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Device and method for measuring thickness variation of large roller element bearing rings



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ABSTRACT

The thickness variation of a large bearing ring is an important measure effecting on the rotational accuracy and partly defining the dynamic properties of the bearing. For example, when a bearing inner ring is installed on a rotor shaft, the final roundness profile of the installed bearing inner ring is the sum of the roundness profile of the rotor shaft roundness and the thickness variations of the inner ring and the possible conical adapter sleeve. In the present study, a device and a method for measuring the thickness variation of large roller element bearing rings was presented. To enhance the measurement quality, each measurement consisted of 20 rounds of measurement data, which were averaged in the frequency domain after the Fast Fourier Transform. In addition, the quality of the measurement was analysed by comparisons with existing devices, coordinate measurement machine (CMM) and roundness measurement machine, and by repeatability measurements. In the analysis, both thickness variation profiles and their harmonic components were investigated. The results show, that the overall agreements with the CMM and the roundness measurement machine were satisfying and good respectively. The repeatability of the proposed device was similar to the roundness measurement machine. According to the results, the device and the method were considered to be valid and deserve further interest and investigation for the bearing ring measurements.

1. Introduction

The modern industry has higher requirements for efficiency and reduced vibration emissions, which have led to an increasing interest towards precise components for large-scale rotor systems. Bearings are a core component of a rotor system. Large-scale bearings are used, e.g., in the fields of power generation, maritime industry and paper and steel manufacturing. Bearing failure related unscheduled maintenance breaks as well as vibratory excitation from the bearings lead to considerable yet avoidable costs. In addition, as renewable energy sources, such as wind turbines, are increasing their market share [1] their reliability and safety are key factors for successful operation and thus for ensuring high availability of critical infrastructure.

Bearing inner and outer ring thickness variation is one of the components determining the quality of a bearing. In large bearings, the ring is relatively thin and flexible compared to the rotor shaft and housing in the final assembly. Thus, the rings deform to the shape of the adjacent parts and the roundness of individual components becomes less significant. Consequently, for example in the case of bearing inner ring, the final roundness profile consists of the geometry of the shaft and thickness variations of the possible adapter sleeve and the bearing inner ring (Fig. 1). Thus, the clearance of an installed roller element bearing may be affected by the thickness variation leading to declined wear and dynamic behaviour properties.

The inner ring, outer ring and rolling elements have geometrical errors, which cause harmful vibration at frequencies proportional to the rotating frequency of the rotor. Remarkable bearing element excitations are caused by the roundness profile of the bearing inner ring, which, in many applications, is attached to the rotor and rotates at the same frequency. The connection between the harmonic components of the roundness profile and the subcritical resonance vibration of the large rotor are investigated and confirmed by two recent publications [2,3]. Excess vibration exerts cyclic forces onto the rotor system and foundation, which may excite harmful vibration in other functional parts of

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Nomenclature		FFT IFFT	Fast Fourier Transform Inverse Fast Fourier Transform
CMM	Coordinate Measurement Machine	L	Length
CAD	Computer Aided Design	PCI	Peripheral Component Interconnect
DAQ	Data Acquisition	STD	Standard deviation
DC	Direct Current	TMM	Thickness Measurement Machine
ENC	Encoder		

the machine and reduce the lifetime of machine components.

The root cause for bearing element thickness variation is presented, e.g., by Deng et al. [4]. The clamping of the bearing ring during the manufacturing process causes deformation to the relatively thin workpiece. The functional surfaces of the bearing rings are turned and ground to a round profile under tension by the clamping forces. The manufacturing process leads to thickness variation, which is dependent on the clamping method of the machine tool.

The thickness variation of bearing rings is assessed by ISO 1132-1 [5], which defines the thickness deviation as a single value. For example, in case of inner ring the definition is "difference between the largest and the smallest of the radial distances between the bore surface and the middle of the raceway on the outside of the inner ring". The standard does not discuss measuring the complete thickness variation profile, which would reveal also the harmonic components of the thickness variation.

The measurement setup defined by ISO 1132-2 [6] is presented in Fig. 2. The ring is supported by three equally spaced fixed supports of equal height in vertical direction. Two radial supports are placed at 90° to each other in the middle of the raceway inside the ring. A measurement indicator is positioned opposite to one bore support. A similar setup is described for outer ring measurements.

The thickness variation of large bearing elements can be measured using existing devices. Coordinate measurement machines (CMM) are able to determine the coordinates of any point reachable by the stylus of the machine. Consequently, the geometry of bearing element surfaces can be measured using such a machine. The thickness is calculated utilizing the measured point data, which are measured in a machine coordinate system reference that has to be transformed to a component fixed system. Measurements with a CMM are influenced by many error sources [7-9] and in this case, the measurand is not trivial as the measurement chain is rather long. This will influence the accuracy of the results. CMMs for large objects such as large scale bearings are available but at a significant cost.

Roundness measurement machines are typically used for measuring the roundness profile of round components. The workpiece is placed on a high accuracy rotary table and the run-out profiles of the outer or inner surface of a bearing element can be measured. The thickness variation can be calculated, when the run-out profile of both inner and outer surfaces is known. The absolute value of thickness may be hard to



Fig. 1. Two examples of shaft and bearing inner ring geometries producing the same final roundness profile of the inner ring. On the left, the shaft is triangular and the inner ring has constant thickness. On the right, the shaft is perfectly round and the inner ring has triangular thickness variation. In reality, the roundness error of an installed bearing element is composed of both error types.

IFFT	Inverse Fast Fourier Transform	
L	Length	
PCI	Peripheral Component Interconnect	
STD	Standard deviation	
TMM	Thickness Measurement Machine	

determine in case of separate measurements of inner and outer roundness profiles as these devices usually only produce relative deviations measurements. The roundness measurement machine could be equipped with two styluses for directly measuring the thickness variation of a bearing inner or outer ring by concurrently measuring both sides. A drawback of using a roundness measurement machine in this application is that the maximum weight of workpieces measurable on available devices of this type is limited.

Roundness measurements are a well-established field of research, and many research studies have discussed improving the accuracy and uncertainty of the measurement methods in addition to the comparison studies [10-15]. Unlike roundness measurements, thickness variation measurements and measurement methods of rings are seldom presented in the literature. In addition to the standard ISO 1132-2 [6], Mao et al. [16,17] presented a method to measure the thickness variations in an automated quality control station. However, the study was not focused on the quality of the measurement, but on the automation of the measurement procedure.

In this study, a novel device and method for measuring the thickness variation of a large-scale roller element bearing inner and outer rings is introduced to overcome the limitations of the existing CMM and roundness measuring devices described above. The measurement method includes a technique to use multiple rounds of measurement data and average the low-frequency components in the frequency domain after to increase the accuracy of the results. The results of bearing ring measurements and a comparison against a calibrated Coordinate Measurement Machine (CMM) at the Finnish national metrology institute (VTT MIKES) and a Talyrond roundness measurement machine are presented.

2. Materials and methods

2.1. Overview of the device and measurement principle

The main concept of the measurement method was to place the bearing element (outer or inner ring) on the device, rotate the element and continuously measure the bearing thickness with two tactile length gauges. One of the sensors was located inside the ring and another outside the ring during the measurement. The thickness value was calculated from the sum of the sensor values at each angular position. The device and the differential measurement unit are presented in Figs. 3, 4 and 6.

The maximum diameter and height of the workpiece were circa 700



Fig. 2. Measurement of variation in thickness between inner ring raceway and bore [6].



Fig. 3. CAD-model of the measurement device and the realized device.



Fig. 4. Differential measurement unit. The sensors were reset by touching the sensor tips together. The steel bar was used to set the vertical measurement height (Z-axis) by touching the flat bearing surface.

mm and 300 mm, respectively. The weight of the workpiece was limited only by the deflection of the aluminium bars, which were used as the frame of the device. The deflection caused by the weight of the workpieces investigated in the present study was negligible. The design enables an effortless scaling of the device for bearing elements of different sizes. The device was operated in a laboratory hall without a temperature control.

The bearing element was supported by three precision roller element bearings in vertical direction. During the measurement, the bearing was rotated with a DC-motor featuring a rubber friction wheel. In the horizontal direction, the element under test rested against two small bearings on one side and the rubber wheel on the other side. An angular encoder was used on a separate, spring-loaded metal friction wheel to determine the angular position of the bearing regardless of slight variations in the rotation speed.

The thickness variation was measured directly with two length gauges installed to a relatively stiff one-piece frame. To ensure the coaxial positioning of the sensors, both the fitting holes were reamed with a single machining operation. An appropriate surface velocity of the length gauges was found to be circa 50 mm/s, which limited the rotating velocity of the bearing element. Higher surface velocities could cause tip flight and vibrations. Thus, the measurement time of bearing rings of different diameters varied.

The differential measurement frame was positioned using precise linear guides and adjusting screws in X, Y and Z directions. A special tool in the measurement program was used to adjust the thickness measurement sensors to a position, where the sensor axis is normal to the bearing element surface tangent (Fig. 5). The position was determined by finding the minimum thickness value indicated by the sensors. This alignment procedure ensured the minimum interference of the curved surfaces in both sensor tips and bearing element to the measurement result. However, the error coming from this kind of misalignment causes typically only negligible cosine type error. In the vertical direction, the measurement height was also measured using a magnetic linear gauge. To determine the absolute measurement height relative to the bearing dimensions, a steel rod attached to the differential measurement frame (Fig. 4) was used by touching the flat bearing side surface. The rod was later removed to conduct the actual measurement.

2.2. Sensors and data acquisition

The differential measurement unit featured two Heidenhain MT12 tactile sensors. The data was acquired at a sampling rate of 100 Hz with two Heidenhain IK 220 evaluation electronics cards, which were installed directly to the computer's PCI interface. The card supplied by the sensor manufacturer was responsible for the signal processing, filtering and digitalization of the raw sensor signals. Finally the digitized values were available for reading. According to the certificate provided by the manufacturer, the accuracy of one sensor is $\pm 0.2 \,\mu\text{m}$.

The encoder (Heidenhain 454M, 500 pulses per revolution) was used to determine the rotation angle of the ring during the measurement. This ensured that slight variations in the rotation velocity did not affect the measurement. The encoder signal was collected using the second Heidenhain IK 220 evaluation card. The core measurement procedure is presented in Fig. 7.

To determine measurement height in vertical direction (Z-axis), an incremental magnetic linear gauge (Balluff BML0019) was used. The measurement data was acquired using the IK 220 also responsible for angular tracking. To ensure concurrent data collection from all four data sources the hardware synchronization feature of the measurement cards was utilized to interconnect them.

2.3. Software

Aside from the hardware, the system includes software components that were developed to aid the measurement process. The software tools written for the device consist of two parts, data acquisition and postprocessing. The data acquisition component contains all necessary features to support the setup process of the device and to acquire the measurement data.

2.3.1. Setup and data recording

The basic function of the acquisition software was to manage communication with the IK 220 interface cards, configure them for the employed sensors, enable synchronization and manage the data flow from the card buffer to the computer's memory. Since there were two acquisition cards installed in the system, they were linked using a hardware channel for the synchronization clock signal, which was generated by the first card.

In addition, the data acquisition software featured functions to determine the Z-position based on the known position of the Z-direction zeroing rod (Figs. 4 and 6) and to align the measurement frame to measure in the normal direction of the bearing surface (Fig. 5). The alignment process was based on finding the minimum thickness value when translating the measurement head as shown in Fig. 5.

Since the device did not feature a rotary table, but the bearing was rotating on auxiliary precision bearings, a zero trigger to collect multiple revolutions of data was realized by using a tape. The rising edge position of the tape could be read properly given a sufficiently high



Fig. 5. Adjusting the sensor axis normal to the measured bearing surface.



Fig. 6. Schematic side view of the device.

sampling frequency.

2.3.2. Signal processing and data analysis

The user interface software stored the raw data either as angle/ thickness pairs or as a table of readings from all connected sensors. 20 revolutions of raw data were collected during one measurement. Each revolution was detected using the zero trigger and the data related to each revolution was stored separately.

The thickness variation data of each revolution was then interpolated using the angular data to represent accurately one revolution with equal angular steps between the samples. Next, the data was transferred to the frequency domain using FFT (Fast Fourier Transform) [18,19]. The FFT enables filtering out the high frequency components effortlessly by setting the phase and the amplitude of the unwanted components to zero [20,21]. The "low pass" filter was set to 15 undulations per revolution. Finally, the corresponding 15 harmonic components of the 20 revolutions of the data were averaged (average of complex numbers) in the frequency domain. This resulted in a single frequency domain dataset representing the harmonic components of the thickness variation profile. The thickness variation profile was then reproduced by utilizing inverse FFT. This frequency domain based averaging method was used to prevent the unwanted, non-periodic noise components from affecting the measurement result.

Finally, graphs of the thickness variation profile and the harmonic component distribution were produced to analyse the results. Investigating the harmonic component distribution gives the possibility to analyse the amplitude and phase of a certain waviness component directly and thus revealing the dominant type of distortion present in the element under test. The block chart (Fig. 8) presents the data manipulation procedure in brief.

2.4. Comparison measurements

The quality and usefulness of the thickness measurement device introduced in this study was evaluated by comparing the results with a measurement performed on a large scale CMM (Fig. 9). The CMM measurement was conducted using a Mitutoyo Legex 9106 coordinate measurement machine at the national metrology institute of Finland VTT MIKES. The $E_{0, \text{ MPE}}$ value (Maximum Permissible Error) defined in ISO 10360-1 [22] of the CMM is $(0.35 + L/1000) \mu m$, where *L* is length in mm, and it is verified with interferometrically calibrated gauge blocks on a regular basis. The diameter of the measured bearing was 420 mm resulting in a position error estimate of $0.72 \mu m$. However, as discussed before, due to the long measurement chain, also higher error estimate can be expected.

The coordinate system of the CMM was aligned to the top surface of the bearing reflecting the guideline for conventional bearing component thickness measurement standardized in ISO 1132-1 [6] as described above.

Since the uncertainty of the CMM was relatively high compared to the actual values of the thickness variation, it was hard to determine the usability of the measurement method. Therefore, a second set of comparison measurements were performed against a Talyrond 31c roundness measurement machine (Fig. 10). The roundness measurement machine was calibrated with flick standards by the national metrology institute of Finland VTT MIKES [15]. The roundness error value produced by the Talyrond deviated max $0.2\,\mu\text{m}$ from the roundness value of the standards in the range of the roundness errors encountered during the present study. The best achievable calibration uncertainty of these flick standards is in the order of $0.1\,\mu\text{m}$ [15]. However, as discussed in the introduction, the size and weight of measured workpieces was limited, and thus a smaller bearing element was used to compare the results.

The roundness measurement machine was used to measure two runout profiles, both inside and outside the workpiece at the same Z-axis height. The run-out profiles were filtered in the frequency domain by the same methods as described in 2.3.2. However, this time only one revolution of data was utilized, and thus the averaging of multiple revolutions of data was not performed, considering the accuracy and typical measurement procedure of the machine. Finally, the run-out profiles were summed to discover the thickness variation profile.

2.5. Measured elements

In the present study, two different bearing elements were measured to investigate the characteristics of the measurement device and method. The first one was an outer ring of a SKF 7340 BCBM single row angular contact ball bearing (later referred to as *large bearing*). The



Fig. 7. Measurement procedure and data acquisition.







Fig. 9. Comparison measurement with Mitutoyo Legex 9106 coordinate measurement machine.



Fig. 10. Comparison measurement with Talyrond 31c roundness measurement machine.



Fig. 11. Schematic drawings of the measured elements. On the left SKF 7340 BCBM (large bearing). On the right SKF 23124 CCK/W33 (small bearing).

second one was an inner ring of a SKF 23124 CCK/W33 two-row spherical roller bearing (later referred to as *small bearing*). The measured elements and their main dimensions are presented in Fig. 11, in addition to the measured surfaces. The large bearing featured two surfaces under investigation, cylindrical (both inner and outer surfaces cylindrical) and spherical (inner surface spherical, outer cylindrical). The small bearing featured a surface, which was cylindrical on the outer side and conical on the inner side. The measurement times excluding the initial setting of the device and the preparation of the workpieces were circa 8 min for the large bearing and 3 min for the small bearing. These measurement times included the acquisition of 20 revolutions of data for the harmonic averaging.

2.6. Repeatability measurement procedure

The actual measurements to analyse the device and its repeatability were conducted by measuring the thickness variation of different measurement cases (large bearing cylindrical and spherical, small bearing) 20 times. Each measurement consisted of 20 rounds of measurement data for averaging. Between the measurements, the device was completely reset and zeroed, including the Z-axis height.

For repeatability comparison purposes, a set of 20 measurements was performed with Talyrond roundness measurement machine as well.

3. Results

This chapter presents the measurement results, in which the developed thickness variation measurement machine (TMM) is compared with two different reference measurement machines. The large bearing element measurement comparisons were made against a coordinate measurement machine due to the large size of the workpiece. In addition, a comparison with a smaller bearing element was made against a Talyrond roundness measurement machine. Moreover, the repeatability of the TMM and the Talyrond were analysed by repeated measurements of the same measurement object.

It must be noted, that the phase values of the harmonic components are expressed in the coordinate system of the corresponding harmonic component in question. E.g., the 15th harmonic component represents thickness variations, which occur 15 times per revolution. The angular period of the 15th harmonic is thus $360^{\circ}/15 = 24^{\circ}$ in the workpiece coordinates. If there is a need to analyse the phase values in the workpiece coordinates, the values must be divided by the harmonic component number in question.

3.1. Large bearing cylindrical surface comparison with CMM

The first comparison case presents the thickness variation profiles acquired from the cylindrical surface of the large bearing. The results were compared against a coordinate measurement machine. Fig. 12 presents the thickness variation profiles measured by both the devices. The overall fitting was observed to be fair, and both devices detected the most remarkable fluctuations similarly.

Table 1 presents some characteristic values of the thickness variation profiles. According to the results, the maximum and minimum



Fig. 12. Comparison measurement of the cylindrical surface of the large bearing element (TMM vs. CMM). Maximum difference of 0.41 μ m was detected at angle 129.4°.

 Table 1

 Maximum, minimum and thickness variation values of the acquired profiles.

	Max thickness	Max angle	Min thickness	Min angle	Thickness variation
TMM	0.76 μm	165.5°	– 1.59 μm	8.0°	2.35 μm
CMM	0.81 μm	165.5°	– 1.52 μm	7.0°	2.33 μm

values and the actual thickness variation value (difference between maximum and minimum) were observed to agree well.

The amplitudes and phases of the 15 lowest harmonic components of the thickness variation profiles are compared in Fig. 13. The first waviness component corresponds to a sinusoidal thickness variation component, which has one maximum and minimum per revolution. Consequently, the second component has two undulations per revolution etc.

All the examined amplitudes and phases of the harmonic components were observed to agree relatively well. The largest difference in the amplitudes was $0.068 \,\mu\text{m}$ (15th component), and the largest phase difference was 140° in the 14th component.

3.2. Large bearing spherical surface comparison with CMM

The second comparison case presents the thickness variation profiles acquired from the spherical surface of the large bearing. Also in this case the thickness measurement machine results were compared against a coordinate measurement machine. Fig. 14 presents the thickness variation profiles measured by both the devices. The overall fitting was observed to be fair. However, major differences were detected especially in the angular range 50° -140° and 340° -360°. The major fluctuations were detected to some extent similarly by both the





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Fig. 14. Comparison measurement of the spherical surface of the large bearing element (TMM vs. CMM). Maximum difference of $0.65\,\mu m$ was detected at angle 108.3°.

Table	n
Table	2

Maximum, minimum and thickness variation values of the acquired profiles.

	Max thickness	Max angle	Min thickness	Min angle	Thickness variation
TMM	1.00 μm	312.9°	– 1.30 μm	17.0°	2.30 μm
CMM	0.93 μm	319.9°	– 1.01 μm	16.0°	1.94 μm

devices, although the amplitudes seem to differ relatively much.

Table 2 presents some characteristic values of the thickness variation profiles. The positions of maximum and minimum values were observed to agree well. However, in both the maximum and minimum values and in the thickness variation a much greater difference compared to the previous case (cylindrical surface measurement) was found.

The amplitudes and phases of the 10 lowest harmonic components of the thickness variation profiles are compared in Fig. 15. A poor agreement of amplitudes especially in the first and the second component was observed. The amplitude differences are remarkably greater in other components as well, when compared to the amplitude differences in previous case (large bearing cylindrical surface).

On the contrary, the phase of the harmonic components was found to have a fair agreement. The largest difference, 85.5° was observed again in the 14th component.

3.3. Small bearing comparison with Talyrond

The third comparison case presents the thickness variation profiles acquired from the cylindrical surface of the small bearing. The thickness measurement machine results were compared against a roundness measurement machine. Fig. 16 presents the thickness variation profiles



Fig. 13. Amplitudes and phases of the harmonic components of the thickness variation profile. The value on top of the bars represents the difference between the values.



Fig. 15. Amplitudes and phases of the harmonic components of the thickness variation profile. The value on top of the bars represents the difference between the values.



Fig. 16. Comparison measurement of the small bearing element (TMM vs. Talyrond). Maximum difference of 0.28 μm was detected at angle 105.6°. The maximum difference value may be misleading, since it was observed at a steep gradient of the thickness profiles and the difference seems to be caused mainly by the phase error.

Table 3

Maximum, minimum and thickness variation values of the acquired profiles.

	Max thickness	Max angle	Min thickness	Min angle	Thickness variation
TMM	1.52 μm	117.4°	– 1.63 μm	321.6°	3.15 μm
CMM	1.52 μm	116.2°	– 1.63 μm	322.0°	3.15 μm

measured by both the devices. The overall fitting was observed to be good. All the fluctuations were detected similarly by both the devices. The most substantial differences are in the peak amplitudes in the angular position range 140° – 240° .

The characteristic values of the thickness variation profiles (Table 3)





Fig. 18. Cylindrical surface repeatability with TMM. Maximum difference of 0.16 μm was detected at angular position 272.7°. Average thickness variation (max value - min value) was 2.35 μm . STD of the thickness variation was 0.0177 μm .

agree well. Only slight differences in the angular positions were detected.

The harmonic component comparison is presented in Fig. 17. The amplitudes of the first and second waviness component had the lowest difference of compared to the previous cases. The largest amplitude difference was observed in the 7th component (0.057 μ m).

The phases of the harmonic components agreed appropriately as well. The largest difference was observed in the 12th component (29.1°) .

3.4. Repeatability

3.4.1. Large bearing cylindrical surface repeatability

Fig. 18 presents the thickness variation profiles of the repeatability test conducted with the developed thickness measurement method. In



Fig. 17. Amplitudes and phases of the harmonic components of the thickness variation profile. The value on top of the bars represents the difference between the values.



this test, the cylindrical surface of the large bearing was measured 20 times. Each of these 20 measurements consisted of 20 revolutions of raw measurement data.

The repeated thickness variation profiles agreed well. All the fluctuations were detected similarly and only some minor amplitude variations were observed. The standard deviation of the thickness variation (max thickness value – min thickness value) was 0.0177 μ m.

The averages and standard deviations of the amplitudes and phases of the harmonic components are presented in Fig. 19. Amplitudes were detected precisely, as the largest standard deviation of 0.008 μ m was observed in the first harmonic component. The standard deviation of the phases was found to have two major outliers, 127.8° in the 9th and 69.3° at the 14th component. However, the amplitudes of the corresponding components were low as well, which might give a partial explanation to the large phase differences.

3.4.2. Large bearing spherical surface repeatability

Fig. 20 presents the 20 repeated thickness variation profiles from the spherical surface of the large bearing. Each of these 20 measurements consisted of 20 revolutions of raw measurement data.

The repeated thickness variation profiles agreed well. Almost all the fluctuations were detected similarly. However, some considerable differences were observed in the angular position ranges 50° – 100° and 340° – 360° , which coincide with the differing ranges in the CMM comparison. The standard deviation of the thickness variation (max thickness value – min thickness value) was $0.0374 \,\mu$ m, which is also significantly higher compared to the cylindrical surface measurement.

The harmonic component analysis is presented in Fig. 21. Overall, the amplitudes were detected precisely, but the largest standard deviation of 0.029 μ m at the first harmonic component was found significantly higher than the corresponding result of the cylindrical repeatability test. On the contrary, the standard deviation of the phases was found to have major differences in the harmonic components 6th (79.6°), 8th (131.1°), 9th (145.2°) and 13th (178.9°). Moreover, these highest phase standard deviations did not coincide with the lowest amplitudes.

3.4.3. Small bearing repeatability

Fig. 22 presents the 20 repeated thickness variation profiles of the small bearing measured with the thickness variation measurement machine. The profiles agreed well. All the fluctuations were detected precisely and no major differences were observed. However, the standard deviation of the thickness variation was $0.0407 \,\mu\text{m}$, being the highest compared to the two previous repeatability tests.

The amplitudes and phases of the harmonic components were all found to have relatively low standard deviations (Fig. 23). The highest amplitude standard deviation was observed in the second component (0.019 μ m) and the highest phase standard deviation in the first component (11.6°).

Fig. 19. The averages and standard deviations of the amplitudes and phases of the harmonic components. The yellow bar represents the average and the error bar represents the standard deviation (average \pm standard deviation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4.4. Small bearing repeatability with Talyrond

For repeatability comparison purposes, a similar set of 20 measurements was acquired with the Talyrond roundness measurement machine as well (Fig. 24). As the results show, all the measured profiles agreed well and the fluctuations were captured precisely. However, the standard deviation of the thickness variation was found slightly higher (0.0492 μ m) compared to the TMM small bearing repeatability test.

The amplitudes and phases of the harmonic components were all observed to have low standard deviations (Fig. 25). However, compared to the TMM repeatability measurement of the same element, the first harmonic amplitude standard deviation (0.018 μm) was found to be slightly higher. All the other components were discovered to have lower standard deviations. Overall, the phase standard deviations were low and the maximum value of 5.8° was detected in the first harmonic component.

4. Discussion

4.1. Comparison with CMM

Since the developed measurement device was intended to measure the thickness variation of large bearing elements, the comparison against a CMM was made due to the sufficient maximum dimensions of the workpiece.

The measurements made on the cylindrical surface show a good overall agreement. The thickness variation value (Max thickness - Min thickness) was found to have a good agreement ($2.35 \mu m$ vs. $2.33 \mu m$) and no major outliers were observed in the harmonic components, albeit the phases of higher harmonic components with low amplitudes had notable differences. However, the measurement on the spherical surface exhibited some major differences, leading the overall agreement to be only fair. The thickness variation values differed also notably ($2.30 \mu m$ vs. $1.94 \mu m$). The amplitudes of the harmonic components



Fig. 20. Spherical surface repeatability with TMM. Maximum difference of $0.27 \,\mu m$ was detected at angular position 223.8° . Average thickness variation was $2.23 \,\mu m$. STD of the thickness variation was $0.0374 \,\mu m$.



Fig. 22. Small bearing repeatability. Maximum difference of 0.37 µm was detected at angular position 345.1°. Average thickness variation was 3.15 µm. STD of the thickness variation was 0.0407 um.

differed especially in the first and second component, which may explain the poor agreement of the profiles.

The fair agreement of the comparison measurements with the CMM may be caused by limitations in the typical CMM accuracy and uncertainty in comparison to the thickness variations as discussed in Chapter 2.4. The measurement chain between the measurand and the final thickness value produced by the CMM is long, which is considered as a source of uncertainty as well. Moreover, the small differences in the Z-axis position and in the selected reference plane of the measurement may affect the measurement substantially, especially in the case of spherical surface. This is suggested by the differences in the harmonic components as well, since the major deviations were observed in the first and the second component.

4.2. Comparison with Talyrond

The comparison against the Talyrond roundness measurement machine was conducted to compare the device with a reference measurement with a lower uncertainty and shorter measurement path.





131.1

6 7 8 9

145 2

178.9

10 11 12 13 14 15

Fig. 21. The averages and standard deviations of the amplitudes and phases of the harmonic components. The yellow bar represents the average and the error bar represents the standard deviation (average ± standard deviation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



Fig. 24. Small bearing repeatability with Talyrond. Maximum difference of 0.17 µm was detected at angular position 67.9°. Average thickness variation was 3.13 µm. STD of the thickness variation was 0.0492 µm.

However, since the dimensions and weight of the measurable workpieces was limited, a smaller bearing was used.

The overall agreement of the thickness variation profiles was considered very good. All the fluctuations were detected similarly. The thickness variation value was observed to be the same by both of the devices. There were no substantial differences in the harmonic components.

The good agreement in the comparison measurements may result from several factors. First, the measurement principle is fairly similar, at least when compared to the CMM measurement (the bearing is rotating and a run-out profile is acquired inside and outside the measured ring). Second, the uncertainty of the Talyrond roundness measurement machine in roundness measurements is more appropriate considering the actual thickness variation values.

4.3. Repeatability

The measurement series conducted with the proposed device suggest a good repeatability of the measurements. The standard deviations

> Fig. 23. The averages and standard deviations of the amplitudes and phases of the harmonic components. The vellow bar represents the average and the error bar represents the standard deviation (average \pm standard deviation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



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Fig. 25. The averages and standard deviations of the amplitudes and phases of the harmonic components. The yellow bar represents the average and the error bar represents the standard deviation (average \pm standard deviation). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

of both the thickness variation values and the harmonic components were considered satisfying, although some outliers in the phase standard deviations were found. These outliers may be caused by the low amplitudes of the harmonic components in question. The maximum standard deviations of the amplitudes of the harmonic components were 0.008 μ m (1st, large bearing, cylindrical), 0.029 μ m (1st, large bearing, spherical) and 0.019 μ m (2nd, small bearing). However, the maximum differences of the spherical surface measurement produced poorer results here as well, suggesting that the measurement task is difficult.

For repeatability comparison, a test series was conducted with the Talyrond machine as well. The results show, that the values are comparable with the TMM, since the largest harmonic amplitude standard deviation was 0.018 μ m (1st), harmonic phase standard deviations were overall lower than TMM values and the maximum difference of the profiles was 0.17 μ m compared to the 0.16 μ m measured with TMM.

5. Conclusion

In the present study, a novel device and method for measuring the thickness variation of large bearing rings is proposed. The comparison and the repeatability results suggest that the device and method are useful and deserve further interest and investigation.

Both the CMM and the Talyrond roundness measurement machine utilize a longer measurement chain to produce the thickness variation profile. Therefore, judging also by the results, there is a possibility that the proposed device is more reliable to measure the thickness variation profile. The device proposed here is a special device designated to measure the specific measurand and thus its usability is limited in other approaches. The CMM and roundness measurement machines are more appropriate in general use, since their flexibility to measure various objects and their properties is better. The measurement principle of the roundness measurement machines is relatively similar compared to the proposed device. However, the proposed thickness measurement machine design features a superior possibility for scaling the method for large bearings without major weight and dimension limits. The measurement time including the setting of the device varied due to the different diameters of the workpieces, and was found to be circa 10 min per measured bearing element.

The relatively low thickness variation values were found even surprising compared to the roundness tolerances given for the bearings of this size. It must be noted, that only two sample workpieces were used in the analysis of the device. In addition, the measurement conducted on the spherical surface was found to be significantly more difficult compared to the cylindrical surfaces. The reason can be in the measurement Z-axis or the definition of the measurement plane, in which the small differences may cause relatively high variations.

As the uncertainty of the measurement sensors of the TMM is of the order $\pm 0.2 \,\mu$ m, the combined uncertainty of the difference of their readings can be estimated to be circa 0.3 μ m. Other error sources, such as alignment, vibration and thermal expansion can be assumed to

increase the uncertainty. However, the repeatability results suggest similar or even lower values to the method. The authors suggest that the 20-round average of the lowest 15 harmonic components is partly the reason for the good repeatability.

As discussed in the introduction, the thickness variation of especially a large bearing inner ring installed on the rotor shaft is a more important measure for the rotational accuracy of the rotor than the roundness alone. Thus, the authors suggest providing the thickness variation values in addition to the roundness values. As further research, a standardized way of measuring different bearing element geometries (spherical, cylindrical and conical) should be investigated. In addition, the performance of the device should be investigated in the case of more than 15 undulations per revolution as well. Moreover, a GUM-based (Guide to the expression of uncertainty in measurement) uncertainty analysis, including uncertainty budgeting and sensitivity analysis of the error sources [23] supplemented with the Monte Carlo method [24,25] would provide a more accurate estimation of the uncertainty of the method.

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