prony Analysis

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Keywords: Electromechanical Axis, Condition Monitoring, Prony Analysis, Data Acquisition.

Abstract: Condition monitoring of modern production systems has established itself as an independent area of research in recent years. Main goal is to achieve an increase in machine productivity by reducing downtime and maintenance costs. In particular, the installed electromechanical axes offer great potential for improvement. Besides an installation of additional sensors, modern drive systems also provide various signals suitable for superordinated monitoring systems. The paper presents a novel approach for monitoring of specific mechanical axis components based solely on internal control loop signals. Fundamental idea is to combine a parametric approach for vibration analysis, the so-called Prony analysis, with a drive-based setpoint generation and data aquisition. The method is verified by detecting emulated malfunctions on a single-axis test stand and a three-axis vertical milling machining center. Experimental investigations prove that the presented approach is capable of reliably detecting the artificially introduced defects on different axis components.

1 INTRODUCTION

In modern production systems, electromechanical feed axes realize the required motion profiles. In the case of metal-cutting machine tools, they generate the feed movements, thus maintain chip removal as well as all other necessary positioning, infeed and tool change movements. In the field of forming technology, servo screw presses gain more and more attention. One ore more electromechanical axes generate the main process movements for different forming processes (Sewohl et. al., 2018). In addition, electromechanical systems are also installed in production systems for conveying, positioning and synchronization applications, in printing and textile machines as well as in packaging, filling and assembly systems. Altintas states that electromechanical axes, together with the main drive, determine the work accuracy and productivity of modern production systems to a particular extent (Altintas et al., 2017). Figure 1 illustrates the general structure of such an axis. It consists of an electrical part including an industrial control, a drive system with servomotor and the associated position measuring systems, as well as a mechanical part. In the case of linear feed axes, the latter is usually designed as a ball screw drive with comprising coupling, bearing and gear elements. The main causes for unplanned malfunctions of feed axes arise from errors in the mechanical subsystem and frequently result in downtime of the machine tool itself (Plapper and Weck, 2001). Therefore, goal of progressive research efforts is to detect damage on mechanical axis components prematurely and derive consecutive maintenance strategies with minimum downtime and costs. In addition, the utilization of drive-internal measuring systems makes additional sensors redundant.

Content of the paper is a novel methodology for monitoring mechanical components of feed axes based on characteristic frequency components. In the context of this paper, the term sensorless denotes that the approach utilizes only signals available in the drive internal control loops and therefore does not require the installation of additional sensors. Furthermore, it is applicable during regular machine operation. In contrast to established methods based on frequency spectra analysis (e.g. Bellini and Tassoni

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Schöberlein, C., Quellmalz, J., Schlegel, H. and Dix, M.
Sensorless Condition Monitoring of Feed Axis Components in Production Systems by Applying Prony Analysis.
DOI: 10.5220/0011287200003271
In *Proceedings of the 19th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2022)*, pages 214-221
ISBN: 978-989-758-585-2; ISSN: 2184-2809

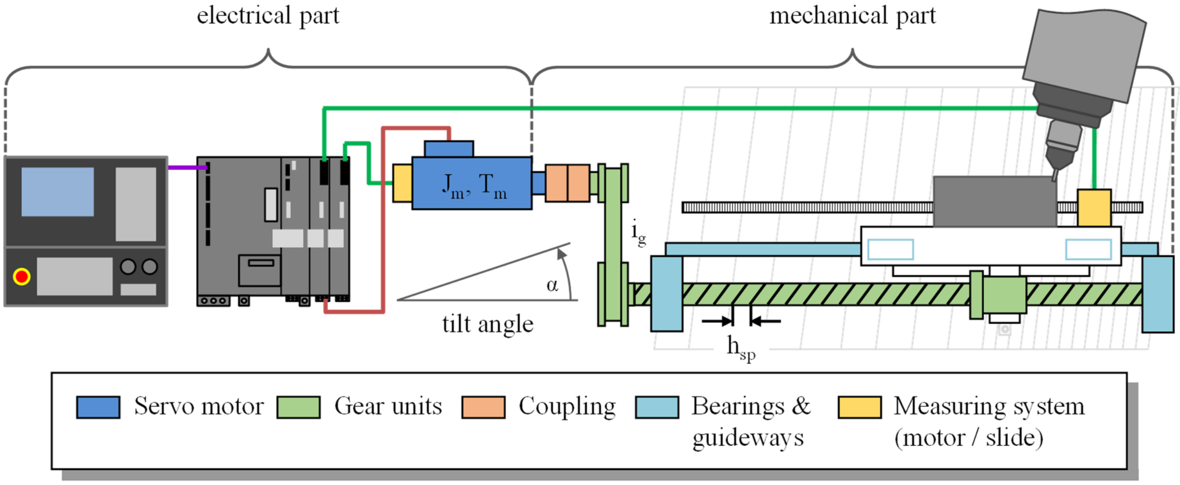


Figure 1: Schematic structure of a typical electromechanical fedd axis.

2008, Huang et al., 2020) or methods of time-frequency analysis (e.g. Putz et. al., 2018), a parametric signal analysis method is used, the so-called Prony analysis. This approach was already successfully applied for the assessment of drive control loops (Neugebauer et al., 2011) or characterization of mechanical transfer systems (Schöberlein et al., 2017). Within the scope of this paper, we extend the analysis method by an automatic, partially invasive test signal application combined with simultaneous data recording for machine tool controls. Functionality is demonstrated in two exemplary cases: detection of an emulated damage on a feed-axis coupling as well as determining preload changes in belt drive systems.

The paper has the following structure. In chapter 2, the basics of prony analysis are explained initially. Subsequently, the overall methodology including automatic test signal generation and data recording is presented. Chapter 3 shows a single-axis test stand for detecting emulated coupling defects as well as a machine tool for belt drive monitoring. Core of the paper is chapter 4 inlcuding experimental investigations on previously described test scenarios. The paper closes with a summary and an outlook on further research topics.

2 METHODOLOGY

2.1 Fundamentals

Similar to Fourier transform, Prony analysis allows the decomposition of a signal into its spectral components. Main difference is that Prony analysis is a parametric method. Due to the low number of required measurement points, short term signals such as impulse or step responses can also be evaluated, which is almost impossible with conventional Fourier analysis (Neugebauer et al., 2011).

The measured input signal is represented as a sum of individual, damped sine oscillations. Starting point is a time signal x_n sampled equidistantly with sampling time T_s, which is reproduced as sum of complex functions $\hat{x}_n$ (Eq. 1).

$$\hat{x}_n = \sum_{m=0}^{p} b_m \cdot z_m^n \qquad (1)$$

$$b_m = A_m \cdot e^{j\Phi_m} \qquad (2)$$

$$z_m = e^{(\alpha_m + j\omega_m)\cdot T_s} \qquad (3)$$

Substituting (2) and (3) into (1), applying Euler's formula results in a sum of p damped sinusoidal signals of magnitude A_m, angular frequency ω_m, initial phase Φ_m as well as damping ratio α_m. For details on mathematical derivation and implementation, consider (Schönherr et al., 2011.). By specifying a fixed model order p and subsampling $n \cdot T_s$ of the input signal, the analysis can be adapted to specific frequency ranges.

Figure 2 shows the result of a Prony analysis for an exemplary signal curve. The input signal is the control deviation after a speed setpoint step, recorded on an exemplary drive test stand. The measured signal (black) is represented by four damped sinoids (dashed) whose sum (green) leads to an appropriate approximation of the input response.

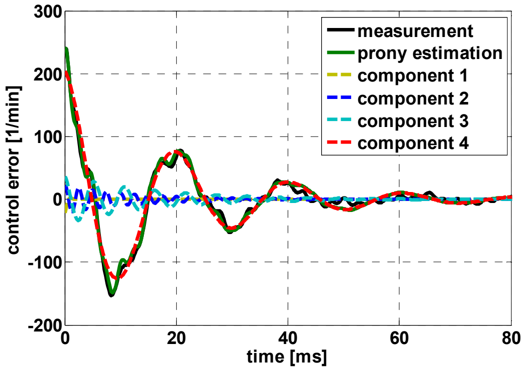


Figure 2: Application of Prony analysis to an exemplary input signal.

2.2 Overall Concept

Application of the described method for monitoring mechanical components of feed axes is carried out by using the overall approach shown in Figure 3. The electromechanical feed axis is excited during conventional operation mode with a superimposed setpoint impulse at level of the speed control loop. This ensures an excitation over a broad frequency range. At the same time, speed setpoint and actual values are recorded utilizing the drive-internal oscilloscope (trace function). Note that control and drive systems usually include all necessary functions for setpoint generation and signal recording. However, one usually controls them manually during axis commissioning or for diagnostic purposes. In order to apply the presented method autonomous during regular machine operation, an interface software developed in (Hellmich et al., 2016, Schöberlein et al., 2018) was utilized. It connects an external computer to the machine control via Ethernet connection and grants remote access to all drive parameters and functions. Data storage via CSV-files ensures further processing of the logged signals. Subsequently, the recorded signal is decomposed into its spectral components using an application-dependent parameterized Prony analysis. Based on calculated vibration parameters, one can derive statements on the condition of specific axis components. The assignment of the considered vibration component to a concrete axis component is based on previously recorded frequency response analysis. The required data is usually available during commissioning of the axis.

3 TEST SETUP

Functional verification of the presented approach is performed on a single-axis test rig and a machine tool feed axis. Both systems are equipped with Siemens drive and control systems. These systems already provide a parameterizable setpoint generator in the drive control unit, which allows generating specific test signals (square wave, sine wave, binary noise signal) at various input points of the control loops. Furthermore, it provides an internal oscilloscope (trace function) for recording time signals with maximum sample frequency of the drive control unit. Smallest achievable sampling time for both test stands is $T_s = 125\ \mu s$.

3.1 Rotary Axis

In the first experiment, we emulate an exemplary damage of a feed-axis coupling on a rotary single-axis. As shown in Figure 4 on the left side the corresponding test stand consists of a servo motor, a coupling, a bearing block as well as optional additional weights. The control is a motion control type SIMOTION D445 with a SINAMICS S120 drive system. The artificially introduced defect is simulated

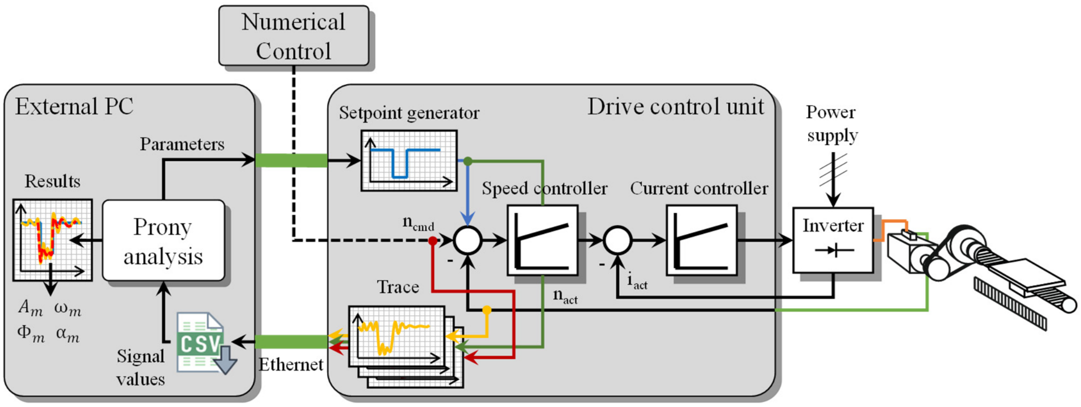


Figure 3: Overall concept of the sensorless monitoring strategy.

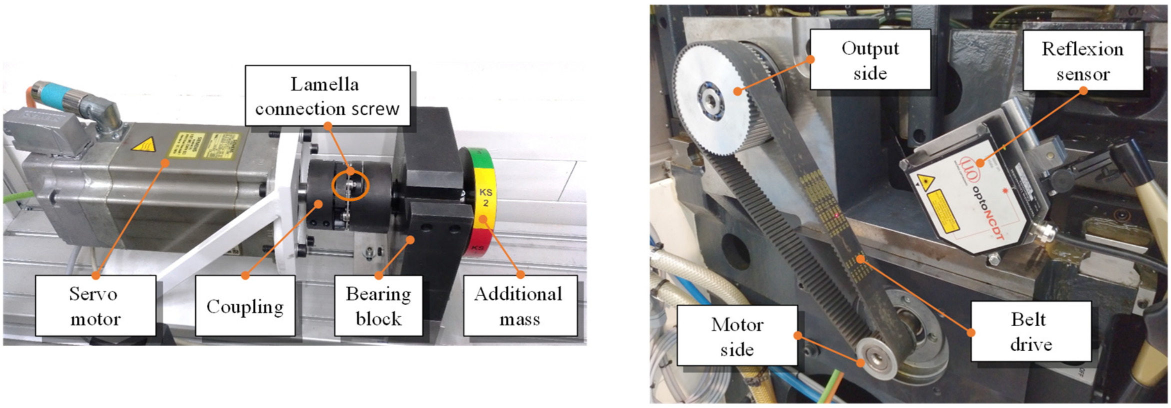


Figure 4: Rotary single-axis test stand (left) and machine tool feed axis with belt drive (right).

by loosening a single lamella connection screw of the coupling (cf. Figure 4). Drive-internal system excitation and recording of measured values are controlled manually via an engineering system. Calculation of Prony method and analysis of the results follows the finished data aquisition in Matlab.

3.2 Linear Feed Axis

The second functional verification is performed on a machine axis (x-direction) installed in a DMG Mori DMC850V three-axis vertical milling machining center (Figure 4, right). The machine tool is equipped with Sinumerik 840D sl CNC control as well as Sinamics S120 drive system. Additional measurements via reflexion sensor confirm correct preload setting of the belt drive. A laptop connected to the controller includes all necessary communication interface for writing and reading required drive parameters and signals. Consequently, test signal generation and recording run fully automated (cf. Figure 3). Prony method estimates the corresponding parameters externally on the laptop after recording is completed. As an exemplary wear feature, the loss of preload of the toothed belt drive is simulated.

4 EXPERIMENTAL RESULTS

4.1 Rotary Axis Test Stand

Main objective is to detect malfunctions on axis couplings represented by an artificially introduced fault in form of a loosened lamella connection screw. Measurements are performed with and without defect. The mechanical configuration corresponds to Figure 4 without additional mass on output side. First, we suggest detecting the introduced defect using conventional spectral analysis in frequency domain. For this purpose, the system is excited by a pseudo-binary noise signal at torque level. Simultaneously, internal trace function records motor torque and speed. After transforming all time signals into frequency domain, frequency response function is plottet in a Bode diagram. Considering Figure 5, one cannot make a clear distinction between functional and damaged coupling. Although a horizontal shift of the mechanical natural frequency is observable in magnitude and phase response, this could also result from deviations in repeated measurements of the frequency responses. Furthermore, the analysis provides the result only in form of a frequency response, which is not easy to interpret without expert knowledge. For direct access, its further processing to characteristic values (e.g. natural frequency) is necessary.

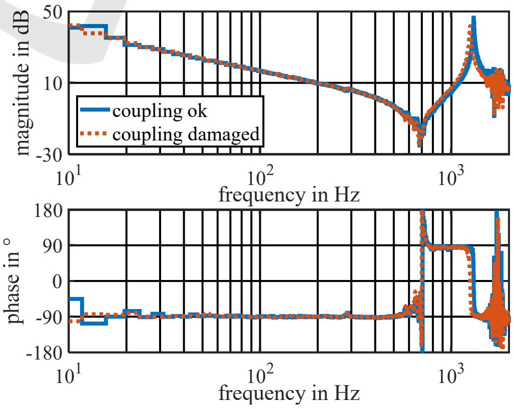


Figure 5: Frequency response function of the speed control plant.

One advantage of Prony method is that all parameters necessary for an interpretation of the vibration components are direct result of the analysis.

Therefore, the methodology described in section 2.2 is applied. All specified parameters for setpoint generator and Prony analysis are listed in Table 1. The axis is moved at constant speed of 200 min^{-1} with closed control loops for speed and current.

Table 1: Parameters for rotary axis test stand.

Parameter	Value
Speed offset	200 min^{-1}
Impulse magnitude	-100 min^{-1}
Impulse duration	500 µs
Sample time	125µs
Recording time	50 ms
Analysis time	15 ms
Model order	4
Subsampling factor	2
Frequency range	1200 – 1400 Hz

Simultaneously, the signal generator creates a speed setpoint pulse with absolute magnitude of 100 min^{-1} and duration of 500 µs while the drive-internal trace function simultaneously records signals for setpoint and actual speed. Subsequently, Prony method with model order $m = 4$ and subsampling time $T_{s,Prony} = 2 \cdot T_s$ is calculated. Based on preliminary tests (cf. Figure 5), the model component with a frequency in the range of 1200 Hz to 1400 Hz is selected. Figure 6a shows the estimation results without defect (top) and with loosened connecting screw (bottom). Comparing the measured time signals and Prony estimation, one may recognize slight differences in decay behavior. By repeating the described procedure five times each with intact and damaged coupling while plotting all output parameters (damping, frequency, amplitude) of Prony analysis individually above test number, one gets the picture shown in Figure 6b. Note that measurements one to five represent the undamaged case while six to ten show results with damaged coupling. Especially in the damping values, significant differences occur. Thus, the value is approximately $D = 0.002$ in the intact case and in damaged case around $D = 0.011$. Although there occur clear differences regarding the frequency values (Figure 6b, center), tests with additional mass have shown that these are occasionally subject to significant fluctuations. Investigations for linear feed axis in the following section confirm this conclusion. Eventually, it can be stated that clear distinctions are possible between undamaged and damaged coupling considering the damping value of Prony estimation.

4.2 Linear Feed Axis

In the next step, the described method is applied on a linear feed axis of a machine tool. Main objective is to detect changes in preload of the installed toothed belt drive (cf. Figure 4, right). The procedure corresponds to the schematic diagram in Figure 3 and previous investigations on the single-axis test rig, respectively. Only difference is the autonomous setpoint connection and signal recording parallel to conventional NC operation. Consequently, all control loops (position, speed and current) are closed. The axis moves at constant feed rate of 2000 mm/min. Magnitude of the superimposed reference pulse is set to 50 min^{-1}. Recording duration and sample time remain unchanged. For model order and subsampling time, previous experiments showed that the values listed in Table 2 lead to better results. Frequency range of the analysis was again determined based on preliminary tests analogous to the single-axis test stand. According to the manufacturer, correct belt tension is present when the manual measurement with reflexion sensor reaches an oscillation frequency of approximately 130 Hz. By applying drive based excitation and calculating the frequency response

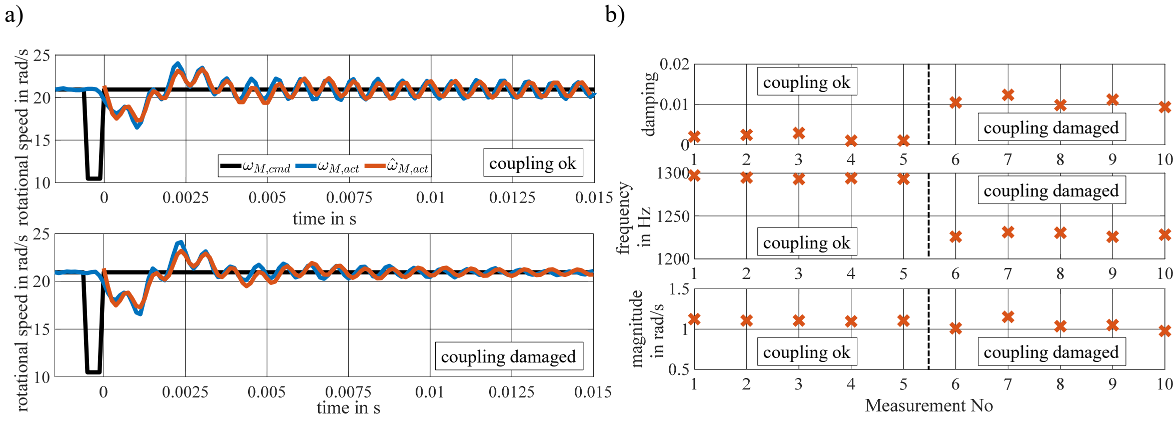


Figure 6: Prony estimation (a) and calculated values for intact and damaged axis coupling (b).

function, this leads to a characteristic natural frequency of approximately 300 Hz. Therefore, we suggest to set the observed frequency range for the Prony analysis as listed in Table 2

Table 2: Parameters for linear feed axis.

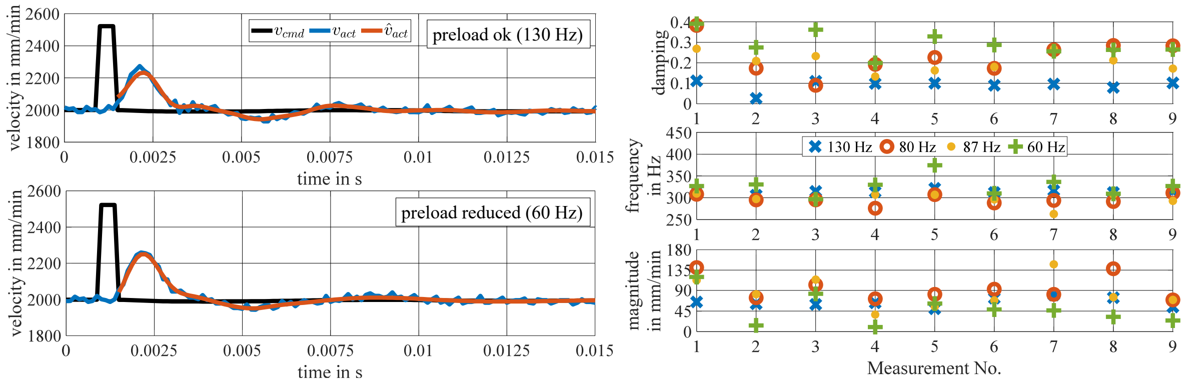
Parameter	Value
Speed offset	2000 mm/min
Impulse magnitude	50 min^{-1}
Impulse duration	500 µs
Sample time	125 µs
Recording time	50 ms
Analysis time	15 ms
Model order	8
Subsampling factor	5
Frequency range	250 – 400 Hz

In a first test, the belt tension was significantly reduced so that manual measurements with reflexion sensor lead to a frequency drop from 130 Hz to 60 Hz. Results of the subsequent Prony analysis are shown in Figure 7a. Again, no significant differences in the signal curves are visible at first sight. However, there occur large differences in the calculated damping values. For correct preloaded belt drive, Prony analysis estimates a damping value of $D = 0.100$. On the other hand, with reduced tension the approach calculates the damping value to $D = 0.329$. If one repeats the measurement at different points over the whole travel range of the axis (Figure 7b, blue crosses and orange circles), single measurements may sometimes lead to unambiguous results (e.g. measurement No. 3). This can be countered by a cyclically recurring application and subsequent averaging of the calculated parameters (cf. Table 3). In real operation mode, however, there is no sudden, but rather gradual drop in belt preload. Consequently, resolution of the analysis is crucial for practical applicability and therefore the method must reliably detect slow tension losses. For this reason, further tests were carried out in which the preload was changed in smaller steps.

Table 3: Results of the Prony analysis for linear feed axis.

Parameter	Average	Standard deviation
Preload appropriate (130 Hz)		
α_m (-)	0.10	0.02
ω_m (Hz)	316.80	9.20
A_m (mm/min)	61.58	15.37
Preload not appropriate (87 Hz)		
α_m (-)	0.20	0.04
ω_m (Hz)	297.50	14.40
A_m (mm/min)	85.22	33.85
Preload not appropriate (80 Hz)		
α_m (-)	0.23	0.09
ω_m (Hz)	296.20	10.70
A_m (mm/min)	95.43	31.81
Preload not appropriate (60 Hz)		
α_m (-)	0.29	0.06
ω_m (Hz)	326.70	22.10
A_m (mm/min)	49.22	34.93

Note that a correctly pretensioned belt drive has a natural frequency of 130 Hz when measured manually by reflexion sensor. Figure 7b shows the results for different preloads and several measurements at different points over the whole travel range of the axis. Considering the individual values, it becomes clear that a single measurement


a)

b)

Figure 7: Prony estimation (a) and calculated values for gradually reduced belt drive preload (b).

can once again lead to incorrect conclusions regarding the belt configuration. However, if one calculates average values of the identified parameters as well as their standard deviation (cf. Table 3), the damping values of the associated vibration component provide a clear result. In case of the frequency values, which can be considered as an alternative comparison criterion, a distinction is not always possible (e.g. between 87 Hz and 80 Hz. Furthermore, when preload is reduced down to 80 Hz, a drop in average frequency is obervable, which, however, increases again in case of 60 Hz. The same applies in reverse for the magnitude values. Only the average damping increases proportionally to the reduction in preload and therefore provides a suitable feature for superimposed condition monitoring and diagnosis.

5 SUMMARY AND CONCLUSION

The paper presents a novel approach for sensorless condition monitoring of mechanical parts of electromechanical axis by applying Prony analysis. Main advantages of the approach are the partially invasive applicability during conventional machine operation without dismantling any axis components. Due to the exclusive utilization of drive internal signals, no additional sensors are required. In contrast to conventional Fourier analysis, Prony analysis decomposes a signal into a series of damped sinusoidal oscillations. In addition, characteristic oscillation parameters (magnitude, frequency, damping, phase angle) are directly calculated output parameters. A communication interface for NC controls including automated setpoint generation as well as drive signal acquisition qualifies the method for application during regular machine operation. This was proven by extensive experimental investigations. Initially, fundamental verification was demonstrated on an exemplary rotational single-axis test rig. The method was able to detect an artificially introduced damage (loosening of a lamellaa connecting screw) by changes in calculated damping values. The subsequent application on the linear axis of a conventional three-axis machine tool shows the capability of the approach. Component damage was simulated by reducing preload of the installed toothed belt drive. However, the experiments led to the conclusion that cyclically recurring analysis is necessary for reliable results. Nonetheless, the average damping values are able to display slow changes in preload.

Future research activities should investigate to what extent the methodology is able to detect malfunctions on other axis parts (e.g. bearing damage). In particular, with regard to the industrial application of the method, reliable threshold values must be defined which classify a component as defective. Suitable reference values can be identified by determining parameters during machine commissioning. In addition, suitable times for connecting the test signal must be specified regarding practical applicability on machine tools. One possible solution is to analyze the current machining program and identify safe motion areas for superimposition (e.g. rapid movements, tool change movements). By connecting a data storage with parameter history as well its combination with an enterprise resource planning system, an extended diagnosis with a suitable maintenance strategy and spare parts supply is possible.

ACKNOWLEDGEMENTS

ZIM
Zentrales Innovationsprogramm Mittelstand

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

Funded by the Federal German Ministry for Economic Affairs and Climate Action.

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