



Good Practice Guide No. 148

Measurement of the Surface Texture of Large Roller Bearings



INTERMEDIATE

TECHNICAL LEVEL



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Abstract

Rolling bearings are common in mechanical systems and are used to reduce friction between rotating components. The performance and lifetime of the bearings is closely linked to the surface texture of their raceways. This guide outlines good practice for surface roughness measurement of bearings, building upon the recommendations of previous Good Practice Guides. Common roughness parameters used when studying bearings are discussed, and differences in terminology clarified.

The guide assumes that the reader is familiar with surface texture measurements, terminology and analysis, particularly focussing on the use of stylus instruments. Readers who are not familiar with these topics are directed to NPL Measurement Good Practice Guide No. 37: The Measurement of Surface Texture using Stylus Instruments, which describes them in detail.

This guide is not intended to be an authoritative guide to the surface parameters and bearing specification standards.

Acknowledgements

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Chapter 1

Overview of bearings

- Bearing geometry and active surfaces
- Bearing surface roughness
- Bearing surface waviness

Bearing geometry and active surfaces

Rolling bearings are common in mechanical systems and are used to reduce friction between rotating components. This Good Practice Guide has been developed with two bearing geometries in mind: spherical roller bearings (SRBs) and tapered roller bearings (TRBs). Spherical roller bearings are designed to work with misaligned axes of rotation. Tapered roller bearings are designed to work with radial and axial loads simultaneously [1]. While the techniques in this guide are primarily aimed at these two designs, they should be broadly applicable to most bearings.

The surfaces of a bearing that are of interest are those which interact during motion, primarily the inner raceway, outer raceway, rollers and the roller cage. These surfaces are indicated in Figure 1.

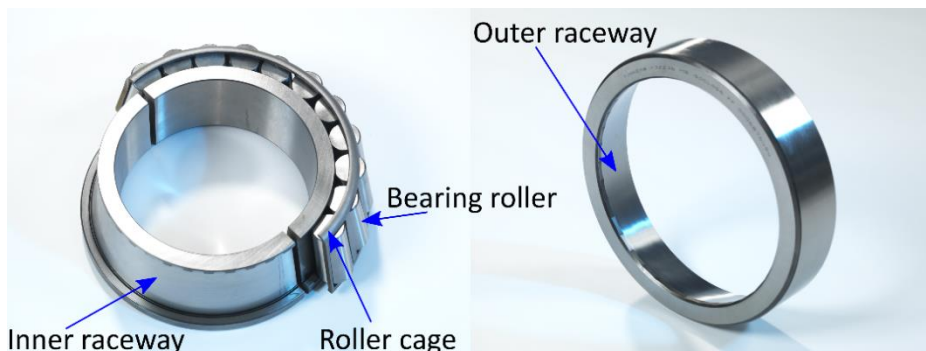


Figure 1. Active bearing surfaces of a tapered roller bearing. The inner raceway and cage have been halved for ease of handling.

The surfaces of the rollers and roller cage are beyond the scope of this guide, but are amenable to standard surface measurement techniques. Measurements of the two raceways are challenging due to the large range of length scales that are of interest when understanding the performance of the bearing and are the primary focus of this guide. These length scales are typically separated into roughness and waviness regions based on the length of the surface features.

Surface features of different sizes affect the bearing performance in different ways. Roughness and waviness features are described in the following sections.

Note on roughness

Bearing literature often defines roughness as surface features which are smaller than the contact area between the raceway and the rolling element. The size of this area varies between applications, but is often around $50\text{ }\mu\text{m} - 500\text{ }\mu\text{m}$ [2]. This definition is not guaranteed to match the metrological roughness cutoff wavelength, the wavelength at which roughness is distinguished from waviness. This guide will use the metrological definition for the roughness cutoff throughout.

Note on waviness

In surface texture metrology, the waviness of a surface is defined as those features which have longer wavelengths than the roughness cutoff, but are short enough that they are not yet considered to be part of the form. While the roughness cutoff is well defined by standards, the boundary between waviness and form is not and the definition is often application specific.

In the bearing industry, waviness (or harmonics) is often used to describe large-period features that occur around the raceways or rollers. The periodicity of such features is defined as a certain number of undulations per revolution (UPR). The undulations are not necessarily present around the entirety of the bearing raceway, but can affect performance even if concentrated in a small region. Where few waves per circumference are present, it is debatable whether this definition of waviness is best described as form rather than surface texture. Further details will be given in the section 'Bearing surface waviness'.

Bearing surface roughness

The roughness components of the bearing's surface texture are small enough that they vary within the Hertzian contact region between the bearing raceway and the rolling elements. The roughness contributes to both the friction and wear of the bearing.

Regularly used parameters are the arithmetical mean deviation of the roughness profile, Ra , or the root mean square deviation of the profile Rq , which are used to describe the overall level of surface roughness. The root mean square slope of the roughness profile $R\Delta q$ is related to the hardness and elasticity of the surface and the Hertzian contact stress that it will experience.

It is common to define the film thickness parameter, Λ or λ , also known as the lambda parameter, using the following equation where h is the lubricant film depth between perfect surfaces and $R_{q,1}$ and $R_{q,2}$ are the root mean square deviations of the roughnesses of the two interacting surfaces [3–6]. The symbol λ is also used to denote film thickness, for example in Figure 2.

$$\Lambda = \frac{h}{\sqrt{R_{q,1}^2 + R_{q,2}^2}}$$

The film parameter describes the likelihood of asperity contact between the two surfaces as they move past each other. Asperity contact leads to friction and damage to the surfaces. The relationship between the film parameter and the coefficient of friction is shown in Figure 2.

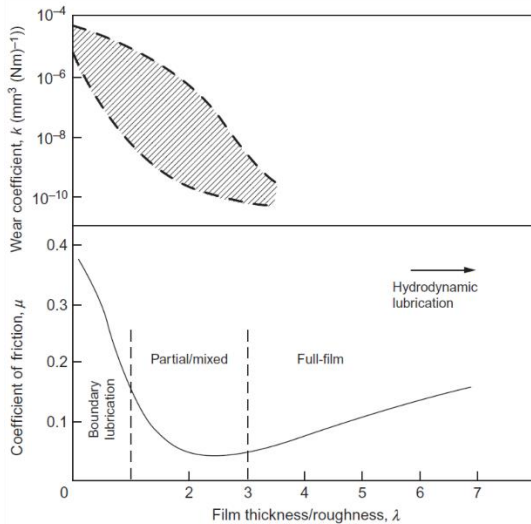


Figure 2. The relationship between the film parameter and the coefficient of friction [5]. Reprinted from *Tribology: Friction and Wear of Engineering Materials*, 2nd Edition, I. Hutchings and P. Shipway, Chapter 5: Sliding Wear, pg. 141, Copyright 2017, with permission from Elsevier. Originally printed in: Czichos, H., Habig, K.-H., 1985. In: Dowson, D., et al. (Eds.), *Mixed Lubrication and Lubricated Wear*, Proc. 11th Leeds-Lyon Symposium on Tribology, Butterworths, pp. 135–147.

Figure 2 is separated into three regions: boundary lubrication, partial elastohydrodynamic lubrication (EHL) and full-film EHL. In boundary lubrication the asperity height is often larger than the lubricant film depth, resulting in frequent contact between the two surfaces, high frictional forces and wear. In the partial EHL regime, asperity contact occurs less frequently, providing reduced friction. In full-film EHL asperity contact is rare, meaning that wear is low,

but viscous drag in the thick oil layer means that frictional forces increase. Most bearings operate in the low-friction, low-wear partial EHL regime.

The damage caused to the surfaces through asperity contact has been reduced through years of bearing development such that the common failure modes in modern bearings are typically due to factors such as poor alignment, incorrect lubrication, contamination or sub-surface defects rather than the surface texture. Other effects such as vibration and chemical effects are also thought to play a part in some applications. The effect of surface texture on bearing lifetime is described in ISO 281, which allows for the surface roughness through the lifetime modification parameter, a_{ISO} . The lifetime modification parameter increases with the film parameter, which can be used to approximate the viscosity ratio. Reducing the overall surface roughness will increase the expected lifetime of the bearing according to the standard (see Chapter 5 for information on standards). This effect has long been discussed in academic literature [7,8], and continues to be investigated [4,9].

Bearing surface waviness

Surface waviness describes features varying in size from the roughness cutoff wavelength up to the full circumference of the bearing raceway. Surface waviness features are sufficiently large that they do not play a role in the contact between the surfaces. The primary effect of such features is to introduce extra vibration into the bearing mechanism as the moving parts periodically encounter, and are displaced by, the same surface deviations. Of the two raceways, the inner raceway is most important with regards to vibration [10,11]. Waviness-based vibration, which typically occurs at frequencies related to the rotation frequencies of the cage, inner raceway or of the rollers themselves [12, 13], can be detected using vibration monitoring equipment [6,14]. Changes in the vibration spectrum can indicate changes in the surface texture of the bearing components and so provide advance warning of mechanical failures.

Knowledge of the waviness of the bearing surfaces enables predictions of the vibration frequencies and amplitudes to be made [12, 13, 15, 16]. The calculation is complex and utilizes the amplitudes of specific wavelengths of waviness, meaning that generalized parameters are not necessarily useful in this case. The vibration frequencies of interest are typically below 60 times the bearing's rotational frequency [14], but frequencies up to 300 times the bearing's rotational frequency are sometimes used [2].

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Chapter 2

Recommendations for bearing end users

To achieve its maximum lifetime, manufacturers typically recommend that a bearing is kept in its original packaging until it is to be installed, which should then be done immediately. A bearing should be protected from the environment by keeping it coated in the recommended lubricant at all times. Once installed, a bearing should not be removed until it fails, shows signs of damage on monitoring equipment or reaches the end of its predicted lifetime.

These recommendations necessarily inhibit surface measurement which requires that the target surface be cleaned and accessible to the measurement instrument. Accessibility can often be an issue – the inner raceway in particular is often contained by the rolling elements and the cage, preventing measurements from taking place.

Surface parameter measurements of bearing raceways is difficult and potentially damaging to the component. Great care is therefore required when performing such measurements.

General measurement recommendations are given below:

1. When considering bearing surface measurements, it may be worth contacting bearing manufacturers or bearing refurbishment services for advice. Such companies routinely measure bearing raceways and are therefore used to handling the delicate bearing surfaces. In addition to being equipped with bespoke equipment that may be required for the measurements, they could also be able to advise on equipment and measurement approaches to minimise damage caused to the bearing.
2. Minimise the time that the bearing is exposed. By cleaning the bearing only for the measurement period and reapplying the protective grease or lubricant once measurements are complete, the risk of contamination can be reduced.
3. Seek advice on whether to reuse the bearing. Even a bearing which has no obvious damage and acceptable surface texture may have developed subsurface cracks which could lead to rapid failure if it was to be returned to use. It is often inappropriate to reuse a bearing that has been removed from its housing.

Chapter 3

Surface roughness measurements

- Surface preparation
- Measurement equipment
- Choice of filter cutoff wavelength
- Choice of measurement direction and identification of typical bearing lays
- Relevant roughness parameters
- Calculating the local slope and $R\Delta q$

This section will describe the conventions of surface roughness measurement for bearings, building upon the general recommendations found in NPL Measurement Good Practice Guide No. 37: 'The Measurement of Surface Texture using Stylus Instruments.' The reader is directed to that guide for detailed measurement good practice.

Surface preparation

Before performing a measurement it is important to remove any oil, grease, dust or mist from the surface of the raceway. Use a suitable solvent to remove oil or grease, a lint-free cloth for dust and mist and a filtered air spray for other gross contamination. Contact the bearing manufacturer for recommendations for suitable solvents if you require recommendations. It is important to replace any grease that is removed once the measurement is complete, as this will prevent unnecessary corrosion of the bearing surface.

Measurement equipment

When measuring the surface roughness of a bearing raceway commercial stylus measurement instruments remain an appropriate choice. Such devices are available from a wide variety of manufacturers.

Table-top stylus instruments are typically designed to measure horizontal surfaces. While it is usually possible to mount standard bearings in such a way that the measurement surface is near-horizontal, this is not necessarily true of large bearings (such as those used in the wind energy industry). Large bearings can deform if positioned in an upright position and it is often recommended to keep them flat until installation. Where the bearing must be kept flat, portable roughness testers may be more appropriate because measurements of the surface roughness must be performed vertically. However, portable roughness testers are less accurate than table-top stylus instruments, which should be taken in to account before choosing this approach.

Choice of filter cutoff wavelength

The choice of a suitable roughness cutoff wavelength is dependent upon the application and the machining method used to produce the bearing raceway. NPL Measurement Good Practice Guide No. 37 provides suggestions for the choice of wavelength for a variety of machining techniques and levels of surface finish. It is also good practice to consider the functionality of the surface being measured, including factors such as the size of the Hertzian and fluid contact regions. For most bearings a λ_c filter wavelength of 0.8 mm is appropriate, but in the case of larger bearings a 2.5 mm filter may be more appropriate.

Choice of measurement direction and identification of typical bearing lays

As with usual surface roughness measurements, the direction of the measurement should be perpendicular to the direction of the lay of the bearing raceway. The direction of the lay is determined by the machining process used to produce the bearing and should be verified before a measurement is performed.

Two examples of bearing lay, along with the appropriate measurement direction, are provided in the case studies on the following pages.

Case Study 1: Inner raceway of a tapered roller bearing

Figure 3 shows the inner raceway of a tapered roller bearing. The raceway has a simple lay which is parallel to the direction of rotation, meaning that the correct direction for a surface roughness measurement is traverse, or parallel with the axis of rotation, directly across the raceway. This measurement is complicated by the slope of the raceway.

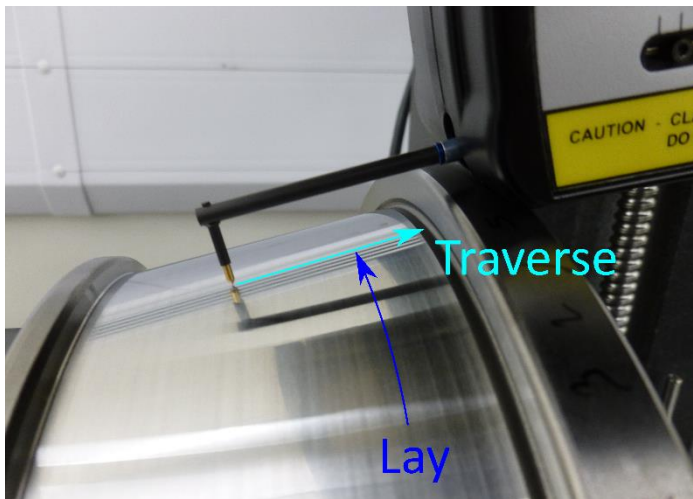


Figure 3. The lay of the inner raceway of a tapered roller bearing. The lay is parallel to the direction of rotation and so the correct measurement direction is across the raceway.

If possible, the bearing should be mounted such that the stylus does not have to traverse a slope. Where a measurement along a slope is unavoidable, it is best practice to perform a measurement in both directions (both ascending and descending the slope). Care should be taken to ensure the measurement direction remains perpendicular to the lay when repositioned. Duplicating the measurement in this way allows direct comparison between the results to ensure that the gradient has not had an effect on the measurement.

Case Study 2: Outer raceway of a spherical roller bearing

The raceway shown below in Figure 4 and Figure 5 has a more complex lay than the tapered roller bearing, consisting of overlapping circular marks. Two measurements would be required in this case, one perpendicular to each mark. The values of the surface parameters that are reported should be the higher of the two values.

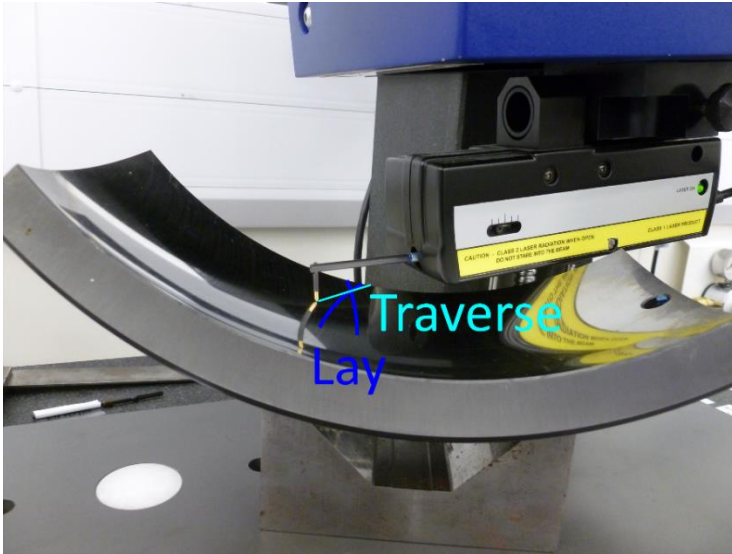


Figure 4. The traverse direction for the outer raceway of the spherical roller bearing. The bearing has two rows of rollers, meaning that the centre of the raceway is expected to be inactive.

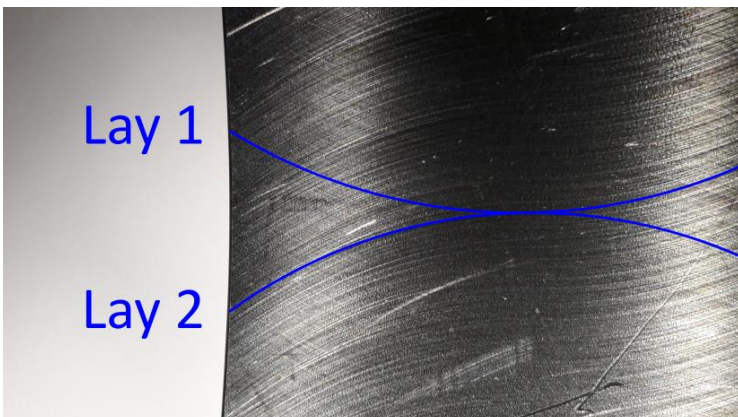


Figure 5. The two spherical roller bearing outer raceway lays.

While the two patterns overlap at the centre of the raceway, this may not be an appropriate measurement position. The primary reason for that decision is that the centre of the raceway should be inactive (assuming minimal misalignment) because the bearing has a double row of rollers. A measurement of the central region is therefore not providing information about the functional region of the bearing. The second reason not to use the central region is purely practical – it is difficult to access it with typical stylus equipment. Measurements towards the edges of the raceway allow access at an angle, but at the centre the stylus instrument would need to be contained within the ring, which is not possible in this instance due to the size of the bearing. These two issues illustrate how practical considerations influence the choice of measurement equipment and direction.

Relevant roughness parameters

The common ISO surface parameters used when evaluating a bearing raceway are the *arithmetical mean deviation of the assessed profile* (Ra) and the *root mean square slope of the assessed profile* ($R\Delta q$). The Rq parameter is used in the calculation of the film parameter, as described earlier. The Ra and Rq parameters are defined in NPL Measurement Good Practice Guide No. 37 and are easily calculated using standard surface analysis software. The calculation of $R\Delta q$ is described below as it was not included in NPL Measurement Good Practice Guide No. 37, although it is included in many software packages.

Calculating the local slope and $R\Delta q$

The local slope (dZ/dX) and root mean square slope of the assessed profile ($R\Delta q$) are defined in ISO 4287:1998+A1:2009 (see Chapter 5 for information on standards). The procedure for calculating the parameters was not described in NPL Measurement Good Practice Guide No. 37 and so is provided here.

The local slope is the slope at a given measurement position, x_i , as shown in Figure 6. It is calculated using the following formula:

$$\frac{dZ_i}{dX} = \frac{1}{60\Delta x} (z_{i+3} - 9z_{i+2} + 45z_{i+1} - 45z_{i-1} + 9z_{i-2} - z_{i-3})$$

where Δx is the spacing between samples in the x direction, and z_i is the profile height at position x_i . Note that this definition means that it is only possible to calculate $N - 6$ values of the slope within a sample of N data points. The slope can be calculated separately for the primary (P), waviness (W) and roughness (R) profiles. It is the roughness profile which is of interest when discussing the surface of a bearing raceway.

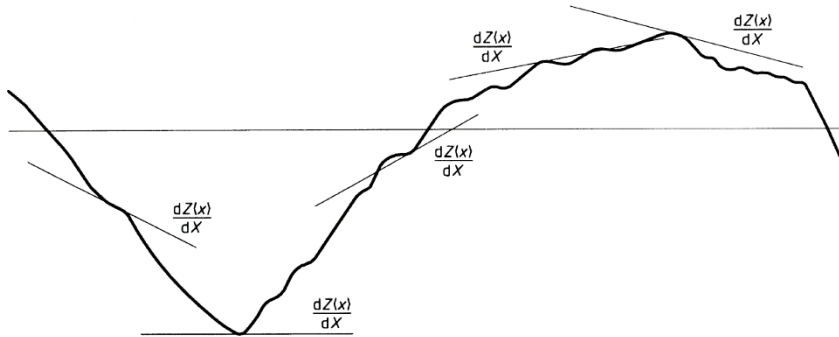


Figure 6. The definition of local slope, reproduced from ISO 4287:1998+A1:2009.

Once the local slopes of the roughness profile have been calculated, the root mean square can be calculated as below:

$$R\Delta q = \sqrt{\frac{1}{N-6} \sum_{i=4}^{N-3} \left(\frac{dZ_i}{dX} \right)^2}$$

Here, N is the number of samples in the sampling length, and the first point is $i = 1$. The above equation is also valid for the waviness and primary profiles if their slope is used in the calculation. The $R\Delta q$ parameter should be calculated over the sampling length.

Chapter 4

Waviness measurements

- Why are circumferential measurements difficult?
- Roundness or waviness measuring machines
- CMM measurements

The best approach to the measurement of the surface waviness of a bearing depends heavily upon the direction of measurement. In the transverse direction (across the raceway), the recommendations from the previous chapter called 'Surface roughness measurements' apply, with the only difference being that the length of the measurement must be long enough for the features of interest to be observed. It should be noted that the cross-sectional profile of a raceway does not necessarily have a simple flat or circular form, and a polynomial fit may be appropriate. The extreme regions of raceways should be avoided when measuring waviness unless required for specific applications.

If the surface waviness measurement is to be made around the circumference, then the task becomes more difficult and typically requires specialist equipment. This chapter will describe the difficulties of such measurements and provide a brief overview of equipment available to perform circumferential waviness measurements. If such measurements are required, we recommend that the reader contact the bearing manufacturer or a metrology company for advice which is tailored to their specific measurement task.

Why are circumferential measurements difficult?

Waviness measurements around the circumference of a bearing are difficult because of the large range of scales that are covered by the term. Any feature which is larger than the roughness cutoff wavelength is describable as waviness. As such, it is important to determine which features will be important to the smooth running of bearing and which features can be neglected. As described in 'Bearing surface waviness' earlier in this guide, waviness mainly contributes to the vibration of the bearing. The frequency of the vibration that is produced is dependent upon the rotational speed of the various bearing components and the number of rolling elements that are present. Waviness features that correspond to low numbers of undulations per circumference are usually the most important, but typical stylus instruments are unsuited to measure such features. In small bearings, the radius of curvature is too large and the stylus instrument will often be unable to fit in a position which enables the measurement to be performed (a problem which is especially acute for the outer raceway of a bearing). When applied to large bearings, a stylus instrument does not have sufficient travel to sample the features of interest. As such, a detailed description of circumferential measurements of bearing waviness is beyond the scope of this guide.

The following sections are included to provide the reader with a brief overview of common measurement equipment, namely roundness/waviness measurement machines and coordinate measuring machine (CMM) measurements. Waviness analysis tools, such as harmonic analysis, are commonly available for both types of system, although the functionality provided will vary between manufacturers.

Roundness or waviness measuring machines

Roundness and waviness measurement machines use a sensor to measure the surface of an object in a manner similar to a typical surface profiler, but rather than traverse a straight line, either the sensor or the target itself are rotated. Such machines are the preferred approach when measuring bearing raceway waviness.

The size of the object that can be measured is limited by the size of the machine itself and the mass of the component. Devices which are capable of measuring components with diameters over 1.5 m have been produced, but are often expensive, bespoke machines.

Measurement machines of this type are produced both by metrology companies and by bearing manufacturers themselves. An example of a large roundness measurement machine, which uses a stylus to measure the surface, is shown in Figure 7. Other measurement systems are based on inductive measuring sensors and systems which measure at multiple positions around the bearing, and are capable of determining the bearing thickness, are available. An example of a waviness measurement machine is shown in Figure 8.



Figure 7. An example of a large roundness measurement machine.
Reproduced with permission from Taylor Hobson Ltd [17].



Figure 8. A waviness measurement machine with inductive sensors.
Reproduced with permission from SKF [18].

NPL does not currently provide a Good Practice Guide for roundness or waviness measurement machines. The user should contact the equipment manufacturer for recommended measurement practice.

CMM measurements

Measurements of the surface waviness of a bearing using a CMM are usually only performed when no suitable dedicated machine is available, for example when measuring very large bearings. A CMM is a general purpose device and as such it is not optimised for waviness measurements. There are two approaches to waviness measurement: discrete point probing or contact scanning. Discrete point probing measurements are useful if the periodicity of interest is known, as this enables the user to select a suitable spacing for measurements of the bearing surface (it is good practice to make at least seven measurements per wavelength of the period of interest). A CMM capable of performing a contact scanning measurement will provide a greater density of information and may be quicker than measuring a series of discrete points, but is also generally more expensive.

NPL has produced several good practice guides for CMMs which are listed in the next chapter.

Chapter 5

Further reading and references

- Stylus instruments
- Other surface texture devices
- CMM measurements
- General interest and dimensional metrology
- ISO standards
- References

This section provides a list of other NPL Measurement Good Practice Guides that may be of interest when measuring the surface characteristics of bearings. It also lists the ISO standards directly referred to in this guide.

Unless otherwise stated, the guides are available from the NPL website:
<http://www.npl.co.uk/publications/guides/>

Note: * indicates a non-NPL author.

Stylus instruments

Measurement Good Practice Guide 37: The measurement of surface texture using stylus instruments (Issue 2), Leach, R K.

Measurement Good Practice Guide 129: Calibration of the metrological characteristics of contact stylus instruments, Giusca, C L, Leach, R K.

Other surface texture devices

Measurement Good Practice Guide 108: Measurement of smooth surface topography using coherence scanning interferometry, Leach, R K, Brown, L*, Jiang, X*, Blunt, R*, Conroy, M*, Mauger, D*.

Measurement Good Practice Guide 116: The measurement of rough surface topography using coherence scanning interferometry, Petzing, J*, Coupland, J*, Leach, R K.

Measurement Good Practice Guide 127: Calibration of the metrological characteristics of Coherence Scanning Interferometers (CSI) and Phase Shifting Interferometers (PSI), Giusca, C L, Leach, R K.

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CMM measurements

Measurement Good Practice Guide 41: CMM measurement strategies (Issue 2), Flack, D.

Measurement Good Practice Guide 42: CMM verification (Issue 2), Flack, D.

Measurement Good Practice Guide 43: CMM probing (Issue 2), Flack, D.

Measurement Good Practice Guide 130: Co-ordinate measuring machine task-specific measurement uncertainties, Flack, D.

General interest and dimensional metrology

Measurement Good Practice Guide 11: A beginner's guide to uncertainty in measurement (Issue 2), Bell, S A.

Measurement Good Practice Guide 36: Estimating Uncertainties in Testing, Birch, K.

Measurement Good Practice Guide 80: Dimensional metrology, Flack, D R, Hannaford, J.

Measurement Good Practice Guide 118: A beginner's guide to measurement, Goldsmith, M.

ISO standards

ISO 4287:1998+A1:2009: Geometrical product specification (GPS). Surface texture: Profile method. Terms, definitions and surface texture parameters.

ISO 281:2007: Rolling bearings. Dynamic load ratings and rating life.

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Measurement of the Surface Texture of Large Roller Bearings

Good Practice Guide No. 148

Rolling bearings are common in mechanical systems and are used to reduce friction between rotating components. The performance and lifetime of the bearings is linked to the surface texture of their raceways. This guide outlines good practice for surface roughness measurement of bearings, building upon the recommendations of Good Practice Guide No. 37: The Measurement of Surface Texture using Stylus instruments. Common roughness parameters used when studying bearings are discussed, and differences in terminology clarified.



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