Intelligent software system for replacing a force sensor in the case of clearance measurement

Meier, Nicolas; Papadoudis, Jan; Georgiadis, Anthimos

Published in:
Procedia CIRP

DOI:
10.1016/j.procir.2019.02.103

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 79 (2019) 517–522

www.elsevier.com/locate/procedia

12th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 18-20 July 2018, Gulf of Naples, Italy

Intelligent software system for replacing a force sensor in the case of clearance measurement

Dr. Nicolas Meier[a,*], Dr. Jan Papadoudis[a], Prof. Dr. Anthimos Georgiadis[a]

[a]*Leuphana University of Lueneburg, Institute of Product and Process Innovation (PPI), Volgershall 1, 21339 Lueneburg, Germany*

* Corresponding author. Tel.: +49-4131-677-5419; fax: +49-4131-677-5300. E-mail address: nicolas.meier@leuphana.de

Abstract

The aim of this work is to develop a method for measuring radial clearance of bearings during the assembly process. A dedicated measuring device was developed. The clearance can now be measured before, during and after the process of mounting bearings. Furthermore, a corresponding intelligent algorithm developed within the frame of this work adapts to different bearing configurations, replaces the metrological identification of the test load. The curve progression of the test load was abstracted by a mechanical model and the characteristic curve correlated with the clearance. The sensor technology originally required could be replaced by an intelligent software system.

Keywords: Bearing; Assembly; Radial clearance measurement; Signal processing; Intelligent system

1. Introduction

Correct installations of rolling bearings increase their lifetime and prevent unnecessary energy losses. One parameter influencing the condition of rolling-element bearings is the clearance. Usually rolling bearings are manufactured with a certain “bearing clearance”. Bearing clearance is defined as the total distance through which one bearing ring can be moved relative to the other in the radial direction (radial clearance) or in the axial direction (axial clearance) [1,2]. The radial clearance is standardized in ISO 5753-1:2009, referring to bearings which are not mounted on a shaft [3].

The radial clearance of a bearing is of considerable importance if reliable operation expected. The clearance affects the bearing stiffness and therefore, the rotor stiffness and dynamic rotor response of induction machines. An increasing clearance leads to a decreasing stiffness [4–6]. Furthermore, the internal clearance strongly affects load distribution as well as wear and therefore, the fatigue life of radially loaded deep-groove ball and cylindrical roller bearings [7, 8].

In case of radial rolling bearings with a tapered bore, which are fastened on the shaft with an adapter sleeve, the radial clearance has to be adjusted (reduced) during the process of mounting.

There are known measuring devices, that allow to check the radial clearance fully automatically in the uninstalled state [9-11]. Methods for checking the radial clearance in the installed state are known as well. The simplest method is the use of feeler gauges [2]. Even simple measuring devices are known where the bearing is turned by hand and the radial clearance is read manually via a dial gauge. This method leads to fluctuations of the results due to the individual use of the tools by the different persons.

The aim of this paper is to demonstrate an automatized method for measuring the radial clearance of bearings during the assembly process without individual influences. An intelligent algorithm is introduced, that adapts to different bearing configurations and it replaces the metrological identification of the test load.

10.1016/j.procir.2019.02.103

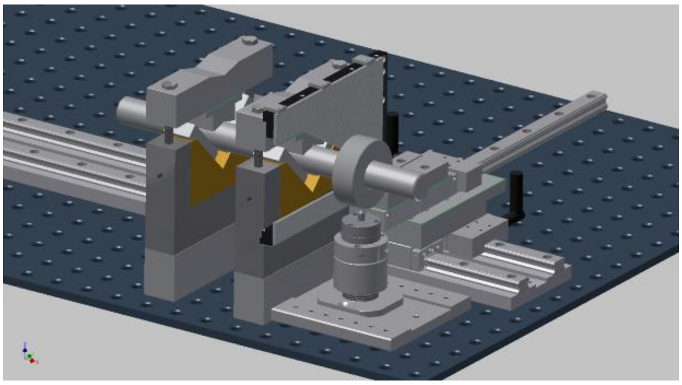

Fig. 1. Construction of the mechanical structure of the advanced measuring system with novel holder of the magnetic actuator.

2. Automated radial clearance measurement

The developed system is able to measure the radial clearance before, during and immediately after the process of mounting bearings with tapered bore which are fastened on the shaft with an adapter sleeve. The measurement is performed automatically and the measured data is directly logged - specifically for each individual bearing.

Figure 1 shows the construction of the measuring system. There are two adjustable prism holders, which ensure that shafts with different diameters can be supported. To avoid slippage of the shaft during the measurements and during the assembly process, the shaft could be clamped securely into the prism holders by using an upper attachment and a screw connection.

Below the bearing, a holder for the electromagnetic actuator can be seen. The holder is fixed permanently to the base plate. To adapt the height of the actuator to the size of the bearing, the holder can be adjusted by an internal screw thread in height. This mechanism can be used for fine adjustment of the high. Rough changes in height can be achieved by placing additional intermediate pieces between the magnetic actuator and the holder

To avoid the tilting of the outer ring with respect to the inner ring a device was developed which is mounted on a linear guiding for an easily and quickly adaption to the position of the bearing on the shaft.

For a complete assembly station, the measuring system shown in Figure 1 is identically constructed on the other side of the rear prism holder. This results in a unit with which both bearings and adapter sleeves can be mounted and measured simultaneously on the shaft

The measurement methodology follows the requirements in DIN 620-1:1995 [12]. During measuring, the outer ring of the bearing is lifted up with a force of approximately 30N by activating the electromagnetic actuator at the bottom of the bearing. The resulting displacement is measured with a dial gauge on top of the bearing (Figure 2) and written into a database. This measurement is repeated three times with a constant lifting force introduced by the actuator. In the next step, the bearing is manually rotated by approximately 120°

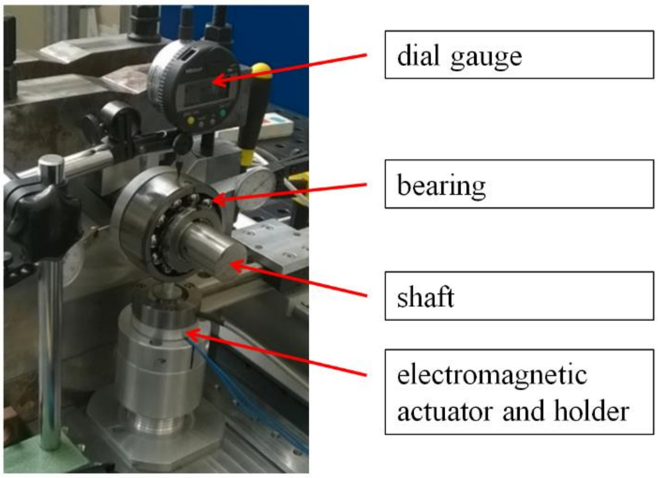

Fig. 2. Clearance measurement setup with a double-row self-aligning ball bearing with tapered bore and adapter sleeve assembled on a 40mm shaft.

and the procedure starts again. This happens a second time, resulting in nine displacement measurements at three different positions. Finally, the mean value and standard deviation of these measurements are calculated. This system for clearance measurement is described also in [13-15].

The program to control the different parts and the system and the signal processing was written in C to provide a real-time application. It is running on a microcontroller (Arduino Due). The application was realized using a state machine. The user can manually change the states via the touch panel in addition to the automatic change during a complete measurement.

A complete measurement consists of the following steps (referring to the ISO 1132-2):

- 1 Round = 3 Rotations
- 1 Rotation = 3 Runs
- 1 Run = up to 64 single measurement

Whereas "Round" refers to a complete measurement, which consists of 3 "Rotations", where the bearing is rotated by 120 degrees. At each of this position 3 "Runs" are performed. A "Run" describes the actual measurement at this position, which can include up to 64 single measurements.

Thus the microcontroller can perform all necessary tasks to complete a measurement and process the data to calculate the bearing clearance.

3. Intelligent algorithm

The automated system needs to recognize during adjustment when the correct reduction of clearance. Thus, the correlation between the increase of the force and the movement of the outer ring was investigated. Based on the tests and a theoretical model it was found that the process can be divided in four different phases. In the beginning the force is too little to move the outer ring (1) until the force exceeds the gravitational force and the ring is lifted (2). If enough force is applied the rolling elements are also being lifted (3).

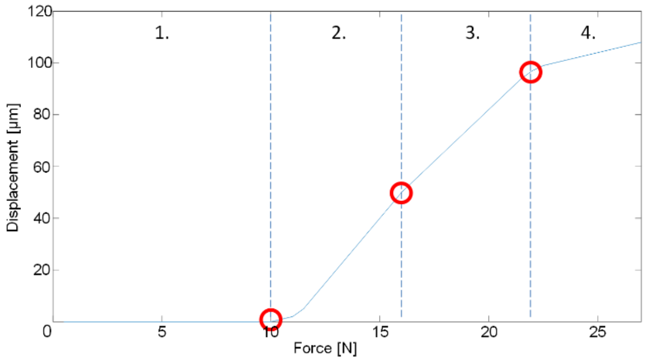

Fig. 3. Theoretical correlation between the force applied to the outer ring and the displacement in relation to the inner ring.

The final stage is reached when the rolling elements reach their final position on the shaft. Any additional applied force would result in an unintentional bending on the shaft (4). These phases are shown in Figure 3.

Based on this general process a suitable algorithm was developed in order to find a stop criterion during runtime. As a stop criterion, the transition from phase 3 to phase 4 was defined. To achieve this an algorithm was used which is based on the extrapolation of the derivation from a regression using a second-degree polynomial function.

$$p(t) = h'(t) \tag{1}$$

The general approach of the algorithm is shown in the following flowchart.

The first task is to define an appropriate starting point t_{start}. This was achieved using the second derivative of the sensor data. It can be shown, that at the beginning of the actual measurement the data describe a transition from a concave curve to a convex curve back to a concave curve. Thus, if a local minimum (with a negative value) was found followed by increasing (positive) values, the start of the measurement was found. So t_{start} can be described as

$$t_{start} = min\{h''(t)\ |h''(t+1) > 0\} \tag{2}$$

Beginning from this point a regression p(t) is continuously calculated to the actual time t_0.

$$p(t) = at^2 + bt + c = h'(t) \quad mit\ D_p = \{t | t_{start} \le t \le t_0\}$$

The vertex of p(t) at the point t_p can be used as an indicator for the stop criterion. The bigger t_p compared to t_0 the steeper the slope of p(t) and the likelier a continuous change of the sensor data. If $t_p < t_0$, the vertex is located in the past, meaning the sensor data already changed their slope. Hence the distance from t_p to t_0 can be used to define a suitable stop criterion.

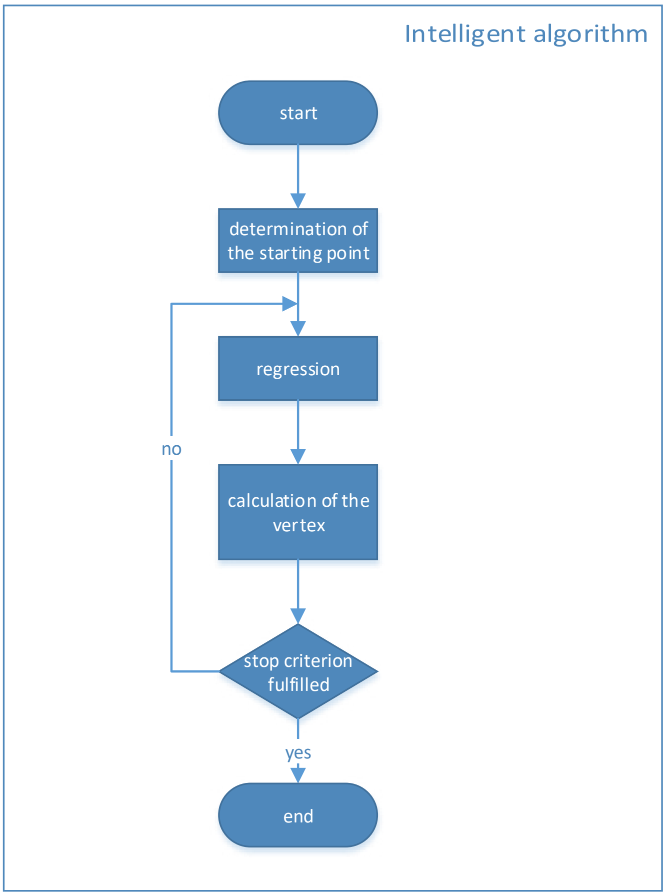

Fig. 4. Flowchart diagram of the intelligent algorithm.

This stop criterion therefore must match the condition

$$t_p = \frac{-b}{2a} < t_0. \tag{3}$$

By using an algorithm based on this principle the force sensor could be replaced.

4. Test setup and results

Three measurements took place for each bearing, at three different positions shifted by 120° to each other in order to prove the repeatability. On each of this position 90 measurements were made before and after adding the adapter sleeve resulting in six tests with 90 measurements.

For each measurement, the applied force was increased to a predefined maximum and the complete sensor data were recorded and stored in order to evaluate the algorithm. Afterwards the algorithm described beforehand calculated for each measurement the stop point. Parallel, the clearance was measured using traditional feeler gauges to compare the results.

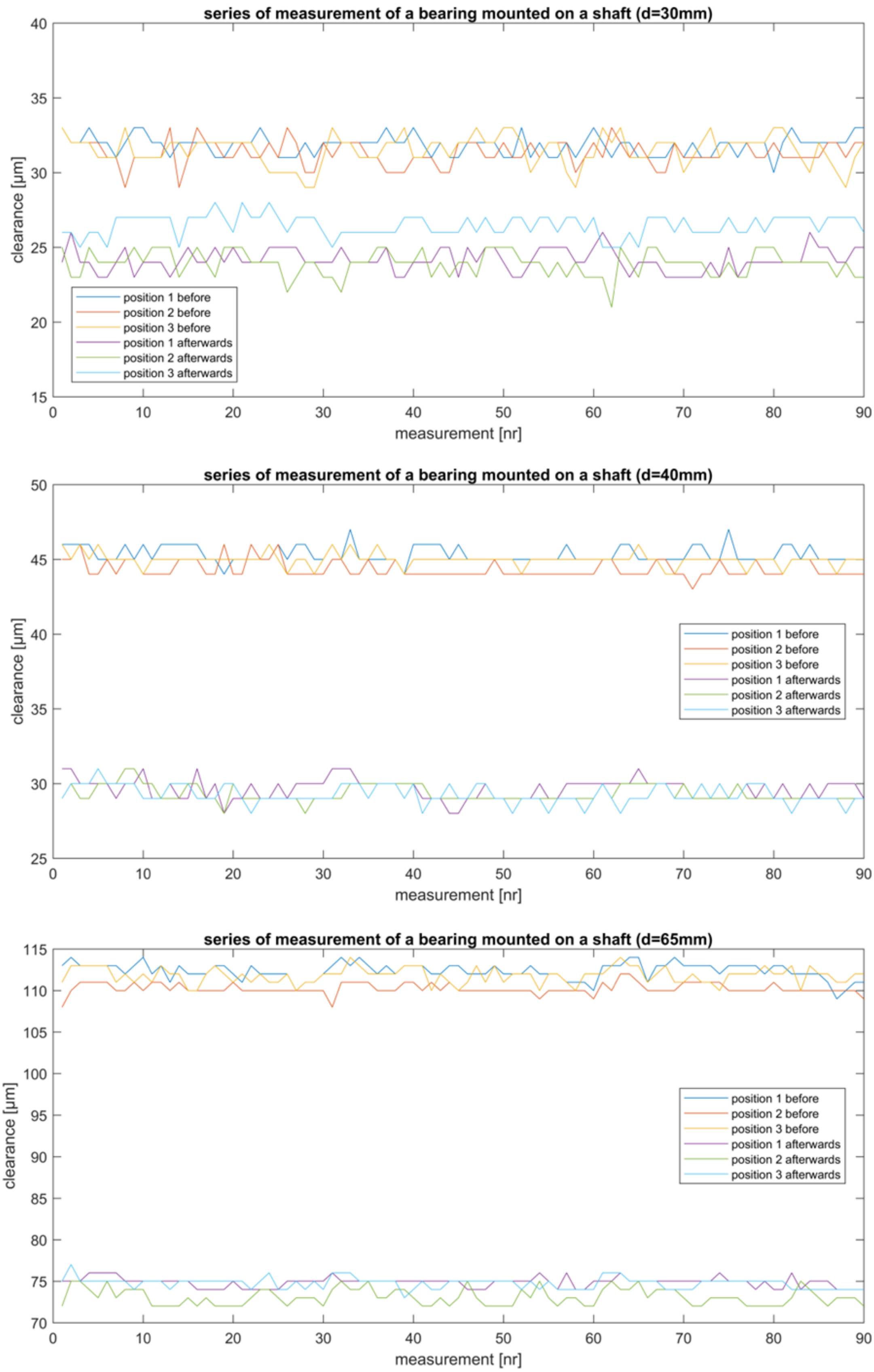

Fig. 5. Individual measurements of each series consisting of 90 separated data points. Each plot consists of six series of measurements representing the radial clearance. The top three series show the values before mounting the bearing on the shaft and the bottom three afterwards. Shown are the results of bearings which are mounted on a shaft with a diameter of 30mm (top), 40 mm (middle), 65 mm (bottom).

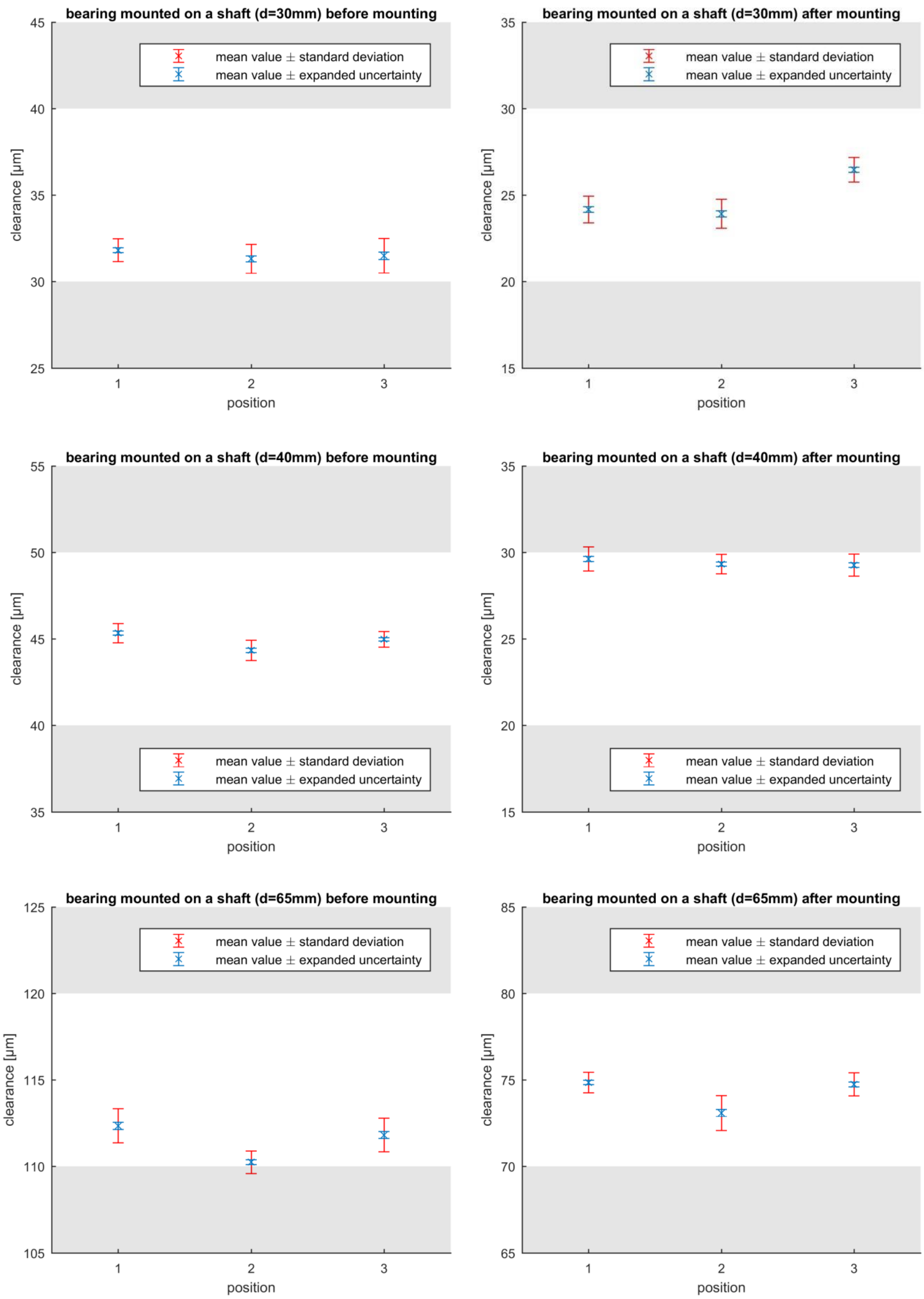

Fig. 6. Error bars for each series of measurements. The middle of each error bar indicates the mean value, the smaller error bar (blue) refers to the expanded uncertainty and the bigger error bar (red) refers to the standard deviation. Shown are the results of bearings which are mounted on a shaft with a diameter of 30mm (top), 40 mm (middle), 65 mm (bottom). On the left side are the results before the process of mounting and on the right side afterwards.

Tests have been done with following three kinds of bearings:

- Double-row self-aligning ball bearings with tapered bore and adapter sleeves assembled on a shaft with the diameter of 30 mm
- Double-row self-aligning ball bearings with tapered bore and adapter sleeves assembled on a shaft with the diameter of 40 mm
- Spherical roller bearings with tapered bore and adapter sleeves assembled on a shaft with the diameter of 65 mm

The uncertainty of the measurement using the algorithm was calculated referring to the Guide to the Expression of Uncertainty in Measurement (GUM). The results regarding the repeatability are shown in the Figure 5.

The upper diagram shows the measurements of a bearing mounted on a shaft with a diameter of 30 mm and a clearance of C3, the diagram in the middle shows the result of the bearing mounted on a shaft with 40 mm diameter and the last one the results of the bearing mounted on a shaft with 65 mm diameter. Within each diagram the upper three lines indicate the results of the calculated clearance from the algorithm before assembling and the other three lines the results after assembling. It can be seen, that the values are within a range of max. 7 µm.
To evaluate the results the standard deviation and the expanded measurement uncertainty was calculated with a coverage probability of 95%. These values only refer to the statistical values of the results from the algorithm and do not include the uncertainty of the measurement device.
In Figure 6 the statistical results are shown with error bars. The middle of each error bar indicates the mean value, the smaller error bar (blue) refers to the expanded uncertainty and the bigger error bar (red) refers to the standard deviation. Additionally, the range of the estimated value of the clearance based on the measurement with feeler gauges is indicated with a white background.
It can be seen that the standard deviation is always below 1 µm, which points to high repeatability of the developed system and the calculated mean is always in the expected range of values. The expanded uncertainty is at max. 0,21 µm.
Thus, the developed system with the intelligent algorithm could be validated as the measured values are within a reasonable range with a high repeatability and low expanded uncertainty.

5. Conclusion

The work presented an automated system for measuring the radial clearance of rolling bearings before, during and after assembly.

The developed, intelligent algorithm adapts automatically to different configurations of bearing sizes and types. The trend of the test force was abstracted by a mechanical model and the characteristic curve correlated with the bearing clearance.

The results show that the measurement system including the algorithm has an expanded measurement uncertainty of max. 0,21 µm.

Thus, the system enables precise adjustment of the radial clearance during the process of mounting. Easily integrated into the quality control system of a rolling bearing manufacturer could help reaching zero defect manufacturing.

References

[1] Brändlein J. Ball and roller bearings: Theory, design, and application. 3rd ed. Chichester and New York: Wiley; 1999.
[2] Schaeffler Technologies AG &Co. KG. Wälzlagerpraxis. Handbuch zur Gestaltung und Berechnung von Wälzlagerungen. Mainz: Vereinigte Fachverlage; 2015.
[3] International Organization for Standardization. Rolling bearings—Internal clearance—Part 1: Radial internal clearance for radial bearings. ISO 5753-1; 2009.
[4] Ganesan R. Dynamic response and stability of a rotor-support system with nonsymmetric bearing clearances. In: Mechanism and Machine Theory 31(6); 1996. p. 781–798.
[5] Tiwari M, et al. Effect of radial internal clearance of a ball bearing on the dynamics of a balanced horizontal rotor. In: Journal of Sound and Vibration 238(5); 2000. p. 723–756.
[6] Sopanen J, Mikkola A. Dynamic model of a deep-groove ball bearing including localized and distribut-ed defects. part 2: Implementation and results. In: Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics 217(3); 2003. p. 213–223.
[7] Oswald F, et al.. Effect of internal clearance on load distribution and life of radially loaded ball and roller bearings. In: Tribology Transactions 55(2); 2012. p. 245–265.
[8] Nguyen-Schäfer H. Computational design of rolling bearings. Cham: Springer International Publishing AG; 2016.
[9] Albert M, Köttritsch H. Wälzlager. Theorie und Praxis. Wien: Springer; 2013.
[10] Zhao RL, Chen YX. A Mechanical Device for Measuring Ball Bearing radial Clearance. Patentnr: ZL 94 2 24150.9; 1994.
[11] Chen YX, Yang SN. Dynamic Measurement of Bearing Radial Clearances. In: KEM 295-296; 2005. p. 361–366.
[12] Deutsches Institut für Normung e.V. Wälzlager 1, vol. 24 of DIN-Taschenbuch, Beuth, Berlin and Wien and Zürich, 7. Aufl., Stand der abgedr. Normen: Januar 1995 edn., 1995.
[13] Meier N, Georgiadis A. A System for Clearance Measurement of Bearings before and after Assembling. In: AMM 870; 2017. p. 179–184.
[14] Meier N, Georgiadis A. Automatic Assembling of Bearings Including Clearance Measurement. In: Procedia CIRP 41; 2016. p. 242–246.
[15] Meier N, Georgiadis A. Messstand zur automatisierten Messung der radialen Lagerluft von Wälzlagern vor und nach der Montage auf einer Welle. Patentnr: DE102015015836 A1; 2017.