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ABSTRACT

The functional behavior of sealing surfaces and bearings depends on the texture direction with respect to the axis of rotation of a machined part, known as the twist or lead angle. We present our lead angle measurement solution using interference microscopy, multi-axis staging, and advanced software for determining surface texture direction and cylinder rotation axis.

Keywords: Interferometry, surface texture, lead angle, twist angle, rotary seal, cross hatch.

1. INTRODUCTION

Friction is the enemy of engine reliability and performance. Manufacturers know this all too well and work to engineer rotary dynamic seals for revolving cylindrical parts to minimize friction and wear. The surface texture of the seal must be precise to maximize performance–a rough seal surface texture wears quickly, while seals that are too smooth do not bed properly [1]. Creating the cylindrical sealing surface may involve a variety of turning, grinding or honing methods.

The machining process for rotatory shafts can leave intended or unintended signatures in the surface texture. These signatures often include groove bands, or more generally, a dominant direction for texture marks. A surface texture directionality that is not strictly circumferential can result in undesirable lateral fluid flow out of the bearing. Following common usage in sealing surface characterization, and in analogy with terminology for screws and gears, the lead or twist angle is the arctangent of the axial advance of the nominally helical structure of the surface texture during one complete turn. The tolerance for lead angle is quite demanding: The angle tolerance must be less than 0.05°, and the metrology precision for lead angle should therefore be 10× better, or 0.005°.

A frequent metrology task is the evaluation of the lead angle [2-4]. Although the dominant metrology methods involve some form of contact metrology; we report here on the development of an optical non-contact method for simultaneously evaluating the surface texture quality and the lead angle direction for cylindrical surfaces. The technique involves a combination of precision staging and interference microscopy, as illustrated in Figure 1. Experimental results demonstrate that the technique is consistent with the demanding requirements of modern precision-engineered seals.

Figure 1. Experimental geometry (left) and example topography (right) for a shaft measurement.

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2. MEASURING LEAD ANGLE

Figure 2 illustrates the concept and geometry of lead angle. A cylindrical part has a rotation axis collinear with the global coordinate axis x'. The 2D image of the surface in the right-hand portion of the figure shows a portion of the cylinder surface orthogonal to the z' axis, with projection of the y' axis illustrating the circumferential direction of rotation of the cylinder. The 2D image has had the cylindrical form component removed to reveal the directionality to the surface texture, here illustrated by groove bands created by a turning process, which define a lead angle $D\gamma$ between the surface texture direction and the circumferential rotation direction [5]. The measurement challenge is to determine this angle.

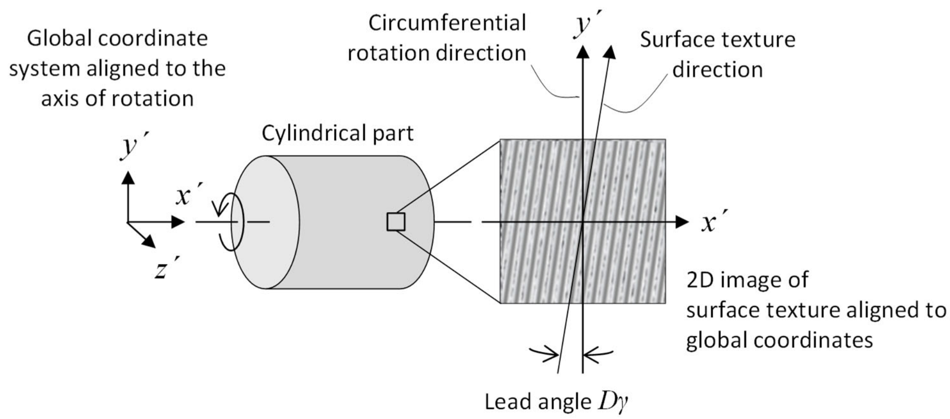


Figure 2. Geometrical definition of the machining lead angle for a cylindrical part.

A once-standard and still common method of lead angle measurement involves a weight suspended from a string draped over the shaft, with the surface lightly lubricated with silicone oil. The texture direction on the cylinder surface causes the string to gradually move left or right, progressing a distance with each full rotation given approximately by the lead angle in radians times the circumference of the cylinder. There are recommendations for the weight (1oz) and even the type of string (0.23mm diameter cotton quilting thread) [6]. The test is straightforward and can be performed on a lathe; however, the string method has not proven to be sufficiently reliable and repeatable for current manufacturing requirements. Measurement results can vary widely from user to user and for different surface wetting and revolution speeds [2].

More recently, this traditional technique has been supplanted by methods based on stylus profiling instruments [7]. These methods have proven to be more systematic, quantitative and repeatable; and have been standardized by many manufacturers [8][9]. The stylus measurement consists of 72 cross-sectional, 4000-point surface profiles, each taken in the direction of the cylinder axis, over a sequence of angular positions indexed in 15° increments. Theses profiles are stacked and analyzed for the orientation of macroscopic grooves (the "macro lead") in the surface texture [7]. A limitation of this type of analysis is that it overlooks fine-scale surface texture (the "micro lead"), mandating further measurements at smaller increments, in an attempt to fill in the gaps between the 2D profiles [7]. The logical endpoint for this development is a full 3D images taken around the circumference of the cylinder; but the implied data density would require too much time using conventional stylus instrumentation. This is a significant issue, given that many new cylinder forming methods generate fine-scale texture that does not resemble surface grooves, but nonetheless has a dominant texture direction that must be controlled.

3. LEAD ANGLE FROM AREAL TOPOGRAPHY

Non-contact optical methods of examining surface texture have proven to be valuable in modern precision machining of many types of sealing surfaces [10, 11], and it is natural to consider 3D optical topography measurements for the determination of lead angle [12]. Coherence scanning interference microscopy [13], based on white-light sources and interference objectives paired with automated data acquisition, has been established as a preferred alternative to the traditional string and contact stylus methods [14].

The evaluation of lead angle using 3D topography requires determination of the dominant direction of the surface texture within the measurement area as well as the orientation of the measurement area with respect to the cylinder axis or axis of rotation [15]. The task is summarized in Figure 3, which illustrates an area measurement of surface topography in a grey-scale image. The local lateral coordinates for the topography image are x, y while the global coordinates aligned with the cylinder are x', y'. If we assume nominal alignment of the local z axis with the global z' axis, then the lead angle is

$$D\gamma = 90° - S_{\text{td}} - \beta \ , \tag{1}$$

where β is the orientation of the topography image with respect to the global coordinates, and S_{td} is the ISO surface texture direction parameter.

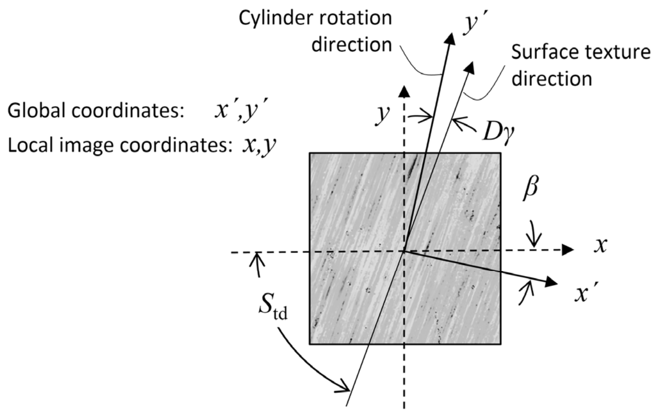


Figure 3. Determining lead angle from a local topography map.

Following ISO 25178-02, to determine the texture direction S_{td}, we calculate the Fourier Transform of the scale-limited (i.e. form-removed) surface topography in two dimensions. In x, y coordinates, this is

$$F(p,q) = \iint_A h(x,y) \exp\left[-(ipx + iqy)\right] dxdy \ , \tag{2}$$

where p, q are spatial frequencies (e.g. in radians/mm), $h(x,y)$ is the surface height data and A refers to the total sampled area. The Fourier Transform $F(p,q)$ may also be expressed in polar coordinates as $F(r,s)$ using

$$\begin{aligned} p &= r\sin(s) \\ q &= r\cos(s) \end{aligned} \ , \tag{3}$$

where s is an angle and r is a radius in frequency space. The angular frequency spectrum for the surface texture is then defined as an integration along the radial direction between two radial positions R_1, R_2:

$$f_{\text{APS}}(s) = \int_{R_2}^{R_1} r\left|F(r,s)\right|^2 dr \ , \tag{4}$$

The texture direction S_{td} is defined as the angle s for which the angular spectrum f_{APS} is maximum [16, 17].

The calculation of the surface texture direction with high resolution is actually quite challenging. We have found that most commercial software packages for surface analysis report an S_{td} with a resolution of about 0.1°, limited by the discrete sampling in the x, y plane. This is far too large for a lead angle measurement, which as noted in the introduction, should be better than 0.005°. In our work, we developed a much higher performance calculation of texture direction that has a resolution of 0.0002°, as confirmed using simulated topography data.

To complete the calculation of lead angle, Eq.(2) requires the orientation angle β for the topography image. One approach is to find the least-squares best fit of a cylinder (or other rotationally-symmetric shape) to the overall form of the topography $h(x, y)$, with the angle β as a free parameter [4, 15, 18, 19]. Another approach uses correlation between overlapping fields taken around the circumference to determine the axis of rotation [20]. The relative benefits in terms of measurement uncertainty depend on the size of the measured field and the radius of curvature of the shaft.

RESULTS

Figure 4 illustrates our implementation of a lead-angle measuring system using a ZYGO NewView™ coherence scanning interferometry microscope and Mx software, which incorporates our high-resolution calculation of the ISO surface texture direction parameter S_{td} [21]. The platform incorporates staging for accommodating precision-manufactured parts that comprise surfaces for rotary seals.

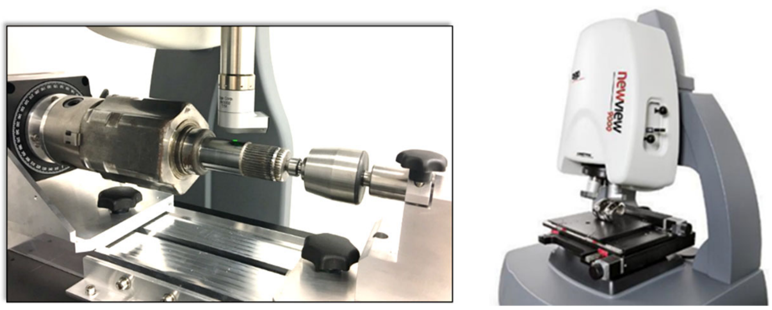
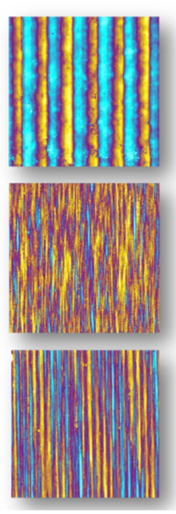


Figure 4: Left: Staging for a sample part. Right: Interference microscope for measuring areal surface topography.



Lead angle	0.0720	Rear differential pinion for heavy duty pickup
Repeatability	0.0239	

Lead angle	0.0140	Rear differential pinion for high quality passenger vehicle
Repeatability	0.0039	

Lead angle	-0.860	Industry specimen for testing lead angle measuring equipment
Repeatability	0.008	

Figure 5: Examples of surface texture and measured lead angle for three different surface textures.

Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	1-σ
0.1711	0.1710	0.1744	0.1744	0.1741	0.1730	0.0018

Figure 6: Reproducibility test for lead angle for an automotive CV (continuously variable transmission) part, involving 5 trials, with part removal and replacement, and randomized starting position around the circumference.

An important observation is that there is a wide variety of surface textures for sealing surfaces, corresponding to different types of grinding and finishing processes. Figure 5 shows three examples and the associated values that we measured for the cylinder rotation, the surface texture direction, and the resulting lead angle. The second texture for the rear differential pinion of a passenger vehicle as shown in Figure 5 is a good example of a challenging surface structure for traditional string and stylus methods, since there are no easily-identifiable grooves, yet there is an identifiable surface texture direction that would influence sealing behavior. These examples also illustrate the importance of a sequence of measurements over a range of rotation angles around the full circumference—a technique common to other implementations of lead angle measurement [4, 20]. As a consequence, he total data acquisition time is approximately the same as for the stylus test, which also involves a sequence of measurements around the circumference. Thus the principle benefits of optical testing are the ability to test complex surface textures for net lead, together with the additional surface structure parameters than may be derived from full 3D surface topography maps with millions of data points around the circumference [16, 22].

The reproducibility test results of Figure 6 show that the technique is gage capable for controlling lead angle to the RMA target specification of <0.05°. We have found that repeatability and reproducibility are consistent with requirements; but it is quite another question how *accurate* the results are, and how well they predict final seal performance. The next step in our research will be to perform comparison tests to stylus measurements using specimens designed to have clear groove structures, to gain confidence in the consistency of results between measurement strategies. In parallel, we are working with first users to establish quality control metrics for our lead angle inspection technique for this important parameter in precision manufacturing.

REFERENCES

[1] Gabryel, G. E., “Optimize shaft surface finish for maximum seal performance,” Plant Services, (2002).

[2] Baumann, M., Bauer, F., Haas, H. W. *et al.*, “How to measure lead in sealing technology?,” Sealing Technology 2013(7), 8-12 (2013).

[3] Kundrák, J., Gyáni, K., Felhő, C. *et al.*, “Analysis of lead twist in modern high-performance grinding methods,” IOP Conference Series: Materials Science and Engineering 161(1), 012005 (2016).

[4] Cohen, D. K., Smith, S., Novak, E. L. *et al.*, “Measuring Surface Texture and Shaft Lead Angle of Dynamic Sealing Systems,” Quality Digest 31(3), 1-11 (2011).

[5] Puente León, F., and Rau, N., “Detection of machine lead in ground sealing surfaces,” Annals of the CIRP 52/1/2003, 459-462 (2003).

[6] RMA, "Shaft finish requirements for radial lip seals," Rubber Manufacturers Association (2004).

[7] Seewig, J., and Hercke, T., “Lead characterisation by an objective evaluation method,” Wear 266(5), 530-533 (2009).

[8] Hercke, T., and Schloz, "MBN 31 007-7: Measurement and Evaluation Method for the Assessment of Lead-Reduced Dynamic Sealing Surfaces," Mercedes-Benz Engineering Standard (2009).

[9] Although ISO ISO 25178-3 is sometimes cited as a standard for lead angle measurement, an informative annex for lead angle appears only in the draft version of this document, not in the final version.

[10] Leach, R. K., ed., [Optical Measurement of Surface Topography], Springer-Verlag, Berlin Heidelberg (2011).

[11] Sachs, R., and Stanzel, F. "Interference Microscopy for Clean Air – How Optical Metrology Is Improving Quality Control of Fuel Injection Systems," [Fringe 2013: 7th International Workshop on Advanced Optical Imaging and Metrology], W. Osten, Ed., Springer Berlin Heidelberg, 96 (2014).

[12] Arnecke, P., "A measurement method for characterising micro lead on ground shaft surfaces",Ph.D. Thesis, Technischen Universität Kaiserslautern (2017).

[13] de Groot, P., “Principles of interference microscopy for the measurement of surface topography,” Advances in Optics and Photonics 7(1), 1-65 (2015).
[14] Shuster, M., Combs, D., Pillar, J. *et al.*, "Development of the Methodology for 3-D Characterization of Oil Seal Shaft Surfaces," SAE International (2002).
[15] Xin, B., "Evaluation of two and a half-dimensional surface data with form component and groove bands," Proc. SPIE 6503, 835-844 (2007).
[16] ISO, "25178 Geometrical product specifications (GPS) — Surface texture: Areal — Part 2: Terms, definitions and surface texture parameters," International Organization for Standardization, Geneva (2012).
[17] Krolczyk, G. M., Krolczyk, J. B., Maruda, R. W. *et al.*, “Metrological changes in surface morphology of high-strength steels in manufacturing processes,” Measurement 88, 176-185 (2016).
[18] Xin, B., "Auswertung und Charakterisierung dreidimensionaler Messdaten technischer Oberflächen mit Riefentexturen",Thesis, (2008).
[19] Novak, E., and Munteanu, F., "Optical measurement of lead angle of groove in manufactured part," US Patent 9,752,868, (2017).
[20] de Groot , P., and Deck, L. L., "Surface topgraphy apparatus and method," US Patent 20180180412, (2018).
[21] Zygo Corporation, "NewView 9000," Specification sheet SS-0100 01/17 (2018)
[22] Blateyron, F. "The Areal Field Parameters," [Characterisation of Areal Surface Texture], R. Leach, Ed., Springer Berlin Heidelberg, 2 (2013).