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Shaft Proximity Probe Track Runout on API Motors and Generators

Approximately 20 years ago, API 541 [1] and API 546 [2] were revised to reflect end-user requirements for lower shaft and bearing housing vibration limits based on a desire to improve the mechanical reliability of motors and generators. This led to increased use of eddy current proximity probes on motors and generators with fluid-film bearings, as these sensors measure and monitor shaft-relative vibration (relative motion between a shaft and its stationary bearing surfaces). Figure 1 shows a typical arrangement of proximity probes for monitoring vibration of a rotating shaft at a single radial bearing location. The X and Y probes determine the instantaneous motion and average position of the shaft centerline as the shaft rotates. The phase reference probe (not shown in Figure 1) is positioned over a machined discontinuity (usually a slot or keyway) in the shaft and provides a once-per-turn reference pulse from which the phase angle of the vibration can be determined along with the frequency of the vibration with respect to shaft speed. Generally, each independent shaft is fitted with its own phase reference probe to allow machines to run coupled or uncoupled while still providing a phase reference.
The X and Y probes are positioned over a specially machined probe track area that is adjacent to each bearing journal. If this probe track has surface imperfections such as scratches, out-of-roundness, or non-concentricity with respect to the bearing journal surface, these mechanical imperfections will appear to be vibration and result in measurement error. Also, variations in the electrical properties of the steel in the probe track area will create measurement error. The vibration reading resulting from these imperfections is known as proximity probe track runout. The error can either add to or subtract from the real vibration measurement depending on the phase angle, so the vibration reading can appear either too high or too low as a result of runout.

The runout error can be corrected by vectorially subtracting the measured probe track runout from the measured vibration. Selected vibration instruments provide the capabilities for this runout compensation.

[Editor’s Note: Runout can, and often does, change over time. A number of portable vibration instruments do provide runout compensation since they are designed to provide vibration readings at a particular instant in time for diagnostic purposes. However, permanent monitoring systems typically do not provide runout compensation because as the runout changes over time, it will result in erroneous indication of the “true” vibration and, potentially, false alarms or missed alarms. For this reason, API Standard 670 [3] prohibits the use of runout compensation in permanent monitoring channels.]

To minimize the runout error, API 541 and API 546 define limits for the maximum probe track runout. In simple terms, these runout limits are 25% of the unfiltered vibration limits, or 0.45 mils (thousandths of an inch) for most induction machines and 0.5 mils for most synchronous machines. These correspond to 11.4 and 12.7 μm respectively.
It turns out that these limits are difficult to achieve for many motors and generators. Unfortunately, the runout is not known for sure until the machine is assembled and the probe track runout is measured with the proximity probes. If the runout is excessive, this often requires disassembly of the machine and re-work of the probe track area. Of course, this is both costly and time consuming, which affects both the manufacturer and the purchaser. In practice, this relatively simple issue has proven to be the most common problem, and one of the most costly issues affecting the manufacture of API motors and generators.

Recognizing this as a problem, API standards provide for alternative methods to check probe track runout during the manufacturing process and before final assembly of the machine. This is usually done with the rotor positioned either in V-blocks or in a lathe, where measurements are made using dial indicators and proximity probes. However, this method of performing preliminary checks is not always completely reliable in predicting the runout that will be present in the final assembled machine.

The following sections discuss how proximity probes work, the nature of probe track runout, how to predict probe track runout, how to correct probe track runout, limitations of the usual runout prediction methods, a new method to predict runout, and a case study example.

**Measuring Runout**

As a rotor coasts to rest, the proximity probe system monitors the shaft proximity probe readings. At approximately 10% to 15% of rated speed, the dynamic effects are negligible and theoretically the proximity probe vibration readings should be zero. However, mechanical imperfections (shaft finish, out of roundness, lack of concentricity, etc.) and electrical imperfections (shaft permeability, signal noise, etc.) lead to signal error, which can be seen at slow shaft speeds. The proximity probe reading at slow shaft speed is referred to as the slow-roll runout.

**Why Is Runout Important?**

Proximity probes are used to monitor the vibration of a machine. Often, the machine control is configured so that if the vibration of the machine exceeds a predetermined value, the machine will be shut down.

The slow-roll runout is essentially the error in the vibration reading. A small slow-roll runout value is an indication that the proximity probes will accurately measure the vibration of the machine. If a machine has high slow-roll runout, then the actual vibration of the machine could be higher or lower than what is being monitored.

Vibration at a particular frequency can be described as a vector that has an amplitude and phase angle. Likewise, the slow-roll runout at the same frequency can be denoted as a vector. Since most vibration on machines normally occurs at rotative (1X) speed, the 1X vibration vector and 1X slow-roll vector will usually characterize the machine quite well. The proximity probe cannot distinguish between these two vectors and therefore will only see the sum. Depending on the phase relationship between the vibration vector and the slow-roll runout vector, the vibration amplitude as measured by the proximity probe can be either larger or smaller than the true vibration amplitude.

Two possible extreme scenarios exist. If the slow-roll runout vector is additive to the vibration vector, then the proximity probe will report a larger vibration amplitude than truly exists. This could lead to the situation where the machine goes into an alarm or trip condition prematurely. If, on the other hand, the slow-roll runout vector is subtractive to the vibration vector, then the proximity probe will report a smaller vibration amplitude than truly exists. In this scenario, the true vibration may actually exceed an alarm or trip condition, but the monitoring system will not detect this due to the slow-roll vector making apparent vibration less than real vibration.

To minimize the possibility of nuisance trips and allow adequate machine protection for vibration, limits are placed on the maximum allowable slow-roll readings. According to API 541 (Section 2.4.5.1.7) and API 546 (Section 2.4.5.1.3), the limit for slow-roll runout is 25%
of the allowable unfiltered peak-to-peak vibration amplitude or 0.25 mils (6.35 μm), whichever is greater.

The factory slow-roll test is one of the last items to be tested on a machine since the machine needs to be fully assembled. If the machine fails to meet the slow-roll runout requirement, significant rework may be required in order to perform the necessary remedial work. For example, the machine may have to be disassembled and the rotor returned to the lathe. This can cause significant delays in shipping the machine on time, resulting in project delays for the purchaser. The end result is that this error is costly for both manufacturer and purchaser. Consequently, both parties have an interest in seeing an inspection strategy that identifies the potential for a slow-roll runout problem early in the manufacturing process so that corrective action can take place before the machine is assembled.

How a Proximity Probe Works

Eddy current proximity probes have a coil at the tip of the probe. A current is passed through this coil to form a magnetic field. As the probe gets close to a conducting surface, eddy currents are induced in the surface of the metal. The formation of these eddy currents reduces the strength of the magnetic field and is detected by the probe coil as a drop in voltage. Over a certain range, the drop in voltage is linearly proportional to the change in the distance of the probe from the metal surface. In the case of a rotating shaft, as the shaft vibrates, its distance (or gap) from the proximity probe changes. This change in gap as the shaft rotates produces a corresponding change in voltage that is proportional to the vibration, typically 200 mV/mil (7.87 mV/μm). This voltage signal is then converted to familiar vibration units in the monitor for display. Vibration measured from shaft-observing proximity probes is usually expressed in terms of peak-to-peak displacement, using engineering units of mils or micrometers.

Figure 2 shows an example of a vibration signal obtained from a shaft proximity probe. The overall waveform represents the total or unfiltered vibration, and each cycle represents one revolution of the shaft. Using Fourier analysis, the signal can be separated into its individual frequency components. Visually, it can be seen in Figure 2 that the waveform is primarily sinusoidal with a period equal to the shaft rotative speed, with a small amount of superimposed noise. Thus, one would
expect the frequency domain to show the vibration signal is predominantly composed of the 1X (rotative speed) frequency component.

Since the eddy currents form on the outer surface of the shaft, any variations in the metallurgy around the circumference of the shaft will affect the proximity probe reading. Because the proximity probe operates at a relatively high frequency, the depth of the eddy currents into the shaft is very shallow. As a result, the final machining operation is especially important on the surface that is being observed by the proximity probe.

Components of Runout

The runout on a probe track is comprised of two components: mechanical and electrical.

Mechanical runout can, in theory, be measured with a dial indicator as it represents dimensional imperfections. No matter how good a machine tool is, there will always be elements of error introduced. Shafts are not machined perfectly round. Nor are adjacent shaft surfaces perfectly concentric.

For a typical installation where the proximity probe is located adjacent to the journal, and assuming no scratches or burrs on the shaft, there are three sources of mechanical error that will influence the slow-roll runout of a machine:

1. The journal diameter will not be perfectly round.
2. The proximity probe track diameter will not be perfectly round.
3. The journal and proximity probe track diameters will not be perfectly concentric.

The electrical component of runout, in contrast, is not dimensional and instead represents metallurgical variations around the circumference of the shaft. These metallurgical variations lead to variations in the electrical conductivity and magnetic permeability of the shaft, affecting the proximity probe signal. Once these variations are introduced in a forging, it is extremely difficult to change them.

By breaking the slow-roll runout into its four components (three mechanical and one electrical), one can more readily identify which component(s) is (are) excessive and develop an appropriate strategy for reducing the slow-roll runout. This is extremely important because not knowing which component(s) is (are) the problem, or misdiagnosing the problem, can make the situation worse. For example, if one believes the problem is with the electrical component of runout when in fact the problem is an out-of-round proximity probe track, an action plan to fix the electrical component will be implemented when the electrical component is fully satisfactory. When this occurs, matters will almost always be made worse by trying to “fix” the non-existent problem.

Limitations of Existing Measurement Method Taken in V-Blocks

In the interest of meeting project schedules, it is imperative to have an inspection plan that is capable of detecting and correcting a slow-roll runout problem early in the manufacturing process.

Before industry standards existed to address the issue, inspection for slow-roll runout was primarily done using dial indicators while the rotor was in the lathe. This method is very unreliable as demonstrated in Figure 3. The lathe bearings are not perfect; as a result, the lathe centers will trace out an orbital path rather than a perfect, unmoving point. As the shaft orbits in the lathe, the cutting tool is removing material in such a manner as to create an elliptical shaft. Figure 3 shows an elliptical shaft superimposed at four different angular positions. Placing a dial indicator on the cutting tool side will suggest that the shaft is running true. However, placing the dial indicator 180 degrees opposite the cutting tool will reveal the true nature of the shaft.
Although many manufacturers use V-blocks to determine the mechanical shape of the shaft, and although API 541 and API 546 both suggest this method as a means for determining slow-roll runout, Littrell [4] has demonstrated some of the limitations of this method as summarized in Figures 4 and 5.

Figure 4 demonstrates how two shafts that are physically different in shape will give the same dial indicator readings. The shaft shown at the top of Figure 4 is two-lobed whereas the shaft below it is single-lobed.

Figure 5 demonstrates how a three-lobed shaft measured in V-blocks will erroneously indicate that the shaft is perfectly round.

In both Figures 4 and 5, the fundamental reason the V-block method fails to work is that the dial indicator
is recording the change in the shaft diameter. To get an accurate indication of shaft shape, one needs to measure the change in shaft radius.

The only way to accomplish this is by understanding where the center of the shaft is at all times during the measurement.

**Description of 5-Probe Runout Detection Using LVDTS**

Figure 6 is a schematic representation of the 5-probe instrument developed by the authors for measuring and predicting probe track runout. Four of the probes are contacting LVDT (Linear Variable Differential Transformer) probes, and the fifth is an eddy current proximity probe.

This article will not describe in detail how an LVDT probe operates. Suffice to say, an LVDT probe acts much like a dial indicator with a precision, spring-loaded rod in contact with the shaft. However, rather than providing a mechanical indication of the displacement, an LVDT probe provides a proportional electrical signal that can be digitized and sent to a computer.

LVDT probes #1 and #2 are placed 180° degrees radially opposite one another on the proximity probe track. Likewise, probes #3 and #4 are placed 180° degrees radially opposite one another on the journal surface. A proximity probe (#5) is located adjacent to probe #1 in the same radial orientation. As the shaft rotates in the lathe or grinder, the signals from the five probes are sent to a computer for post processing. Data from the probes are collected for every few degrees of rotation.

The LVDT data can then be graphed as shown in Figure 7, providing precise visual representations of the mechanical variations in the shaft surfaces. Surface #1 represents a perfectly round journal surface. Surface #2 represents an exaggerated view of the journal surface as measured by LVDT probes 3 and 4. Surface #3 represents a perfectly round proximity probe track surface. Surface #4 represents an exaggerated view of the proximity probe track surface as measured by LVDT probes 1 and 2. The actual shaft surfaces are plotted on an expanded scale for ease of visual interpretation. For this example, one division is equal to 0.25 mil (6.4 μm). The angular location of each data point is recorded and used to develop the plot shown.
Figure 8 shows the 5-probe instrument set up in the lathe to check the machined shaft. It is important to note that imperfections in the lathe bearings can be removed from the data. Assume, for example, the following hypothetical case: The shaft is perfectly round, but it has been placed in a lathe where the lathe bearings cause the shaft to orbit. Consider Figure 6 and imagine that it is a plan view of the shaft. As the perfectly round shaft rotates, the shaft centerline moves upward in the Figure. Probes 2 and 4 will observe the shaft moving towards them (a positive signal) while probes 1 and 3 will observe the shaft moving away from them (a negative signal of equal amplitude). Adding the two signals results in zero amplitude—indicating that the shaft diameter has not changed. Consider another idealized case where the shaft is elliptical, and placed in a lathe with perfect bearings. At first, the minor axis of the ellipse is in the horizontal orientation. As the shaft rotates and the major axis rotates into the horizontal orientation, probes 2 and 4 will observe the shaft moving towards them (a positive signal) while probes 1 and 3 will also observe the shaft moving towards them (another positive signal of the same amplitude). Adding the two signals results in a positive signal indicating the shaft diameter has increased.

The electrical runout at each angular location of the shaft can be determined by comparing probes 1 and 5. Probe 1 is the LVDT probe that is observing the shaft motion adjacent to the proximity probe (probe 5). Probe 1 can be thought of as the “real” mechanical shaft movement as it includes only mechanical runout. Probe 5 is a proximity probe, and therefore includes both mechanical and electrical runout. By taking the proximity probe reading and subtracting the LVDT reading, one is left with only the electrical runout. In equation form, this becomes:

\[
(\text{Proximity Probe Signal}) - (\text{LVDT Signal}) = (\text{Mechanical Runout} + \text{Electrical Runout}) - (\text{Mechanical Runout}) = \text{Electrical Runout}
\]
Figure 9 shows a plot of the signals from probes 1 and 5 for one shaft revolution and the difference between the two signals (i.e., the electrical runout).

Now that the mechanical shape of the shaft surfaces is known, and the electrical runout of the target surface is known at each angular location, a prediction of the final runout from proximity probe readings in the assembled machine can be made.

To see how this prediction is made, refer to Figure 10 where a cross section of the shaft is depicted with the shaft variations exaggerated. The bearing surface on which the journal will rest is shown along with the proximity probes and the geometric centers of measured journal and probe track diameters. Figure 10 also depicts six vectors, summarized on the following page.
Figure 10 – Method of predicting runout on final assembled machine from 5-probe measurements.

A Vector from the bottom surface of the journal that is in contact with the bearing to the geometric center of the journal surface.

B Vector from the geometric center of the journal to the geometric center of the proximity probe track.

C Vector from the geometric center of the proximity probe track to the proximity probe track immediately under the Y probe.

D Vector from the geometric center of the proximity probe track to the proximity probe track immediately under the X probe.

E Vector describing the electrical runout at the proximity probe track under the Y probe.

F Vector describing the electrical runout at the proximity probe track under the X probe.

By summing vectors A, B, C and E, a prediction can be made as to what the Y probe reading will be. Likewise, by summing vectors A, B, D and F, a prediction can be made as to what the X probe reading will be. By rotating the shaft to each angular location for which data was collected, a prediction can be made as to the expected signals of the two proximity probes as shown in Figure 11.

Case Study

Figure 12 provides a comparison of the prediction based on the 5-probe instrument and the proximity probe reading taken in the test area for a recent project. The first curve is a graph of the predicted proximity probe reading based on the data collected by the 5-probe instrument at the lathe. As can be seen, this curve has a peak value of 0.53 mils at the 280-degree location on the shaft. Likewise, this curve has a minimum value of 0.07 mils at the 15-degree location. The peak-to-peak range is therefore 0.46 mils. The second curve is a graph of the proximity probe data from the assembled machine as it rotates at 200 rpm in the test bed.

Except for the spikes at 210 and 240 degrees, one can see that the two curves are in agreement within approximately ±0.10 mils. Because of this, it is important to establish an acceptance criterion on the 5-probe instrument, which ensures the customer specification is met when the machine is fully assembled and tested.
Some of the reasons for the observed variation between the two curves are:

1. The readings taken on the test bed are with the shaft resting on an oil film. The dynamics of the oil film will affect the proximity probe reading.

2. As with every electronic device, the LVDTs and proximity probes have their own tolerances. Considering the very small distances being measured, this tolerance will clearly contribute to the error between predicted versus actual results.

3. In the post processing of the data from the 5-probe instrument, prediction of what will happen in the assembled machine requires the addition of many small vectors as Figure 10 shows. The accumulation of many tolerances introduces error.

The two spikes in Figure 12 represent small scratches that were introduced during manufacturing. This highlights the importance of proper protection of the proximity probe target surface while the rotor is being handled. It also highlights the need to properly communicate the importance of this surface to the people who handle the shaft.
APPLICATIONS

“THE 5-PROBE METHOD ALLOWS THE SLOW-ROLL RUNOUT READING TO BE DECOMPOSED INTO FOUR CONSTITUENTS, SIGNIFICANTLY IMPROVING THE ISOLATION AND CORRECTION OF THE OFFENDING PARAMETER.”

Methods of Reducing Electrical Runout

Satisfying the required limits for the mechanical components of runout is relatively straightforward and simply requires following proper and well-established machining techniques. However, the electrical runout component is often the problem when excessive runout levels are experienced. Correcting excessive electrical runout is usually difficult because it relates to the characteristics of the shaft steel. In order to reduce electrical runout, the properties of the shaft should be uniform around the circumference. One of the most successful methods of reducing electrical runout is burnishing the area of the shaft that is being observed by the proximity probe. Burnishing is a process done in a lathe. The tool is a spring-loaded piece with a diamond tip. This process essentially smears the metal and forms a near mirror finish. The uniform force (due to spring-loaded tip) used to work-harden the shaft surface produces relatively uniform properties around the shaft circumference.

Local corrections to the electrical runout can be made using approaches like micropeening. This method uses an engraving tool with a blunt tip. Essentially, it is impacting the shaft with a tiny hammer. This method is time-consuming and is more art than science. This type of procedure is typically only used as a last resort.

One hypothesis on the cause of the electrical component of slow-roll runout is that much of it is due to metallurgical variations within the forging. What is known is that once the electrical component is present, it is extremely difficult to reduce. The authors are continuing to research this area with a major forging supplier in an effort to find a relationship between the electrical component of slow-roll runout and the forging process or forging characteristics. As a start, an evaluation is being done on whether variations in surface hardness, variations in grain size, distribution of chemistry within the forging, or forging processes have an effect on the electrical runout component. If this research is successful, it will help establish specifications for shaft forgings for motors and generators that will provide improved electrical runout characteristics.
Conclusion

The shaft probe track runout requirements for API 541 and API 546 motors and generators are often problematic and can create schedule delays when found late in the manufacturing process. API 541 and API 546 provide for in-process checks of slow-roll runout using V-blocks to help avoid first identification of a runout problem late in the manufacturing cycle when the machine is finally assembled for the first time. However, the V-block runout check does not always accurately predict the probe track runout that will be observed by the proximity probes in the assembled machine. An alternate (LVDT) method used with the rotor in the lathe for accurately predicting slow-roll runout has been described in this article and has been successfully employed.

The LVDT method allows the slow-roll runout reading to be decomposed into four constituents, significantly improving the isolation and correction of the offending parameter.

The approach of using a measurement procedure to anticipate slow-roll runout in the lathe was also shown to have several advantages. Most notable among these was that the shaft is still in the lathe (or grinder) when the check is made. This avoids the need to potentially disassemble a machine and return the rotor to the lathe for rework. Instead, the rework can be done in the initial setup. This minimizes the impact a slow-roll runout problem can have on the cycle time of a machine. As a result, the likelihood of a missed shipping date due to slow-roll runout problems is greatly reduced. This is a tremendous benefit to both the purchaser and manufacturer of the machine.

Finally, it was noted that much work remains if significant gains are to be made in reducing the electrical component of slow-roll runout, and that the authors are involved in ongoing research on this topic in conjunction with a major forging supplier.

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References