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Published in: CIRP Journal of Manufacturing Science and Technology

DOI: 10.1016/j.cirpj.2020.05.002

Published: 01/08/2020

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

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Please cite the original version:

Viitala, R. (2020). Minimizing the bearing inner ring roundness error with installation shaft 3D grinding to reduce rotor subcritical response. *CIRP Journal of Manufacturing Science and Technology*, *30*, 140-148. https://doi.org/10.1016/j.cirpj.2020.05.002

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CIRP Journal of Manufacturing Science and Technology xxx (2019) xxx-xxx



Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology



journal homepage: www.elsevier.com/locate/cirpj

# Minimizing the bearing inner ring roundness error with installation shaft 3D grinding to reduce rotor subcritical response

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#### ARTICLE INFO

Article history: Available online xxx

Keywords: In-process measurement Manufacturing for operating conditions Measurement based trajectory update Roundness profile Low-order waviness Large rotor

#### ABSTRACT

The modern industry has a constantly increasing demand toward vibration-free rotating machines. Large rotor systems are commonly operated in the subcritical speed range. In the subcritical speed range, the bearings can be a significant source of vibration excitation. The bearing inner ring excites the rotor system at a frequency, which is the rotating frequency multiplied by the waviness component number in the roundness profile of the bearing inner ring. Consequently, subcritical resonance peaks can be observed when the bearing excitation frequency coincides with the rotor natural frequency.

The present study utilized a novel compensative 3D grinding to manufacture the bearing installation shaft into a geometry, which minimized the roundness error of the installed bearing inner ring. The decreased roundness error reduced the bearing based excitations to the rotor system. The successful grinding operation was confirmed with roundness measurements. The relevance of the method and the study was proven with rotor dynamic measurements.

The results clearly suggest that the compensative 3D grinding reduced the roundness error in both bearing inner rings of the rotor system. The decreased roundness error led to a significantly improved rotor dynamic response, which was observed as reduced amplitudes of the subcritical resonance peaks in the typical operating rotating frequency range.

The present study includes also a comparison between the proposed method and a previous steel strip method. The comparison shows that the proposed compensative 3D grinding method produced increasingly better roundness profiles and thus also better rotor dynamic responses.

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#### Introduction

The modern rotating machinery industry has a constantly increasing demand toward lightweight and vibration-free solutions. Large rotor systems are found, for example, in electric motors and generators, turbines, paper machines, steel rolling mills and in non-ferrous metal manufacturing. The need for vibration-free conditions during rotating machine operation without active vibration control systems has led to ever tightening tolerances and increased need for precision manufacturing methods in the manufacturing of large-scale rotor components and complete rotor systems.

The subcritical vibration occurs consequently below the natural frequency of the rotor. The harmonic subcritical resonance peaks can be observed, when the excitation frequency of a rotor coincides with the natural frequency. For example, excitation occurring two times per revolution, such as excitation caused by bending stiffness

variation of the rotor, induces harmonic subcritical resonance at a frequency, which is half of the natural frequency of the rotor system. Furthermore, when the excitation occurs three times per revolution, the subcritical resonance is observed at one third of the natural frequency. Rotor balancing is a widely studied field (e.g., [1–6]), but it mainly affects the vibration occurring once per revolution and thus its usefulness in reducing the subcritical harmonic vibration is limited.

Bearings are an essential part of every rotor system since they sustain the loads of the rotor and enable the rotating motion. Roller element bearings are widely used to support heavy rotors because of their suitable properties. However, despite the effective quality control, bearing components contain always slight manufacturing imperfections, such as roundness error and thickness variation. Roller element bearings are a typical source of harmonic excitation in the subcritical rotating frequency range, inducing also subcritical resonance peaks. For example, low-order roundness error of a roller element bearing inner ring excites the rotor particularly in the subcritical speed range, since the bearing inner ring typically rotates at the same frequency as the rotor itself – this applies

https://doi.org/10.1016/j.cirpj.2020.05.002

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3D	three dimensional
$\Delta r$	two-point diameter variation profile
$\varphi$	rotational angle
С	control curve
F	Fourier transform
$F^{-1}$	inverse Fourier transform
FFT	Fast Fourier Transform
Н	harmonic component
m	Ozono three-point roundness profile
п	number of iterative cycle
r	roundness profile
S1S4	four-point roundness measurement sensors

consequently only to designs, where the outer ring is stationary and fixed to the foundation and the inner ring rotates with the rotor. Therefore, e.g., ovality in the installed bearing inner ring causes excitation twice per revolution, whereas triangularity causes excitation three times per revolution. This links the roundness error of an installed bearing inner ring to the harmonic subcritical vibration discussed in the previous paragraph.

Roller element bearings are typically installed on the rotor shaft in three ways. These installation designs are a shrink fit on a cylindrical shaft, a cone manufactured on the rotor shaft, or a conical adapter sleeve between the bearing inner ring and the cylindrical rotor shaft. Nevertheless, the roundness profile of an installed bearing inner ring consists of the following parts: the roundness profile of the installation shaft, thickness variation of the possible conical adapter sleeve and thickness variation of the bearing inner ring. The manufacturing error in each component stacks to the final roundness profile of the bearing inner ring, as presented in Fig. 1 [7].

Recently, Viitala et al. [8] published a study, where the roundness profile of the bearing inner ring was modified utilizing thin steel strips between the rotor shaft and the conical adapter sleeve. Five different geometries were achieved, one of them minimizing the roundness error of the installed bearing inner ring. Increasing a certain harmonic component of a roundness profile increased the corresponding subcritical resonance vibration amplitude (e.g., increasing triangularity of the roundness profile increased the 3rd harmonic subcritical resonance vibration occurring at one third of the natural frequency). Consequently, reducing the roundness error led to decreased vibration amplitudes throughout the subcritical vibration response spectrum. However, the authors questioned the reliability of the steel strip method in industrial continuous operation. In addition, installing the steel strips in correct positions required several trial and error rounds.

Earlier experimental investigations examining the effect of bearing roundness profile on the rotor vibration suggest that the



**Fig. 1.** Exaggerated schematic figure depicting the stacking of the roundness error of the installed bearing inner ring. The final roundness profile consists of the shaft roundness profile and the thickness variations of the conical adapter sleeve and the bearing inner ring.

bearing waviness excites the rotor system at a frequency which is the number of lobes (for example two in case of ovality, three in case of triangularity) in the bearing inner profile multiplied by the rotating frequency of the rotor-bearing system [9,10]. The results have later been confirmed for example in [11–13].

Sopanen and Mikkola investigated the bearing low order waviness components in a large rotor system with a simulation model and concluded that roundness profile waviness components of orders 2,3,4 and 5 clearly increase the subharmonic resonance vibration at rotating frequencies 1/2, 1/3, 1/4, 1/5 times the natural frequency [14,15]. Recently, Heikkinen et al. [16] could accurately capture the frequency of the half-critical resonance vibration due to bearing ovality in a similar large rotor system with bearing waviness model. The results were verified against measurements. The captured half-critical response amplitude was in the same range with the measurements, but the accuracy was not satisfying.

3D grinding [17] is a manufacturing method, which enables manufacturing micrometer-level geometries on large cylindrical workpieces. The method utilizes the four-point roundness measurement method [18,19] to determine the realized roundness profile. This roundness profile is used as a feedback to the grinding process to enhance the accuracy of the result.

This paper presents a novel in-process measurement, computer based compensation and manufacturing method to reduce the roundness error of an installed bearing inner ring. Using the error compensative 3D grinding method, the installation shaft of the bearing inner ring was ground to a geometry, which minimized the roundness error of the roller element paths of the bearing inner ring, when the bearing was assembled into its final position. The successful performance of the error compensation process was ensured with rotor dynamic response measurements, which showed a remarkable decrease in the subcritical resonance amplitudes in the operational rotating frequency range of the rotor.

### Materials and methods

### Four-point method

The roundness measurements and the rotor response measurements in this paper were conducted using the four-point method (e.g. [8,18,19]). The four-point method is a combination of the Ozono [20] three-point method and the traditional two-point diameter measurement method. The angular sensor positions of the three-point method were determined in [21].

The main advantage of the four-point method is that it is able to measure and separate the roundness profile and the centerpoint movement of a rotating workpiece. Thus, it can be used for roundness and run-out measurements of large workpieces, which cannot be measured using traditional roundness measurement machines (such as Talyrond) due to the size and weight limitations.

In brief, the method utilizes four sensor signals collected at certain sensor positions (Fig. 2) and a combination of two algorithms (Fig. 3) to finally produce the roundness profile.

### Rotor and bearing

The rotor investigated in the present study was a paper machine roll (Fig. 4). The measurement setup was built on a roll grinding machine (Fig. 7). The rotor was supported by spherical roller element bearings SKF 23124 CCK/W33 (Fig. 5).

### Bearing inner ring roundness measurement

To obtain the bearing inner ring roundness profile as it is during rotor operation, the inner ring was measured while installed on the

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 $S_2$  $S_1$  $S_2$  $S_1$  $S_2$  $S_1$  $S_2$  $S_1$  $S_2$  $S_3$  $S_4$  $S_4$ 

**Fig. 2.** The sensor setup of the four-point method. S1 and S4 are utilized in the traditional diameter variation measurement method. S1, S2 and S3 are utilized in the Ozono three-point method. The combination produces a reliable roundness measurement dataset, where the center-point movement is separated and obtainable as well [19].

rotor shaft (Fig. 6). In brief, the roundness profile was measured as follows:

 A rotary encoder was used as a trigger and a measurement clock to ensure equal angular intervals between the samples (1024 samples per revolution).
2. One revolution of run-out signals were acquired from Heidenhain MT 12 sensors with Heidenhain IK220 interface electronics.

- 3. The roundness was measured in the middle of both of the roller element paths of the bearing.
- 4. The four-point method was applied to the measurement and the roundness profile and its harmonic components were analyzed in Matlab.

#### Rotor dynamic measurement

The effect of the compensation grinding on the rotor response was investigated by measuring the response before and after the grinding. The vibration spectrum was measured from five different cross-sections of the rotor body using a measurement setup built on a rotor grinding machine (Fig. 7). The response was measured using the four-point method; however now the method ensured an accurate acquisition of the center-point movement of the rotor, without being affected by the rotor roundness profile in the particular cross-section. In brief, the rotor response was measured as follows:

- 1. A rotary encoder was used as a trigger and a measurement clock to ensure equal angular intervals between the samples (1024 samples per revolution).
- 2. The low-pass filtered analog signals from the laser triangulation sensors Matsushita NAIS LM 300 were acquired by National Instruments USB-6215 data acquisition card.
- 3. The rotor response was measured in a rotating frequency range from 4 Hz to 18 Hz with 0.2 Hz increments. 100 revolutions of data at each rotating frequency were acquired.
- 4. The 100 revolutions of data were synchronously averaged [8,22–25].
- 5. The four-point method was applied to the measured signals and the center-point movement and its harmonic components were analyzed in Matlab.



**Fig. 3.** The four-point method combines the traditional two-point diameter variation method ( $\Delta r$ ) and the Ozono three-point method (m). After Fourier transform (*F*) with FFT, odd harmonic components of the roundness profile are obtained from the three-point method, since it does not suffer from harmonic filtration and even components are collected from the two-point method. The combination can be finally inverse transformed ( $F^{-1}$ ) to reveal the roundness profile [19].



Fig. 4. The main dimensions of the rotor and the measurement cross-sections from 1 to 5. The results chapter presents the rotor response measured from the middle (3) cross-section [8].

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	d <sub>1</sub>		110	mm
	D		200	mm
	В		62	mm
	d <sub>2</sub>	*	139	mm
	d <sub>3</sub>		155	mm
	D <sub>1</sub>	~	174	mm
	B <sub>1</sub>		88	mm
	B <sub>4</sub>		22	mm
	b		8.3	mm
	К		4.5	mm
	r <sub>1,2</sub>	min.	2	mm

Fig. 5. Spherical roller element bearing SKF 23124 CCK/W33 with a conical adapter sleeve H 3124 (SKF 2017).



**Fig. 6.** The bearing inner ring was installed on the rotor shaft and the roundness profile was measured with the four-point method. The rotor was supported with auxiliary rollers during the measurement [19].



**Fig. 7.** Rotor dynamic response was measured with a measurement device based on the four-point method [8].

#### Compensative grinding

The bearing installation shafts of the rotor were compensatively ground (Fig. 9) using the 3D grinding [17] originally developed for paper machine rolls. The operating principle of this manufacturing method is that the final geometry is achieved with an iterative process using the roundness measurement data as feedback. However, unlike in the original 3D grinding method, the feedback roundness profile *was not acquired from the ground surface itself, but from the bearing inner ring*, after it was installed on the shaft (Fig. 8). Consequently, this was laborious and required multiple iterations, since the bearing inner ring had to be assembled, measured and disassembled between every grinding occasion.

The process described above was used to ensure the desired effect (minimized roundness error) on exactly the desired machine element (installed bearing inner ring). Since the installed bearing inner ring roundness error is composed of the roundness error of the shaft and the thickness variation of the conical adapter sleeve and the bearing inner ring, the measurement has to include the geometry information of all those components. Consequently, as a result of the iterative compensation grinding process, the installation shaft was ground to a non-circular roundness profile, which finally minimized the roundness error of the installed bearing inner ring.

The computation of the control curve c during the *n*th iterative grinding cycle is presented in Eq. (1).

$$c(\varphi)_n = \begin{cases} -r(\varphi)_n, & n = 1\\ -r(\varphi)_n + c(\varphi)_{n-1}, & n > 1 \end{cases}$$
(1)

During the first cycle (n=1), the roundness profile vector  $r(\varphi)$  (256 points, where  $\varphi$  represents the rotational angle) is only multiplied with -1 and used as such as a control curve. During possible further iterations, the negation of the new roundness profile measurement result is summed to the previous round control curve.



Fig. 8. The compensative grinding feedback cycle. The target roundness profile was consequently a perfect circle in this particular case. The control curve computation included the comparison to previous iterations.

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### Results



**Fig. 9.** Compensative grinding of the bearing installation shaft. The shaft was ground to a geometry, which minimized the roundness error of the assembled bearing inner ring.



**Fig. 10.** Schematic describing the functional principle of the grinding wheel position control. *X*-axis positioned the wheel to the grinding range and the actual grinding profile was realized with the *U*-axis.

The grinding tool itself consisted of a grinding wheel, the position of which was controlled with three axis. *Z*-axis positioned the wheel in the axial direction of the roll, *X*-axis positioned the wheel to the grinding range and *U*-axis was used in the actual grinding cycle to realize the control curve (Fig. 10). Consequently, the rotor was not supported by its own bearings, but by auxiliary rollers, which were in contact with the roll body (Fig. 9).

#### Experiment procedure

In the following, the experimental procedure is summarized in a step-by-step process. The repetitive assembly and disassembly of the components was conducted with a particular meticulousness to ensure similar conditions between the different stages of the process. The conical adapter sleeve and the bearing inner ring were assembled to the very same angular position throughout the study. There were reference markings in all the parts (rotor shaft, conical adapter sleeve and bearing inner ring) and these reference markings were carefully aligned after each iteration.

- 1. Initial grinding of the tending side bearing installation shaft.
- 2. The bearing inner ring was assembled and its roundness profile was measured.
- 3. The bearing inner ring was disassembled and the installation shaft was ground using the compensative grinding cycle (Chapter 2.5).
- 4. Stages 2 and 3 were repeated until no improvement was observed in the roundness profile of the installed bearing inner ring.
- 5. Stages from 1 to 4 conducted to the drive side bearing.
- 6. The complete rotor system with the bearings was assembled.
- 7. The rotor dynamic response was measured (Chapter 2.4).

The results from the bearing inner ring roundness profile measurements after the compensative grinding are presented and analyzed as angular domain roundness profiles and as harmonic component distributions. The rotor response in the middle crosssection is presented as frequency domain spectra in horizontal and vertical directions. In addition, the subcritical resonance peak amplitudes are presented separately. In all the cases, the results of the present study are compared to the original geometry data and the data obtained after the roundness error minimization with steel strips (both published earlier in [8]).

Fig. 11 presents the bearing inner ring roundness profiles and the corresponding subcritical rotor response spectra in the horizontal and vertical directions. The two roundness profile curves in red and in blue represent the roundness profile measurements in the middle of both the roller element paths of the two row spherical roller element bearing. The harmonic component distributions of the roundness measurements are collected in Fig. 12. Fig. 13 presents the resonance peak amplitudes of the response spectra in a bar chart form. Finally, Table 1 presents the rotating frequencies at which the subcritical resonance peaks were captured and the estimated natural frequencies.

In general, reducing the roundness error of the bearing inner ring decreased the subcritical resonance peak amplitudes substantially (Fig. 11). However, while the compensative grinding efficiently reduced the low-order (2nd and 3rd) harmonic resonance amplitudes, some increase in the higher order resonance responses was observed, especially in the 4th and 5th harmonic vibration component in the horizontal (x) direction.

A visual inspection of the roundness profiles revealed some additional noise in the roundness profile curves, particularly in the drive side, after the compensative grinding. However, this increased noise was not that clearly observed in the roundness profile harmonic component distributions presented in Fig. 12.

The compensative griding of the bearing installation shafts both in the drive and in the tending end of the rotor appears to function satisfactorily. The roundness error of the bearing inner ring could be further reduced from 10.4  $\mu$ m to 6.5  $\mu$ m in the tending end and from 8.5  $\mu$ m to 7.3  $\mu$ m in the drive end. Relatively, the reduction in the tending side was significantly greater.

When looking at the harmonic component distributions of the roundness profiles in Fig. 12, it can be observed that the grinding reduced most of the harmonic component amplitudes of the tending side below one micrometer. The 3rd harmonic component increased slightly in the 1st path of the tending side, in addition to the slight increases in the 5th harmonic component (both paths). In the drive side bearing, the most remarkable change was observed in the reduction of the 2nd harmonic component. However, the amplitudes of the 2nd and 3rd harmonic components of the second path of the drive side bearing remain clearly over one micrometer after the grinding. The 3rd harmonic component (2nd path) increased relatively much. Slight increases were observed in the 5th harmonic component (2nd path).

Fig. 13 presents the resonance amplitude peaks corresponding to the spectra presented in Fig. 11. The first harmonic component is excluded from the study, since the bearing geometry has only a minor effect on it. Typically the first harmonic component is concerned in the balancing process. In addition, the first harmonic component is converning the spectrum, when the rotating speed is approaching the natural frequency; in the present study, the focus was mainly on the subcritical response. The figure clearly shows that most of the amplitude reduction occurred alredy when minimizing the roundness error with the steel strips in the earlier published research. In addition, in the original case, the 2nd

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**Fig. 11.** The bearing inner ring roundness profiles and the corresponding response spectra of the rotor. The 1st harmonic component is excluded from the study. The X-axis of the response spectrum represents the harmonic components of the vibration, i.e., the number of vibration cycles per revolution. The drive end bearing geometry was not modified when minimizing the roundness error with steel strips. Both the bearing installation shafts were ground when minimizing the roundness error of the bearing inner ring with compensative grinding. The red and blue roundness profile curves represent the roundnesses in the middle the two rolling element paths of the bearing. The roundness error value was calculated from the curve producing the larger value. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

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**Fig. 12.** The distributions of the harmonic components of the bearing roundness profiles. The drive end bearing roundness was not modified when minimizing the roundness error with steel strips, and thus the distribution is not repeated in the figure. Both the bearing installation shafts were ground when minimizing the roundness error of the bearing inner ring with compensative grinding. The 1st and 2nd path represent the roundnesses in the middle of the two rolling element paths of the bearing and correspond to the red and blue roundness profile curves in Fig. 11.



**Fig. 13.** The subcritical resonance peak amplitudes in the middle cross-section of the rotor in the horizontal (x) and vertical (y) directions. The cases "strips" and "ground" were measured after the bearing inner ring geometry was modified and the roundness of the inner ring measured. The amplitude values presented here correspond to the peak amplitudes of the rotor response spectra presented in Fig. 11.

harmonic resonance was obviously the governing vibration component, which was efficiently reduced.

The compensative grinding reduced the 2nd and 3rd harmonic vibration components both in the horizontal and vertical directions remarkably. The reduction was relatively high, being in the range of 50% compared to the minimizing with steel strips. The vertical direction responses decreased more, but the difference in the responses may originate from other excitation sources as well. The 4th harmonic response in vertical direction did not change notably. However, the 5th harmonic component in both the direction increased significantly. The most remarkable relative growth was in the 5th harmonic horizontal response, which increased tenfold. These response increases can clearly be observed in the frequency spectra after grinding in Fig. 11 as well.

Table 1 presents the frequencies, at which the subcritical resonance peaks were captured. Utilizing these frequencies, the

natural frequencies in both horizontal and vertical directions are estimated (2nd harmonic resonance frequency is half the natural frequency, 3rd harmonic resonance frequency is one third of the natural frequency, etc.). It can be seen, that the natural frequency in the vertical direction remained almost unchanged despite the modifications of the bearing inner rings. Only minor reduction of ca. 0.1 Hz was observed comparing the original case to the modified cases. However, the natural frequency in the horizontal direction decreased more remarkably. Ca. 1 Hz difference in the natural frequency was observed between the original and the ground case.

## Discussion

The results clearly suggest that the compensative grinding of the bearing installation shafts can efficiently reduce the roundness error of the bearing inner ring. Despite the increases in certain waviness components of the roundness profile, the overall result implied that the method is usable. The relative reduction of the roundness error in the tending end was substantially larger, but finally the roundness error was in the same range (tending 6.5  $\mu$ m, drive 7.3  $\mu$ m). In addition, the results suggest that the compensative grinding method reduced the low order waviness components (2nd and 3rd) better, since even increase of some higher order components was observed.

Consequently, the efficiency of the compensative grinding was evaluated by measuring the subcritical response of the rotor. Particularly the amplitudes of the subcritical resonance peaks were investigated. The results, especially in Fig. 13, show that the grinding successfully reduced the amplitudes of the 2nd and 3rd harmonic subcritical resonance peaks. The decrease is notable compared to the compensation with steel strips and remarkable compared to the original bearing geometry. However, the amplitudes of the 4th and 5th harmonic resonance peaks increased unintentionally compared to the compensation with steel strips. Particularly, the 5th harmonic resonance in horizontal direction increased larger than in the original case. Such an increase cannot be explained with the bearing roundness profile waviness components, since in total the 5th harmonic components in the drive and in the tending side bearings are substantially lower after the compensation. The explanation may be some other excitation source or a coupling of the excitation coming from the both bearings. The phases of the waviness components of the roundness profiles have allegedly changed during the grinding and now certain waviness components in different bearing inner rings may reinforce each other. The rotor response was measured only after both the ends were ground, thus individual investigation of the effect of each bearing was not possible.

Although the 4th and 5th subcritical resonance amplitudes unintentionally increased, their significance in practical engineering is not that critical. The increased 4th and 5th subcritical resonances were detected at rotating frequencies from 4.2 Hz to 6 Hz, which are relatively low compared to the typical operating speed range of such rotors for example in the paper industry. The decrease of the resonance amplitudes of the 2nd, 3rd and vertical 4th resonance amplitudes can be seen highly valuable and relevant, since the effect was observed in the speed range 7.6 Hz–14.9 Hz, which can be seen to coincide with the typical operating speed range.

Table 1 shows a significant decrease in the horizontal direction natural frequency after the roundness error minimizing. The decrease may be caused by the increased radial clearance of the bearing producing a more flexible stiffness of the rotor in the horizontal direction. Although the bearing was assembled and disassembled with particular meticulousness to ensure equal measurement conditions, the clearance may have changed. The

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# 8 Table 1

The subcritical resonance peak frequencies and the estimated natural frequencies. The estimated natural frequency was calculated by multiplying the rotating frequency, at which a subharmonic resonance peak was detected, with the harmonic component number in question.

Case	Harmonics	Horizontal		Vertical	
		Rotating frequency [Hz]	Estimated natural frequency [Hz]	Rotating frequency [Hz]	Estimated natural frequency [Hz]
Original	2	10.8	21.6	15.0	30.0
	3	7.2	21.6	10.0	30.0
	4	5.4	21.6	7.6	30.4
	5	4.4	22.0	6.0	30.0
	Average		21.7		30.1
Strips	2	10.7	21.4	15.0	30.0
	3	7.2	21.6	10.0	30.0
	4	5.4	21.6	7.4	29.6
	5	4.2	21.0	6.0	30.0
	Average		21.4		29.9
Ground	2	10.4	20.9	14.9	29.8
	3	7.0	20.9	9.9	29.8
	4	5.2	20.7	7.6	30.2
	5	4.2	20.9	6.0	29.8
	Average		20.8		29.9

effect of radial bearing clearance is investigated, for example in [26].

The phenomena discussed in the last two paragraphs are interesting and pose a possibility for further research, for example, with a simulation approach. For example, the simulation tools introduced in [16,27–29] provides usable and unlaborious tools to investigate the effect of varying amplitude and phase of the waviness components of the bearing inner ring roundness profile on the rotor response, and may thus help to reveal the root causes.

The dynamic response of the rotor was measured from 4 Hz to 18 Hz with 0.2 Hz increments. Such a sparse measurement grid may not be able to capture the amplitudes and frequencies of the subcritical resonance peaks as accurately as possible, since the actual resonance may occur at very narrow frequency range. In the future studies, the frequency increment is suggested to be lowered. However, the results of the current study remain valid, since the purpose of the study was not to obtain the most accurate absolute values, but to investigate the change in the response after the compensative grinding.

The present study was partly initiated by the questioning of the industrial applicability of the steel strip method for roundness optimization used by Viitala et al. [8]. The steel strip method provided a proof-of-concept, which showed that modifying the bearing inner ring geometry is able to reduce the subcritical vibration responses. However, the method was very time consuming, and was prone to random error sources for example in the strip positioning. In addition, the durability of the steel strips during the continuous inprocess operation of a rotor was questioned. The present study, in which the geometry error is minimized with 3D grinding, provides a deterministic way to reduce the subcritical vibration excitation from the bearing assembly. The industrial implementations of the method show that the compensative shaft geometry can be ground whit existing 3D grinding machines, when the final geometry of the bearing installation shaft is manufactured anyway. In addition, it seems that sometimes even one measurement and grinding cycle is able to reduce the roundness error to a sufficient level, when the grinding parameters are carefully chosen. This signifies that the method looks promising and economic from the industrial perspective as well, especially when bearing excited subcritical vibrations induce severe problems to the actual operating process utilizing the rotor.

In addition, the aim was to further improve the roundness of the installed bearing inner ring. The present study suggests, that compensative grinding of the bearing installation shafts provides a reliable way to improve the roundness profile of the installed bearing inner ring. The manufacturing operation can be completely automated to remove the human factor. In addition, based on the result of the present study, the computation of the grinding control curve in the feedback loop of the manufacturing process (Fig. 8 and Eq. (1)) can be further improved to reduce the number of iterations. The present study shows that using the compensative 3D grinding method in a novel way to reduce the roundness error of the bearing inner ring without grinding the ring itself is fully functional and may next be applied to industrial processes as well. Although the bearing inner ring was assembled using a conical adapter sleeve (Fig. 5) on the rotor shaft (the actually ground component), the sufficiently linear fitting of the components ensured the roundness error reduction in the desired component.

One option to improve the roundness profile of the installed bearing inner ring is to reduce the thickness variation of the bearing components (inner ring and conical adapter sleeve) and to improve the fit between those two components. Thus, the rotor manufacturer could concentrate on manufacturing the bearing installation shafts of the rotor as round as possible, possibly using the grinding method presented here. Another option is to measure the bearing components and the installation shaft and then install the components in angular positions, which results in the lowest roundness error with the available components and their geometries.

The relative accuracy of the compensative grinding was found very satisfactory compared to the large size of the workpiece (residual roundness error of the bearing inner rings ca. 7  $\mu$ m, rotor length 5 m, rotor body diameter 320 mm). The presented compensative grinding method does not set an upper limit to the workpiece size. The measurement uncertainty of the measurement methods used in the present study are discussed in [18,19,30], resulting in a sub micrometer uncertainty in both the bearing inner ring roundness measurement and the dynamic response measurement of the rotor.

### Conclusion

The present study introduced a novel measurement, compensation and manufacturing method to reduce the roundness error of a bearing inner ring, which is installed on a shaft of a large rotor. Compensative grinding was utilized to manufacture the installation shaft to a roundness profile, which minimized the roundness error of the roller element paths of the installed bearing inner ring.

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Briefly, the method consisted of the following procedure. First, the roundness profile of the installed bearing inner ring was measured. Second, the bearing inner ring was disassembled. Third, the installation shaft on the rotor was ground to a non-circular compensative geometry, which should minimize the roundness error of the installed bearing inner ring. The method could be used iteratively, i.e., repeating the procedure until the end result is satisfying.

The successful performance of the grinding operation was confirmed by the reduced roundness error in both the drive and tending end bearings. The method was found the most effective on the low order waviness components (particularly 2nd and 3rd H) of the roundness profile.

Moreover, the dynamic response of the rotor was measured before and after the roundness error minimization. The dynamic response measurement showed significant decrease in the subcritical resonance peak amplitudes in the operating rotating frequency range of the rotor, which proved the relevance of the method and the study.

The method can be considered to be suitable for industrial applications. Furthermore, the study provides essential technical and scientific information of the bearing excitations in rotor systems, and methods how to reduce them. The results presented here can be used to develop the design of bearing components and rotor-bearing systems.

Future studies should include the investigation of other bearing installation designs, such as a cone manufactured directly on the rotor shaft.

#### **Declaration of interest**

The author has nothing to declare.

#### Acknowledgements

This work was supported by Academy of Finland (TwinRotor, grant number 313675).

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