

Application Note #549

Quantitatively Measuring Surface Texture and Shaft Lead of Dynamic Sealing Systems

The average automobile has over eighty dynamic seals that can fail at any given time.¹ Failures attributed to leaking seals cost the transportation and power industry many tens of millions of dollars a year in warranty costs, recalls and fines. Advances in seal/shaft design and materials have extended the service life and reliability of vehicles and engineered systems. However, traditional measurement techniques are unable to keep pace with today's smoother shafts and more rigorously controlled seal interfaces. Tighter specifications demand a more robust, gage-capable metrology solution that can quantitatively measure lead angles to the tolerances outlined in industry specifications, such as ISO 6194-1:2009 and RMA OS-1-1 rev. 2004, thereby improving production quality and yield. This application note details a metrology solution that addresses these issues and provides manufacturers a way to measure lead angle both quantitatively and repeatably with complete confidence in the results.

Shaft Surface Texture

Shaft surface texture and machine lead are critical to maintain minimal fluid leakage and friction for rotary dynamic seal applications.² For optimum performance elastomeric radial lip seals require a precise shaft surface

texture and zero machine lead angle. When initially run, the primary lip of a new seal contacts the shaft and begins to wear. If the surface texture of the shaft is too rough the seal is quickly worn away, leading to a leak. Conversely, if the shaft is too smooth, the seal will not bed correctly, and again will cause failures. Ideally, the shaft surface texture needs to be such that the lip wear is sufficient to allow a small quantity of fluid (typically of the order of 0.25um thick) to enter the shaft-seal interface. At this point the lip wear stops and the sealing system is deemed to be in equilibrium. It should be noted that the lip seal actually runs on a fluid film.

Of equal importance is the absence of machine lead, also known as "shaft lead," "lead angle," or simply "lead." There are two lead paradigms that need consideration, namely macro and micro lead.³ Macro lead is an axial periodic structure that is singularly or multiply circumferential, while micro-lead is generally used to describe high-frequency features on the shaft, either periodic or non-periodic, which are tilted with respect to the workpiece.

The introduction of lead angle on a shaft is inherent in all shaft manufacturing processes. Two of the many factors that contribute to the overall lead angle of a shaft are the

feed rate of the cutting tool for a turned shaft, and the part orientation during turning of either the workpiece or grinding disc. Fine helical shaped grooves are thus inadvertently machined into the shaft during the manufacturing process. In actual operation, as the shaft rotates this helical pattern leads to a “wicking” of the lubricant through the shaft-seal interface. A left hand (LH) lead is defined as that which moves the application oil in the direction of the source, causing the seal to dry out, while a right hand (RH) lead pulls lubricant away from the seal, causing the seal to leak.

The issue of measuring lead angle is not new to the automotive and precision manufacturing industries. Over the past decades, investigations have been performed to understand the shaft surface texture and lead requirements. The International Standards Organization (ISO) recommends in their document ISO 6194-1:2009 that the seal contact surface shall normally be free of machining leads.⁴ Similarly, the Rubber Manufacturers Association of North America (RMA) RMA OS-1-1 rev. 2004 specifies a lead angle of zero degrees ±0.05 degrees for shaft lead.⁵ Both of these standards also list shaft surface roughness parameters that are coupled with the lead angle specification. Table 1 provides a summary of both the RMA OS-1-1- rev. 2004 and ISO 6194-1:2009 specifications for lead angle and surface roughness.

In addition to defining the requirements, the RMA standard discusses possible methods for measuring the parameters, namely the string method for lead and a stylus profiler for surface texture:

The String Method

For determining shaft lead angle, RMA OS-1-1 rev. 2004 outlines a methodology for measuring the angle via the use of a string and weight. The string method suspends a 30g weight from a length of 0.23mm diameter quilting thread draped across the shaft under investigation in such a way that the thread-weight assembly makes an arc of contact with the shaft surface ranging between 220 and 240 degrees. Nylon lines should not be used because they

flatten and don’t track lead, nor should un-waxed dental floss due to its tendency to wrap around the shaft as it rotates. The shaft is center balanced so that the string/weight assembly can translate along the shaft. Movement along the shaft can be measured using an optical eyepiece with a vernier scale or precision calipers. The shaft is rotated in both the clockwise and counter clockwise directions, and if the thread translates in both directions it signifies the presence of a lead angle. This lead angle is then determined via the formula: $\text{Arc Tan } A = \text{Thread advance per shaft revolution/shaft circumference}$.

While the string method is relatively cheap to implement, it is not particularly reliable since it is influenced by the geometric accuracy of the shaft, lubricant type, surface finish, and the actual string used in the testing. In addition, some authors have reported a dead-band or lack of response when measuring ±0.03 degrees of shaft lead.⁶ Shafts with lead of less than 0.05 degrees often have such a dead band, which leads to the broad designation of “no lead” as being from 0.05 degrees RH to 0.05 degrees LH. Furthermore, many parts, such as those with yokes or geared ends, must have non-cylindrical components cut off for proper measurement, causing the string method to be a destructive test, and thus not allowing the test of parts to be put into actual operation. Also, certain surfaces have large lead angles where the string moves quickly to the end of the shaft, and thus may not have sufficient resolution to measure the lead. A final limitation of the method is that since the string must translate a significant distance to achieve good accuracy, localizing measurements in the critical seal contact areas is not possible.

The general sentiment throughout the precision manufacturing sector is that while the string method was acceptable at the time the RMA OS-1-1 rev. 2004 standard was developed, it is deemed unviable for today’s automotive, aerospace and general precision machining industries due to the increased constraints placed on machined parts and the increased difficulty in acquiring 100% cotton quilting thread.

Table 1. Shaft surface texture/lead specifications

	ISO 6194-1: 2009	RMA OS-1-1 rev. 2004
Shaft Lead	Free of machining lead. i.e. zero lead angle	<0 ±0.05 degrees
Surface Texture	Ra = 0.2µm to 0.5µm Rz = 1.2µm to 3µm	Ra = 0.02 to 0.43µm Rz = 1.65 to 2.90µm Rpm = 0.5 to 1.25µm
Stylus Instrument Parameters		0.25mm (0.01in) cutoff 5µm 90° diamond stylus Digital 50% Gaussian phase-corrected filter

String Method



Figure 1a. Typical string method assembly with test shaft mounted.

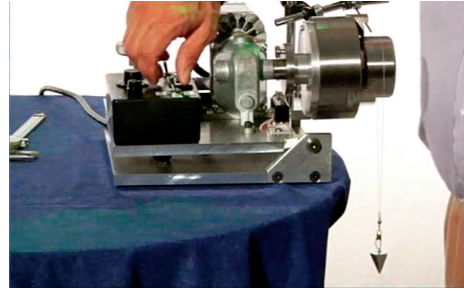


Figure 1b. Shaft is rotated both clockwise and counterclockwise to inspect string traverse.



Figure 1c. Distance of string traveled is measured with verniers.

Stylus Metrology

Traditionally, shaft surface texture has been measured with a stylus, or contact profilometer. While stylus profilometers are indeed useful, there are limitations in measuring surface parameters, such as R_a , R_z and R_{pm} . It is important to understand that these 2D R-parameters were created in the 1930s and have remained relatively unchanged though surface finishing techniques have greatly advanced. While parameters such as R_a remain useful as a general guideline of surface texture, 2D parameters typically prove too general to describe the surface's functional nature. For example, a surface with sharp spikes, deep pits, or general isotropy may all yield the same average roughness value. R_a makes no distinction between peaks and valleys, nor does it provide information about the spatial structure of the surface. In addition to the ambiguity that accompanies measurement of R_a , R_z and R_{pm} , the stylus tool itself can contribute to error in the measurement. The stylus is generally placed on the part and translated across the sample surface. Shaft alignment is critical, as the stylus orientation with respect to the shaft will affect the measured roughness. Even if the stylus scan begins with the stylus translating parallel to the shaft, the tip can sometimes catch in a groove and translate off-axis.

These 2D R-parameter limitations are well known throughout the precision manufacturing industry. To overcome this, the ISO has developed a set of comprehensive 3D surface parameters, called

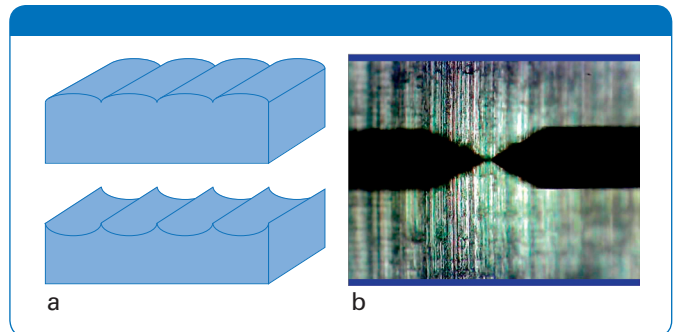


Figure 2. Surface textures can vary widely while their R_a values are similar (a) when using a 2D contact stylus technique (b).

S-parameters, for quantitative 3D metrology. These standards are under final balloting and are expected officially to be adopted in the near future.

Stylus-based metrology has also been employed recently to measure lead angle.¹ While this is an elegant solution and a significant advance over the string method, it is generally acknowledged that this metrology is confined to determining macro lead angle only and is limited in its ability to measure quantitatively micro lead angle. Where macro lead can manifest as a leak that can be detected within minutes of operation, micro lead results in a slow leak over a period of days or weeks. In reality, it is the combination of both macro and micro lead angle that correctly determine the overall functional properties of the shaft.

White Light Interferometry

As early as 2002, the Dana Corporation initiated a program to understand if optical-based 3D profilometry could be employed to quantitatively measure surface texture and lead angle.⁶ The conclusions indicated that white light interferometry is the appropriate technology to bring a quantitative capability to the market.

White light interferometry, also known as optical profiling, is a well-established technique for non-contact, 3D surface roughness and topography measurements. The method's unique combination of resolution, speed and repeatability has proven ideal for R&D, process development and quality control in industries ranging from automotive and aerospace to ophthalmology and orthopedics as well as semiconductor and data storage. Specifically, the automotive industry is using optical profiling for in-situ cylinder bore measurements, as well as for the characterization of metals, polymers, sensors and more in R&D and QA/QC.

An optical profiler is a specialized microscope that utilizes the properties of light to achieve topography measurements of surfaces with feature heights from nanometers to several millimeters. In an optical profiler, light approaching the sample is split and directed partly at the sample and partly at a high-quality reference surface. The light reflected from these two surfaces is then recombined. Where the sample is near focus, the light interacts to form a pattern of bright and dark lines that track the surface shape. The microscope is scanned vertically with respect to the surface such that each point of the test surface passes through focus. The location of maximum contrast in the bright and dark lines

indicates the best focus position for each pixel, and a full 3D surface map is generated.

The Bruker NPFLEX-LA 3D Surface Metrology System for Lead Angle

Bruker developed the NPFLEX-LA with participation from several industry partners who were interested in a single comprehensive system to measure key properties of sealing surfaces. During the design and verification process, a variety of parts were measured on multiple systems to assess repeatability, reproducibility, linearity, and system-to-system correlation.

Self-Referencing Metrology

Developing a quantitative metrology tool that must measure the lead angle of a shaft to $0^\circ \pm 0.05^\circ$ while allowing for multiple operators and multiple locations dictates that the system must be self referencing in some fashion. The engineers at Bruker's Nano Surfaces Division have designed the NPFLEX-LA to be able to measure the lead angle regardless of part alignment.

The system is designed such that an operator loads a shaft in a three jaw chuck, defines the measurement area along both the length and circumference of the shaft, and specifies the required number of locations to measure, typically 250 for a plunge ground shaft. At each location, the system measures a best fit to true cylinder and lead angle with respect to the CCD camera. The system also simultaneously conducts a Fourier transform of the data to determine an angular power spectral density of the angle of the marks on the shaft, again with reference to a CCD camera. These two calculations are subtracted from each other at every measurement point, to eliminate any off-axis variation associated with the mounting of the part. The result is a lead angle and surface roughness measurement value at every point specified in the measurement set-up.

A Technique Ideal for Lead Angle Evaluation

A single NPFLEX-LA measurement field of view ranges from 0.5mm x 0.5mm up to about 3mm x 3mm. This provides very high lateral resolution, but data is acquired from only a small surface area. Many fields of view are averaged to produce a single result, reducing the effect of local machining variations that can skew both the roughness and lead angle values. The operator can choose whether such measurements should be spread evenly over the entire shaft or only localized near the seal contact region. Typically, 250 measurements take approximately 30 minutes to complete. Fewer individual scans may be used to increase throughput, such as for highly uniform surfaces, but for this research 250 measurements were used throughout.

Plunge grinding is one of the most common production processes for precision shafts. A series of plunge ground shafts was obtained with designed lead angles from

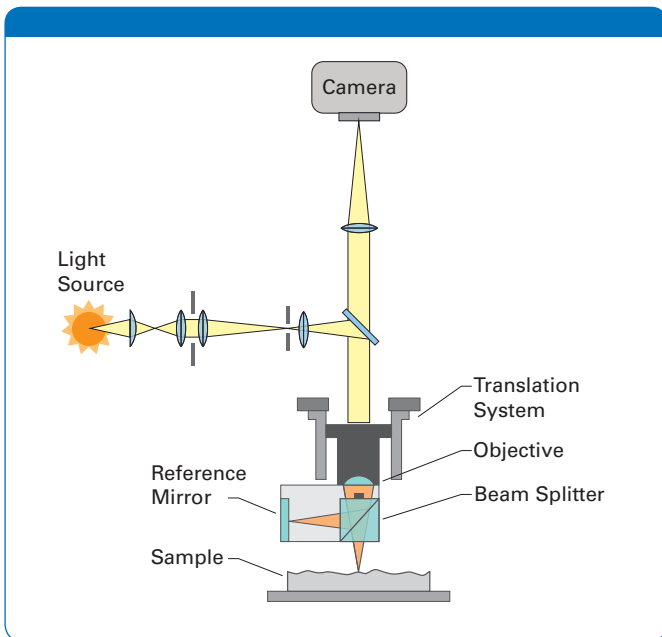


Figure 3. Standard schematic of an optical interferometer.

0.5 right hand (RH) to 0.5 left hand (LH) in increments of 0.1 degrees for testing. Two additional shafts with 0.05 RH and LH leads were also obtained. Shaft diameter was approximately 3 inches (76.2mm) and average roughness approximately 600nm (23 microinches). Shafts were tested for lead angle as well as roughness. Results reported were the lead angle of the shafts in degrees, and the 3D roughness parameters Sa, Sz, and Spm, which are the equivalents of the 2D roughness parameters Ra, Rz, and Rpm. The primary advantage of the 3D parameters is their insensitivity to part alignment. Since they calculate over an entire field of view, there is no worry that a single trace will affect the calculation by not being aligned along the shaft direction. Also, by using an entire field of view, these parameters are far less sensitive to local part variations. Additional parameters are calculated by the NPFLEX-LA and may be reported as needed, such as the spatial frequency of the machining marks, the amplitude of the machining marks, and more.

The first test performed was to determine system repeatability. Shafts were mounted on the NPFLEX-LA and the measurement sequence run 30 times without removing or replacing the part. For these shafts, the one-sigma standard deviation of the lead angle results was less 0.005 degrees. The one-sigma standard deviation for Sa was less than 1.4 nm (0.05 microinches) while for Sz and Spm it was 25nm (0.97 microinch) and 18nm (0.72 microinches) respectively.

Next, system reproducibility was studied. In this test, a single operator was asked to load and unload the shaft between 10 measurement sequences. The starting location of measurements was not controlled in any way between runs to represent an operator randomly approaching the system with a part to be tested. In this case, the one-sigma standard deviation of lead angle across the runs was 0.02 degrees. This seems mainly driven by variability

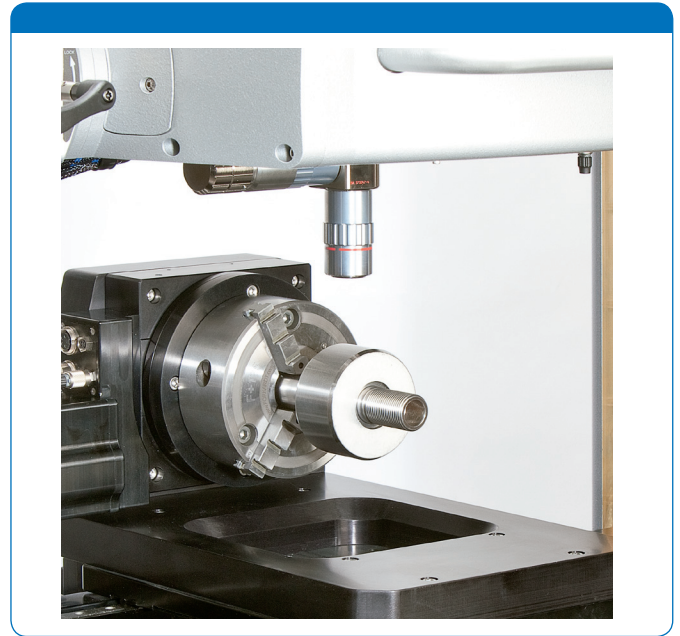


Figure 4. Test shaft mounted on NPFLEX-LA.

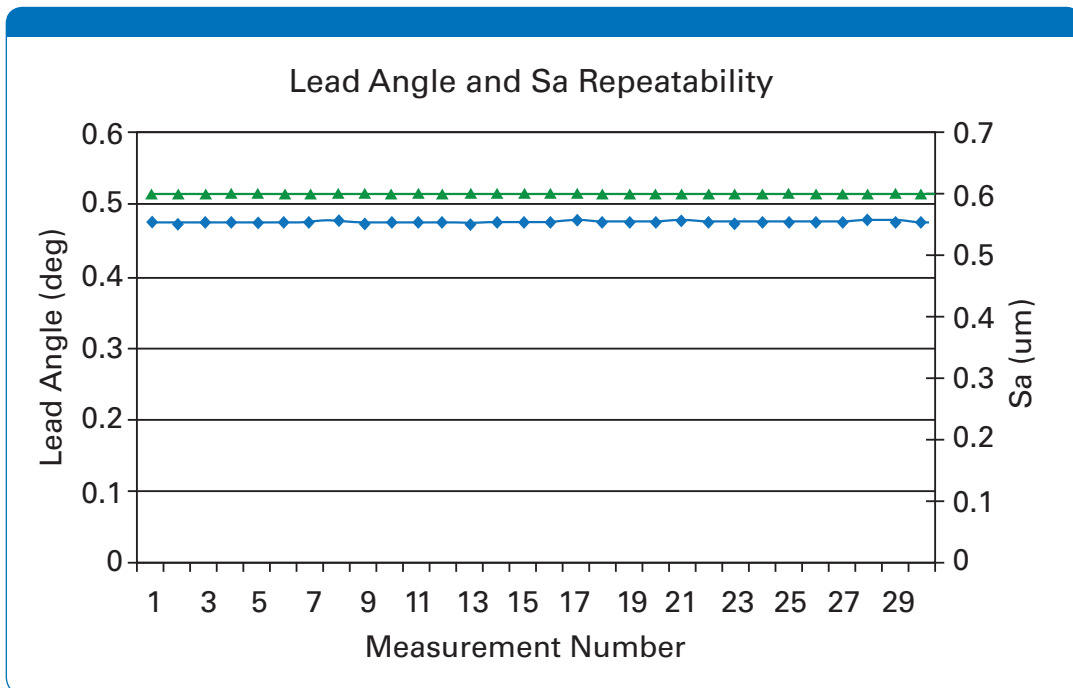


Chart 1. NPFLEX-LA shows a lead angle static repeatability result better than 0.005 degrees. The green-triangle line represents global lead angle results from 30 measurements. The blue-diamond dataset is the average roughness (Sa) over these same 30 measurements.

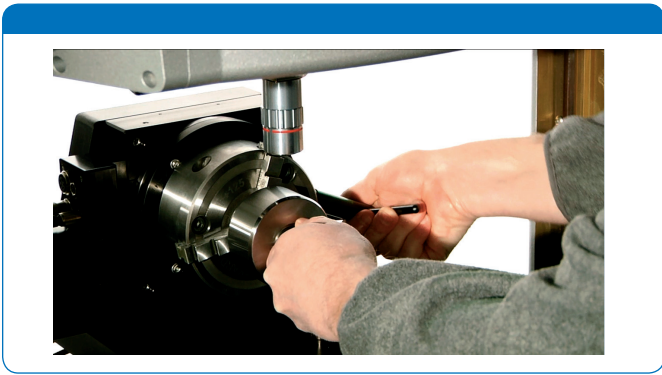


Figure 5. NPFLEX-LA is designed such that operators do not have to be concerned with perfect part level or wobble during mounting.

of the part itself, because when the starting position was roughly controlled, standard deviation dropped to between 0.005 and 0.008 degrees, depending on the specific part measured. The one sigma standard deviation of S_a , S_z , and S_{pm} were 1.2nm (0.05 microinches), 76nm (3 microinches) and 38nm (1.5 microinches) respectively.

Finally, lead angle results were compared across three different systems. Due to minor imperfections in the optics used to image samples and the high sensitivity required for lead angle results, all systems are calibrated against known lead angle samples so that they will obtain the most accurate results possible. Three systems were calibrated this way and parts of 0.4RH, 0.4LH and 0.05RH lead were measured three times each on the three systems, using several different operators. The maximum deviation of results between systems was 0.08 degrees for the 0.4 degree RH part and was 0.04 degrees for the other two parts. One sigma standard deviation of results between the systems ranged from 0.02 to 0.04 degrees. S_a agreed to within 30nm across all systems with a standard deviation of 7nm. Thus, even measuring parts across different systems, using different operators, and not controlling where the parts were measured, agreement between systems is quite good.

Conclusions

Bruker's NPFLEX-LA measurement system provides comprehensive quantification of critical shaft parameters. This non-contact measurement system can handle shafts from 38 to 203mm (1.5 to 8 inches) diameter and reports lead angle and all critical roughness parameters

for each measurement. Unlike the string method, where increasing lead means fewer shaft rotations and less resolution, measurement accuracy is not affected by the amount of lead present. Also, the NPFLEX-LA has been proven to accurately measure leads on ground shafts with lead of 0.05 degrees and less, where the string method encounters dead spots making measurement impossible. System repeatability and reproducibility are excellent and system-to-system measurements agree quite well. Setup time is only a few minutes and operators can concentrate lead measurements only over the sealing surface, or perform them over a large area of the shaft as desired. The accurate, comprehensive, 3D information provided by the NPFLEX-LA will enable tighter quality control of shafts. This method is anticipated to save time and money both in the initial verification of critical shaft parameters as well as in reducing field failures and warranty costs through more accurate, operator-independent measurements of all key shaft parameters.

References

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