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Adaptive and adequate lubrication for highest component-lifetimes in feed drive axes with ball screws

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Abstract

This paper presents an approach to raise the resource-efficiency of machines with ball screw based feed axes over their whole life cycle. Core of the approach is the usage of adaptive lubrication, which supplies optimal amounts of lubricant to the ball screw. This leads to increased lifetimes, reduced friction torques and more sustainability due to less consumption of lubricant. Therefore the resource-efficiency of feed axes is significantly enhanced. With a test rig the adaptive lubrication was validated by performed lifetime tests. Within the tests conventional non-adaptive lubrication was compared to adaptive lubrication. Results are lubricant savings and significant increases in component-lifetimes of approximately 70 %.

Keywords: Resource efficiency; ball screw; adaptive lubrication;

1. Introduction

One of the objectives in Life Cycle Engineering is to save precious resources. Improvement potentials to save those resources can be found in all life cycle phases from pre-manufacturing to final disposal. By recommendation of [1] an effective strategy during the phase of product-use, where this paper focuses on, is the design for maintenance to achieve high product-lifetimes. Especially in manufacturing industries maintenance can be a significant factor in an organization´s profitability [2]. To reduce maintenance to the essential, it is expedient to focus on components with a high risk of failure. [3] showed within a study that in machine tools, which build the core of modern manufacturing industries, feed axes have the highest risk of failure caused by wear.

Core of this paper is the demonstration of an adaptive lubrication method for feed axes with ball screws based on the consideration of the parameters friction torque and temperature. Objectives are to achieve increased component-lifetimes and more sustainability of feed axes due to less consumption of lubricant and reduced energy consumption due to less friction.

In feed axes ball screws are a widespread element for transforming rotary motion into translatory motion. During this transformation a friction torque arises which results in wear. Wear is inherent in the ball screw but can be minimized by an optimized lubrication strategy. To raise the resource-efficiency of machines with ball screw based feed axes it is important to supply optimal amounts of lubricant over their whole life cycle, what can be enabled by the usage of adaptive lubrication [4].

[5] describes adaptive lubrication as a system that allows to adapt, change, or modify the lubrication mechanism as conditions change to provide the optimal lubrication and wear protection best suited to the system's current needs. A lubrication system that regards the ball screw´s friction and temperature is more beneficial when compared to a system that uses manual or non-adaptive automated lubrication which have high risks of over- or under-lubricating the component.

To understand the importance of the correct amount of lubricant for ball screws, Fig. 1 visualizes the influence of over- and under-supply. Under-supply results in too less lubricant in the contact-zone of spindle, balls and ball screw nut and therefore in increased contact-friction which in turn

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results in increased wear [6]. However, even an over-supply with lubricant reduces the achievable lifetimes of the component because of churning losses and an increased resistance against the motion of the balls [7]. This increased resistance results in high friction-torques and finally lower lifetimes. [8] analyzed the influence of friction on achievable lifetimes of ball screws and emphasized, that wear resulting from rolling and drilling motion friction can only be minimized by an adaptive procedure of relubrication.

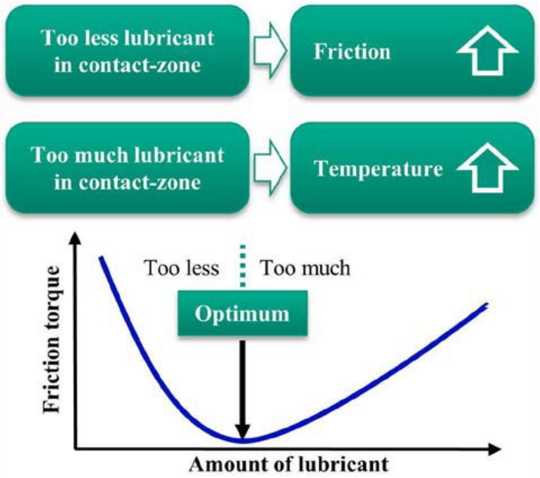

Fig. 1. Influence of over- and under-supply with lubricant.

Ball screws can be lubricated with oil or grease. Benefit of grease-lubrication is on the one hand the higher interval of relubrication-cycles and on the other hand a lower emission of pollutants to the machines as well as the environment. These reasons suit grease-lubrication from an economic and an environmental point of view.

In the following sections an adaptive lubrication method for ball screws is presented, which is based on the consideration and monitoring of the target parameters friction torque and temperature. Therefore the detection of an occurring demand for lubricant is essential, what can be enabled by a monitoring system combining metrology and simulation. Furthermore the results of performed lifetime tests, where conventional lubrication is compared to the new method, are presented.

2. Detection of demand for lubricant in ball screws

To lubricate ball screws with the optimal amount of grease at the right time it is important to detect and interpret an occurring demand for lubricant correctly. Therefore an adaptive lubrication system was developed, which detects occurring demands based on the deviation of the target parameters friction and temperature. Initially the detection of the ball screw´s specific ideal friction torque is presented. For a comparison between simulated values and actual values additionally a measurement system is necessary. Both systems were finally combined in a reliable lubrication algorithm.

2.1. Detection of ideal friction torque

In preliminary work a simulation model for ball screw based feed axes was developed, whose fundamentals were published in [4] and [9]. The model allows the simulation of a friction torque based on the ball screw´s temperature, load and revolution for constant operating conditions. According to Balys theory for calculating the friction torque in angular contact ball bearings [10], the simulation regards the tribological components of irreversible deformation work, hydrodynamic rolling friction and the part from drilling motion of the balls. With respect to the specific kinematics in ball screws the alternation between 2- and 4-point contact loads and changing angular velocities of the balls can be considered. The simulation submits the calculation of friction torques for ball screws in wear-free condition.

In consequence of deviations in production, assembly and primal lubrication at the manufacturer the friction torque of structurally identical and equally strained ball screws differs over their whole lifecycle. This issue makes every ball screw individual, what has to be considered in the calculation of an ideal friction torque as well as the lubrication method.

Fig. 2. illustrates the measured friction torques of eight ball screws of size 40x20 for 7 000 cycles (1 400 mm each) at the beginning of their lifetime. The feed axes were constantly loaded with 50 % of their maximal admissible dynamic load and driven with 800 rpm. The measured values show, that on one hand the friction torques deviate till 55 % (Minimum = 4.5 Nm, Maximum = 7 Nm) and on the other hand the friction torque of ball screws has a tendency to decrease during start-up phase. This decrease can be attributed to the continuous distribution of balls and lubricant in the ball screw nut as well as the initial wear of the sealings. As illustrated in Fig. 2. the friction torque of ball screws tends to decrease during the start-up phase till it settles at a constant value, which differs for every individual ball screw and is strongly dependent from load and revolution. This value of the friction torque is selected as the ideal friction torque for a specific ball screw for specific operating conditions in further analysis.

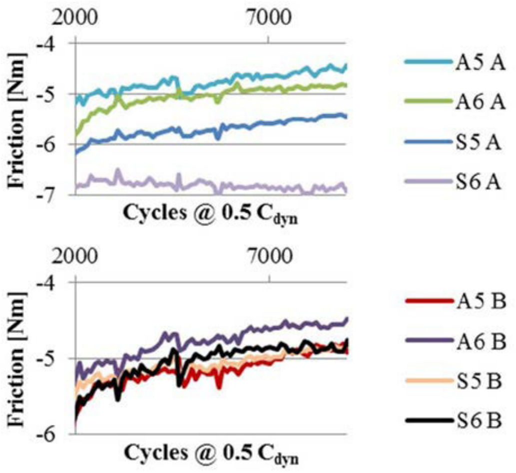

Fig. 2. Measured friction torques of eight ball screws at start-up phase of lifetime and individual, ideal friction torques at end of start-up phase.

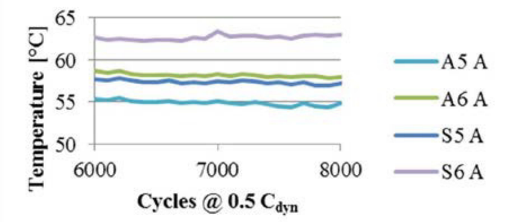

Fig. 3. Measured temperatures of four ball screws at start-up phase of lifetime and individual temperatures at end of start-up phase.

Ball screw S6 A is the only who shows no positive development in friction torque during start-up phase. It is also the one with the highest overall friction torque. Both can be seen as indicators for a relatively weak condition of the ball screw, which could be a result of deviations in production or assembly. The high friction of S6 A results also in high operating temperatures of the ball screw, what can be seen in the measured values of Fig.3. In case of a non-adaptive lubrication an early failure of S6 A can be assumed, because of increased wear resulting from increased friction and operating temperature. With the knowledge about those specific properties of S6 A, its lubrication could be adapted to maximize its lifetime even with inherent wear-causing characteristics.

To fit the simulation model on the specific condition of each ball screw the calculation of the ideal friction torque has to be metrological adapted to its starting situation. To enable this adaption, the calculated ideal friction torque has to be continuously compared to the measured actual friction torque during start-up. If a deviation between simulation and measurement occurs, the considered correction factors for dependency of the revolution, temperature, load and a correction torque will be accommodated.

With regard to the already considered dependencies of the simulation model (temperature, load and revolutions) future research is focusing on the calculation of ideal friction torques for changing operating conditions.

2.2. Metrological detection of actual values on test rig

For enabling the continuous comparison of measured actual values of ball screw´s friction with the ideal friction torque a test rig was equipped with a measurement system.

The test rig consists of four spindles with two ball screw nuts each, where every ball screw nut has its own travel range. Due to this, every ball screw nut characterizes a substantive ball screw. The two nuts per spindle were connected by tension and pressure rods, which strain them with a constant axial load. To proof the constancy of the axial load the rods were equipped with strain gauges. The friction torque of every ball screw is measured with customized torque-sensing capsules with an accuracy of 0.02 Nm. The temperature of the ball screw nuts is measured at its exterior and the temperature of the spindle is measured close to the nut with thermo-sensitive Pt100-elements as Fig. 4. presents. The Pt100-elements were calibrated with an accuracy of 0.2°C.

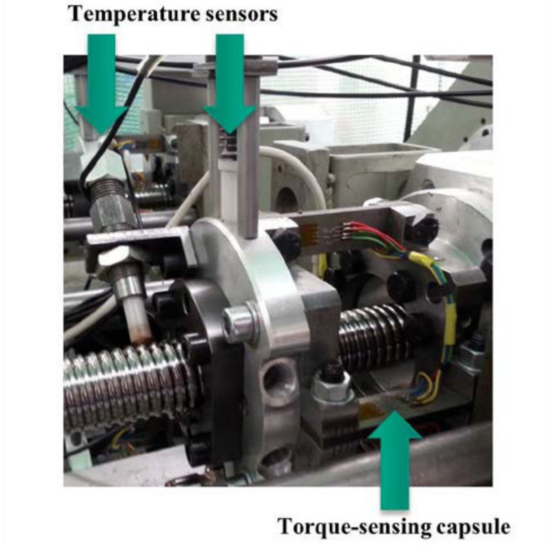

Fig. 4. Measurement system at ball screw nut.

2.3. Combination of metrology and simulation

Objective of the following section is the combination of the in [4] and [9] described simulation model and the previously introduced measurement system to a reliable lubrication algorithm (Fig. 5.).

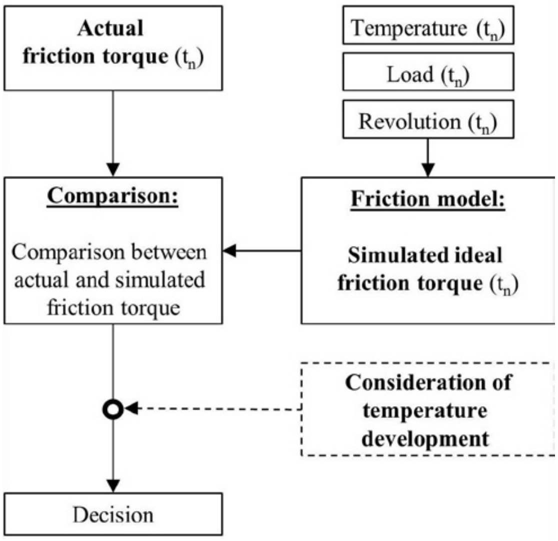

Fig. 5. Lubrication algorithm for continuous comparison of measured and simulated values of ball screw friction torque.

For this purpose a continuous comparison of the measured values of the actual friction torque and the simulated ideal friction torque was set up in LabView. Inputs for the algorithm are the measured torques from the torque-sensing capsules and the simulated ideal friction torque for every ball screw. At present state the simulation model calculates ideal friction torques for constant operating conditions, what implies that rapid changes of the simulation´s dependent variables temperature, load and revolution lead to negligent deviations in the calculation. This will be optimized in future research. To validate the combination of metrology and simulation at this point, the carried out tests were performed with constant operating conditions.

To get a reliable decision if lubrication is necessary, measured and simulated values of ball screws friction torque are compared. If the measured friction is lower than or as high as the ideal value, no lubrication is necessary. If the measured friction exceeds the ideal friction, the development of ball screws temperature is considered. This is done to proof, if the friction´s excess results from common oscillation of inherent deviations like thread lead e.g., or if it results from a degradation of the lubrication. An increasing friction torque joint with an increasing temperature can be interpreted as an indicator for a degraded status of the actual lubrication.

Lifetime tests

Objective of the following section is the validation of the developed method for adaptive lubrication of ball screw based feed axes on a test rig.

2.4. Experimental set-up and procedure

To validate the method of adaptive lubrication on the test rig, ball screws of size 32x5 were divided into two groups. On two spindles with two ball screw nuts each, ball screws were lubricated according to the manufacturer's recommendation and thus according to the state of the art. On the other two spindles four ball screws were lubricated by the usage of the adaptive lubrication algorithm and a mechatronic dosing unit, which is set up to supply lubricant to the ball screw effectively in consideration of the lubrication algorithm´s decision.

The mechatronic dosing unit (Fig. 6.) consists of four small lubricant pumps based on pneumatic cylinders. To enable adaptive and adequate lubrication every adaptive lubricated ball screw got a separate lubricant pump. Minimum quantity of lubricant output is 3.8 mg. With this, the quantities of lubricant and intervals can be applied to the decisions of the lubrication algorithm for every tested ball screw individually, whereby the ball screw is lubricated optimally and in a resource-saving way.

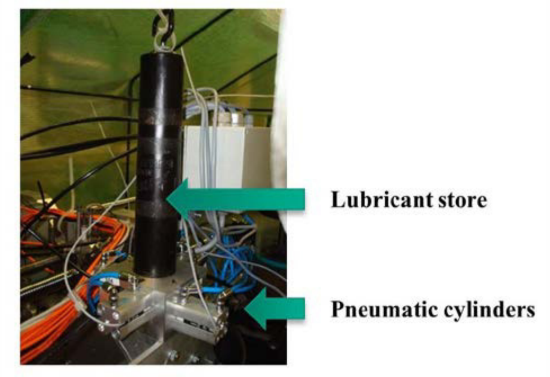

Fig. 6. Mechatronic dosing unit.

For a better understanding of the correlations between friction, temperature and wear, the process parameters revolution and acceleration as well as the load of the ball screws were kept constant on the test rig during the examinations. The process consists of a back and forth movement at constant speed. A short dwell time is implemented at the reversal points of every stroke. The dwell time will be adapted in order to maintain the temperature of one of the test rig´s fixed bearings. Thus submits a thermal consistent lifetime test, which compensates small deviations in ambient conditions. To avoid adverse influences of deviating ambient temperatures during the test, the rig was surrounded by an enclosure.

Fig. 7. Procedure for constant operating conditions.

To compare the achieved lifetimes of ball screws, their nominal lifetime is calculated according to ISO 3408-4 [11]. For the first nominal lifetime (0 – 100 %) the axial load is kept at 30 % of the maximal admissible dynamic load. When 100 % of the nominal lifetime is achieved, the axial load is increased to 50 %, when 250 % of the nominal lifetime is achieved, the axial load is increased to 75 %. This happens to shorten the test duration. The revolution is set to 1000 rpm for the complete lifetime test. During the lifetime test the friction torque and temperature of every ball screw are measured in intervals of 50 cycles, what equals a range of 70 m.

Fig. 7. presents the simplified test procedure for constant operating conditions. For constant operating conditions every combined increase of friction torque and temperature is based on a degradation of the lubrication status. If an increasing friction torque of a ball screw is metrological detected, it´s temperature development is analyzed. In case of an increase of the friction torque combined with an increasing temperature the ball screw is lubricated automatically. Fig. 8. shows schematically a sequence of balls screw´s friction- and temperature-development, as well as two schematic examples for the detection of adaptive lubrication-points.

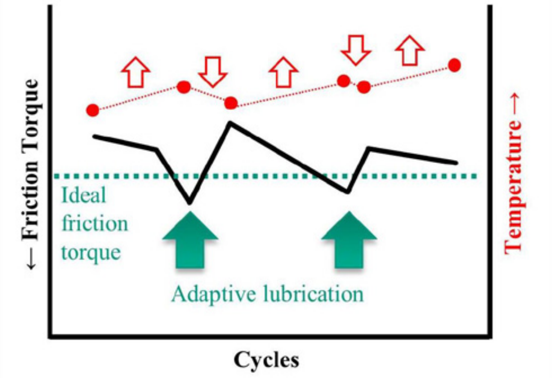

Fig. 8. Adaptive detection of lubrication-points (schematic).

Fig. 9. shows the detection of an adaptive lubrication-point and the development of friction torque and temperature on the test rig before and after adaptive relubrication. As presented the friction torque of the ball screw alternates around the ideal value at the beginning of the sequence (cycle 32 000). At 33 000 cycles the friction torque crosses the ideal line for the first time, but due to a constant temperature no adaptive lubrication is issued. When the friction torque crosses the ideal line at 33 500 cycles for the second time, a continuous increase in temperature can be detected, what is answered with an adaptive relubrication. As a result of the adaptive lubrication the friction torque as well as the temperature decrease and both values settle in a resource-saving value range.

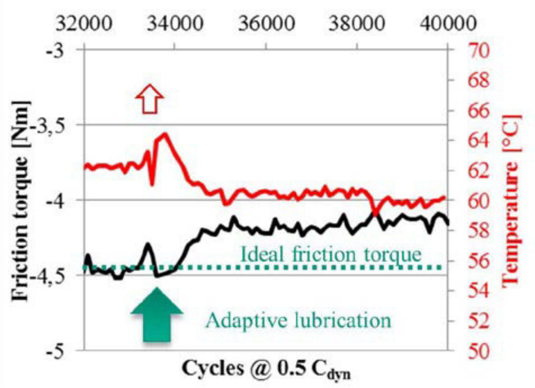

Fig. 9. Adaptive lubrication on test rig.

For adaptive relubrication it is important to use small amounts of lubricant. This is necessary to avoid an over-supply of the ball screw, which would lead to even more increasing values of temperature and friction torque and in turn to another relubrication. For the tested ball screws of size 32x5 an optimal amount of 250 mg was found empirically in preliminary work. This equals 12.5 % of the recommended amount by the ball screw´s manufacturer per standard relubrication.

The lubrication algorithm prevents over-supply by an implemented break-time for lubricant-supply after an accomplished adaptive lubrication. During this break-time the algorithm analyzes the further development of friction torque and temperature. In case of a slightly decreasing friction torque, which converges to a value higher than the ideal friction torque, another relubrication will be executed after the break-time. If the friction torque converges to a value lower than the ideal value, no relubrication is necessary till the friction torque breaks the ideal-line at a later time.

In case of an increasing friction torque accompanied by an increasing temperature immediately after relubrication, a further over-supply of the ball screw must be prevented. For this purpose the algorithm suspends further injection of grease until the friction torque is lower than the ideal friction torque.

2.5. Results

According to the previously explained procedure 16 ball screws of size 32x5 performed a lifetime test with constant operating conditions. The achieved nominal lifetimes are presented in Fig. 10. where red columns represent ball screws lubricated by the manufacturer´s recommendation and green columns represent adaptive lubricated ball screws. The two ball screw nuts of each spindle are summarized in the diagram, since by design of the test rig the failure of one nut determines the relief of both ball screw´s load. As failure criterion the positive finger test was used, where solid residues must be included in the ball screws washed out grease.

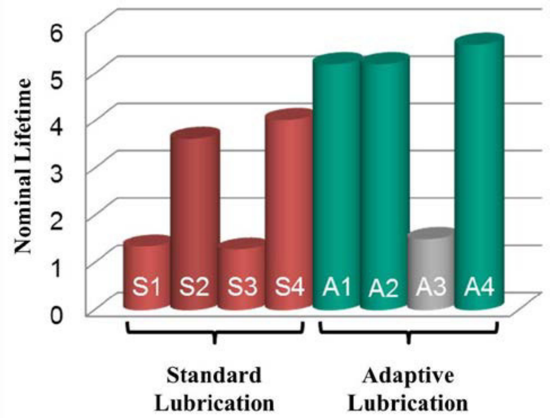

Fig. 10. Achieved nominal lifetimes of tested ball screws.

The diagram shows, that the adaptive lubricated ball screws significantly exceed the standard lubricated ball screws regarding their achieved nominal lifetime. The first failure of a ball screw lubricated according to manufacturer´s recommendation was recorded at 128 % of the nominal lifetime (S3), first failure of an adaptive lubricated ball screw was recorded at 151 % (A3). In case of A3 a ball deflection broke, what is considered in the statistic but does not correlate with insufficient lubrication. The next failures of standard lubricated ball screws were detected at 135 % (S1), 363 % (S2) and 403 % (S4). The first wear-related failures of adaptive lubricated ball screws were detected at 521 % (A1 and A2) and 563 % in case of A4. Table 1. presents the statistical evaluation of the achieved nominal lifetimes.

Table 1. Comparison of nominal lifetimes for constant operating conditions.

	Average lifetime	Coefficient
Standard Lubrication	257 %	1
Adaptive Lubrication	439 %	1,7

As a result of the performed lifetime tests with constant operating conditions an average increase of 70 % in achieved nominal lifetimes can be stated due to an adaptive lubrication based on the consideration of the parameters friction torque and temperature. Within the project further optimization and refinement of the used lubricating strategy is planned, what could result in a possible further increase of achievable component-lifetimes. A further increase in the overall efficiency of feed drive axes with ball screws could be achieved due to a declining energy demand of the drive units resulting from reduced friction in the feed axes.

Regarding the consumed amount of lubricant a significant reduction of grease-consumption could be achieved due to the adaptive and adequate lubrication. Whereas standard lubrication focusses only on an approximated average load and carried out revolutions, the new demand-based method focusses on actual values of ball screw friction torque and temperature. Due to the demand-based method, lubricant is only supplied to the ball screw when really needed. For the tested ball screws of size 32x5 an adaptive supplied amount of 250 mg of grease per relubrication seems particularly promising. Adaptive relubrications with 250 mg of grease did not result in over-supply of the ball screws during the lifetime tests, but the amount was high enough to reduce friction torque and temperature as intended in an appropriate way. The overall grease-amount which was adaptively injected to the ball screws in servings of 250 mg was only approximately 30 % compared to standard lubrication.

Reviewing the achieved results in a monetary point of view it must be emphasized, that an increase of 70 % in ball screws component-lifetime could significantly increase the profitability of machines with feed axes. With the knowledge about the high risk of failing feed axes [3] adaptive lubrication could therefore be one future approach in increasing machines overall equipment effectiveness. Additional economic savings could be achieved due to saved costs for lubricant, because the necessary amount of lubricant was only approximately 30 % compared to standard lubrication. Energetic savings due to reduced friction can at this point of the project not be finally quantified. This results from the individuality of each ball screw and in consequence of non-existent energetic references to standard lubricated ball screws.

3. Summary and Outlook

Objective of the work at wbk is to increase the lifetime and resource-efficiency of machines with ball screw based feed axes by the use of adaptive and adequate lubrication.

For this purpose initially the importance of the correct amount of lubricant was explained, because over-supply as well as under-supply with lubricant reduces the achievable component-lifetime of ball screws.

To enable adaptive and adequate relubrication the detection of an occurring demand for lubricant is essential. Therefore a simulation model which calculates ideal friction torques of ball screws for constant operating conditions was introduced.

In the following work package a measurement system and the simulation model were combined to a lubrication algorithm for the continuous comparison of measured and calculated ideal values of ball screw´s friction torque. The algorithm analyzes the development of the ball screw´s friction torque and temperature and starts demand-based injections of grease to the component. A mechatronic dosing unit was set up, which lubricates four ball screws adaptive, based on the decisions of the lubrication algorithm.

With a test rig the adaptive lubrication was finally validated by performed lifetime tests. Within the tests conventional non-adaptive lubrication was compared to adaptive lubrication. Results are lubricant savings and significant increases in component-lifetimes of approximately 70 % for constant operating conditions.

It must be noted, that the developed adaptive lubrication strategy currently suits only ball screws under constant operating conditions in thermally balanced state. The operation of ball screws in industrial use is characterized by changing conditions resulting from permanent changing loads and variable velocities. Therefore future research at wbk will focus on the adaption of the developed lubrication algorithm to changing operating conditions of ball screws. To ensure resource-efficient, adaptive lubrication for industrial operating conditions, the simulation model must enabled to consider rapid changing loads, velocities and the lubrication algorithm must be connected to a database, where information about past lubrication is available.

Acknowledgements

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References

[11 Alting L, Legarth J.B. Life Cycle Engineering and Design. CIRP Annals Manufacturing Technology, Vol. 44(2), p. 569-580; 1995.

[2] Haroun A.E, Duffuaa S.O. Maintenance Organization. In: Handbook of Maintenance Management and Engineering. Editors: Ben-Daya M, Duffuaa S.O, Raouf A, Knezevic J, Ait-Kadi D, Springer Dordrecht Heidelberg London New York; 2009.

[3] Fleischer J, Munzinger C, Schopp M, Hennrich H, Broos A, Wieser J. Ermittlung der Komponentenbelastungen von Werkzeugmaschinen für einen lebenszyklusoptimalen Betrieb. atp – Automatisierungstechnische Praxis, Vol. 7; 2008.

[4] Fleischer J, Leberle U, Maier J, Spohrer A. Resource-efficient ball screw by adaptive lubrication. Trondheim: 21st CIRP Conference on Life Cycle Engineering, Procedia CIRP 15; 2014.

[5] Zeng H. Polymer Adhesion, Friction, and Lubrication. New Jersey: John Wiley & Sons, Inc; 2013.

[6] Walter M. R. N. Antriebsbasierte Zustandsdiagnose von Vorschubantrieben, Dissertation at University of Stuttgart, 2011.

[7] Forstmann J. Kugelgewindetriebe im Einsatz an Kunststoffspritzgieß-maschinen – Lebensdauerprognose und Optimierung, Dissertation at University of Duisburg-Essen, 2010.

[8] Hoyer H.G. Reibung und ihr Einfluss auf Funktion und Lebensdauer von Kugelgewindetrieben, http://www.konstruktionspraxis.vogel.de/themen/antriebstechnik/lineareinheiten/articles/409487/, 2013.

[9] Hennrich H, Fleischer J. Increase of maintenance efficiency by a hybrid diagnosis and prognosis approach. 10th International Conference and Exhibition on Laser Metrology, Machine Tool, CMM & Robotic Performance, Euspen, Bedfordshire, 2013.

[10] Baly H. Reibung fettgeschmierter Wälzlager, Dissertation at University of Hannover, 2004.

[11] ISO 3408-5:2006. Ball screws - Part 5: Static and dynamic axial load ratings and operational life, 2006.