Procedure to Check for Residual Machine/Shaft Lead

Background

Manufacturing a shaft generally is done by 'turning'; removing material by rotating the part on its axis and moving a cutting tool axially. Turning leaves a helix pattern similar to a screw thread, commonly called machine lead or shaft lead, Figure 2. Subsequent manufacturing operations may leave a residual helix even though it is no longer visible. This test is based around application of spring energized elastomeric lip seals, but works equally well for applications using O-rings and quad-rings sealing rotating shafts.

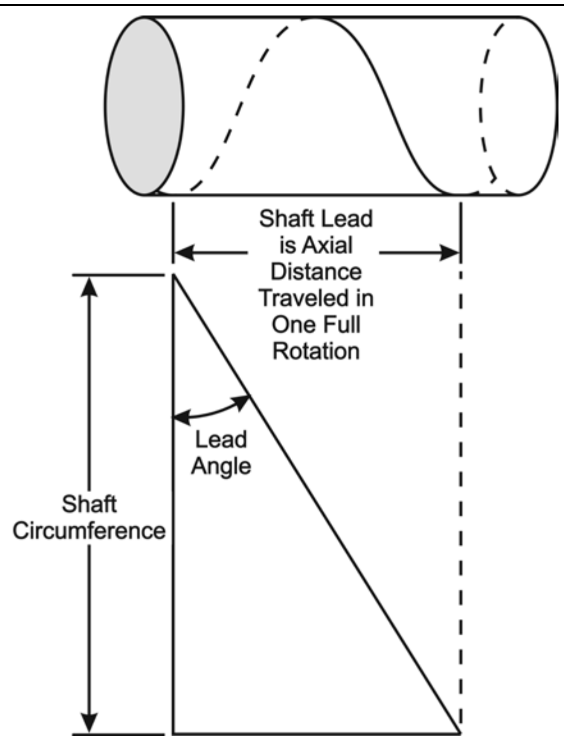

Figure 1 Shaft Lead

The best test for shaft lead is not very high-tech but works. All of the special equipment that is not already in a typical machine shop can be purchased at a Wal-Mart.

A separate page of the test procedure was created so it can be given to an inspector to perform as a work instruction. At the end is all of the math if you want to wade thru it to better understand the theory behind the procedure. Seeing the math makes the procedure less like magic.

Every company where I implemented this test thought it was a joke, until they saw the results. At one company the VP of Operations disliked the concept so much he spent thousand dollars on a sophisticated surface finish tester to prove it would predict shaft seal leaks and the piece of thread would not.

He lost!

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Theory

A loop of thread is used to act a stylus that rides in the lead grooves. A light weight is attached to the thread hold it in contact and prevent it from rotating with the shaft. The shaft is coated with thin film of oil and rotated at a consistent speed to mitigate problems with friction and inertia. By knowing the shaft rotation speed and the time it takes the thread to travel a distance the lead angle can be determined.

As the angle of wrap increases toward 360° the tension in the thread and its grip on the shaft approach infinity. The thread length is sized so that the tension in the loop is kept low. The maximum wrap should be less than 255° and preferable less than 240°. Typically less wrap (i.e. longer thread) is better.

The standard test speed is considered to be 60 rpm. However this is based on the diameters of standard shaft seals available. This does not account for extremes in shaft diameters. Large diameters the speed must be reduced because of the high surface speed. High surface speed will prematurely wear out the thread, or make it begin to travel with the shaft rotation; this is evidenced by the weight bouncing. Small diameter shafts the speed must be increased because the surface speed is too slow to mitigate problems with friction and inertia. This is evidenced by the weight swing like a pendulum. The low rubbing velocity makes coefficient of friction vary. The weight should remain relatively stable in its motion.

This is not something where deviation from the rules will invalidate the test. Depending on your application you may be required to use trial and error to find the best combination of thread wrap, shaft speed, oil, and weight.

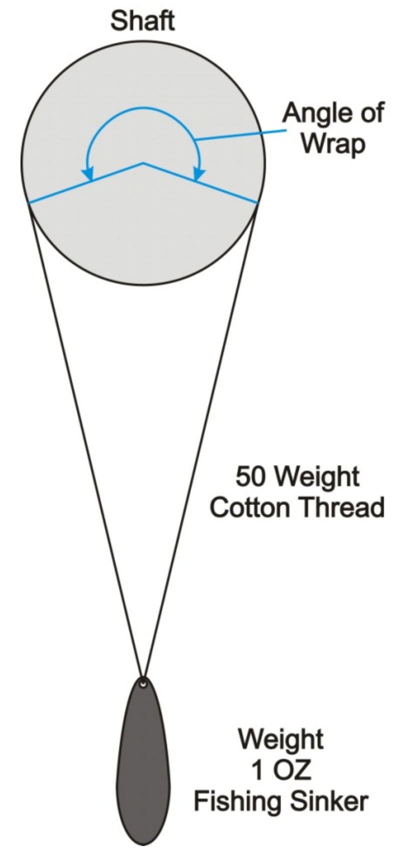

Figure 2 Lead Test Diagram

For more details on shaft seals see "Leaky Shaft Seals" by this author

About the author:
James K. Simonelli is a Licensed Professional Engineer with 30 years experience designing and troubleshooting machine automation, heavy duty equipment and industrial products. He has a broad background with department head roles in engineering, quality and business development in companies varying from startups, turnarounds to Fortune 100 corporations. Mr. Simonelli has served on committees developing industrial standards for the American Gear Manufacturers Association and the Hydraulics Institute.

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Residual Machine Lead Test Procedure

Equipment

- Stop Watch
- Cotton quilting thread (i.e. 50 weight cotton thread) or unwaxed dental floss. Thread length 5 times the shaft diameter.
- 1 ounce fishing sinker
- 3-in-one[1] machine oil, sewing machine oil or silicone oil viscosity 5 to 10 cps
- Lathe or other device to hold the shaft horizontally and rotate consistently at a set speed
- Distance Indictor; Piece of metal or cardboard to mark two lines a distance apart

Steps

1) Make a thread loop by knotting both ends at the weight.
   a) Check the free loop perimeter is 4 or more times the shaft diameter.
2) Place the loop around the shaft.
3) Mount the shaft in the lathe.
4) Thinly coat the surface to be tested with oil.
5) Position distance indicator near the shaft in the sealing area. Mark 2 lines near the limits of the seal area and record the distance.
6) Place the string to one end of the sealing surface outside of the indicators.
7) Set the lathe rotation speed; nearest available speed to w=130/Diameter in inches or w=5/Diameter in mm
8) Start the lathe. If the thread is moving away from the first position mark reverse the lathe.
9) Start the stopwatch when the thread reaches the first position mark
10) Stop the stopwatch when the thread reaches the second position mark. Record the time.
11) Check the thread for wear. Replace as needed; every 50 to 100 tests.

D = Shaft Seal Diameter
X = Distance Between Position Indication Marks
t = Time to Travel X Distance (sec)
ω = Shaft Rotation Speed (rpm)
λ = Lead Angle

$$\lambda = \tan^{-1} \frac{60 \times X}{\pi \times D \times \omega \times t}$$

Equation 1 Lead Formula

Diagnosis

<table>
<tr><th colspan="2">Observed Thread Movement</th><th>Interpretation</th></tr>
<tr><td colspan="2">Stationary in both rotations</td><td>No lead present</td></tr>
<tr><td colspan="2">Thread travels axially with rotation. Reversing rotation reverses axial travel.</td><td>Lead present
Maximum Allowable Shaft Lead
0.05° (3.5 arc minutes)</td></tr>
<tr><td colspan="3">Results where shaft lead cannot be determined</td></tr>
<tr><td colspan="2">Thread travels away from the center for both rotations</td><td>Crowned shaft; Barrel</td></tr>
<tr><td colspan="2">Thread travels toward the center for both rotations</td><td>Cupped shaft; Hour Glass</td></tr>
<tr><td colspan="3">Thread travels in same direction for both rotations</td></tr>
<tr><td rowspan="3"></td><td colspan="2">Remount the shaft end-for-end and retest</td></tr>
<tr><td>Reverses direction of thread movement</td><td>Tapered shaft</td></tr>
<tr><td>Does not reverse direction of thread movement</td><td>Machine holding shaft not level</td></tr>
</table>

1 Is a brand produced by WD-40 and generically is severely hydrotreated heavy naphthenic oil

The Math

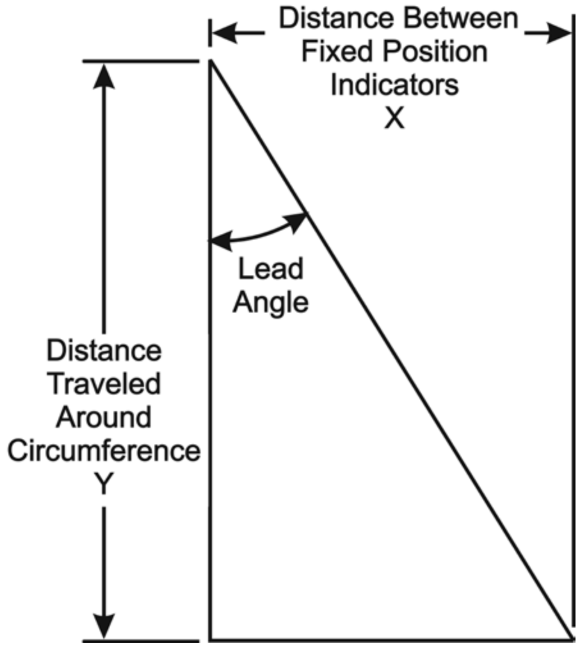

Figure 3 Lead Angle Diagram

D = Shaft Seal Diameter

C = Shaft Circumference

Y = Distance Traveled Around Circumference

X = Distance Between Fixed Position Indicators

t = Time to Travel X Distance (sec)

ω = Shaft Rotation Speed (rpm)

n = Number of Shaft Rotations

λ = Lead Angle

$$C = \pi \times D$$

$$n = \frac{\omega \times t}{60}$$

60 converts w in rev/min and t in seconds

$$Y = C \times n \Rightarrow Y = \frac{\pi \times D \times \omega \times t}{60}$$

$$\tan \lambda = \frac{X}{Y} \Rightarrow \lambda = \tan^{-1} \frac{X}{Y}$$

$$\lambda = \tan^{-1} \frac{60 \times X}{\pi \times D \times \omega \times t}$$

Equation 2 Calculating Lead Angle

D = Shaft Diameter

C = Shaft Circumference

s = Surface Speed

ω = Shaft Rotation Speed (rpm)

$$C = \pi \times D$$

$$s = \frac{C \times \omega}{12} \Rightarrow s = \frac{\pi \times D \times \omega}{12}$$

12 Converts inches to feet

$$\omega = \frac{s \times 12}{\pi \times D}$$

$$s = 20 \text{ fpm} \Rightarrow \omega = \frac{240}{\pi \times D} \Rightarrow \omega = \frac{76.4}{D}$$

$$s = 50 \text{ fpm} \Rightarrow \omega = \frac{600}{\pi \times D} \Rightarrow \omega = \frac{191.0}{D}$$

Select mid range to create a rule of thumb

$$\omega = \frac{130}{D} \text{ for } D \text{ in inches or } \omega = \frac{5}{D} \text{ for } D \text{ in mm}$$

Equation 3
Calculating Shaft Rotation Speed

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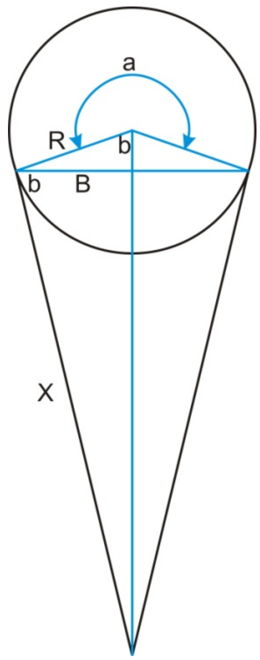

a= Angle of Wrap in Degrees
R= Shaft Radius
A= Thread Length in Cotact with Shaft
X= Length of Thread to Weight
T= Total Length of Thread (not including length knotted at weight)

$$T = A + 2 \times X$$

$$R = \frac{D}{2}$$

$$A = \pi \times D \times \frac{a}{360}$$

$$b = \frac{360 - a}{2} \Rightarrow b = 180 - \frac{a}{2}$$

$$B = R \times \sin b$$

$$B = X \times \cos b \Rightarrow X = \frac{B}{\cos b}$$

$$X = R \times \frac{\sin b}{\cos b} \Rightarrow X = \frac{D \times \tan b}{2}$$

$$\tan(180 - \theta) = -\tan \theta$$

$$X = \frac{-D \times \tan \frac{a}{2}}{2}$$

$$T = \pi \times D \times \frac{a}{360} + 2 \times \frac{-D \times \tan \frac{a}{2}}{2}$$

$$T = D \times \left[\pi \times \frac{a}{360} - \tan \frac{a}{2}\right]$$

$$a = 240° \Rightarrow T = D \times 3.83$$

5 times the shaft diameter easily gives enough extra thread length to tie the knot at the weight

Equation 4 Calculating Thread Length

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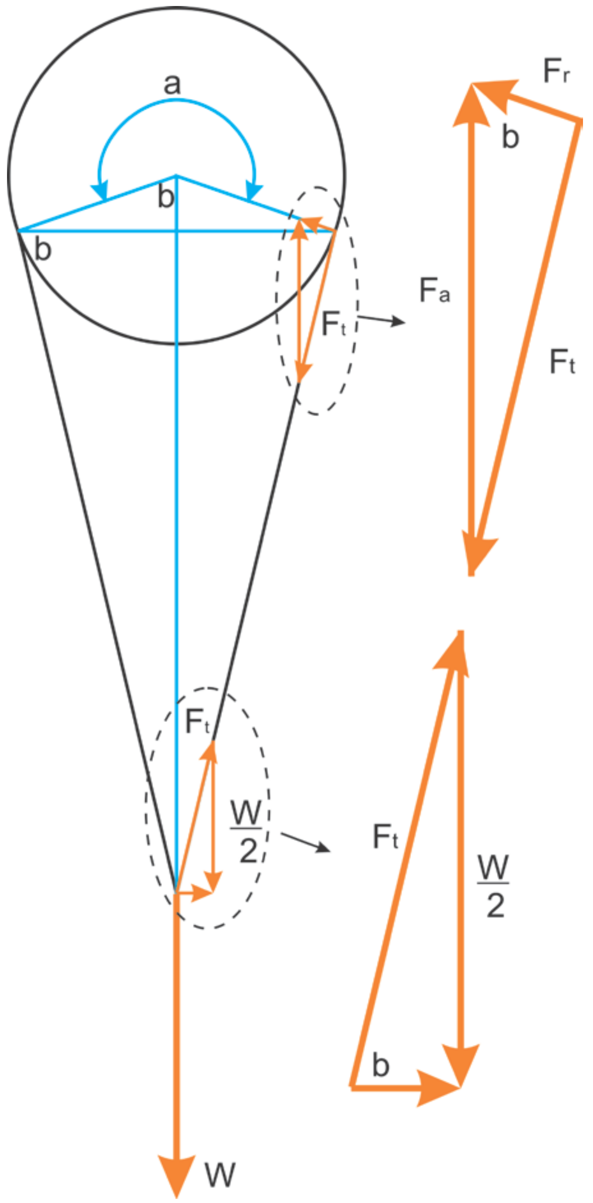

a= Angle of Wrap in Degrees
R= Shaft Radius
A= Thread Length in Cotact with Shaft
W= Weight Hanging in Thread
F_t= Tension Force in Thread
F_r= Radial Force on Shaft from Thread
F_a= Apparent Force

By Symetry, Force Applied to Each Thread Strand is Half the Total Weight

$$b = \frac{360 - a}{2} \Rightarrow b = 180 - \frac{a}{2}$$

$$\sin b = \frac{\left(\frac{W}{2}\right)}{F_t} \Rightarrow F_t = \frac{W}{2 \times \sin b}$$

$$\tan b = \frac{F_t}{F_r} \Rightarrow F_r = \frac{F_t}{\tan b}$$

$$F_r = \frac{W}{2 \times \sin b \times \tan b}$$

Trigonometric Identities

$$\frac{\sin\theta}{\cos\theta} = \tan\theta$$

$$\sin\theta \times \tan\theta = \sin\theta \times \frac{\sin\theta}{\cos\theta} = \frac{\sin^2\theta}{\cos\theta}$$

$$\sin(180 - \theta) = \sin\theta$$

$$\cos(180 - \theta) = -\cos\theta$$

$$\sin\frac{\theta}{2} = \pm\sqrt{\frac{1 - \cos\theta}{2}} \Rightarrow \sin^2\frac{\theta}{2} = \frac{1 - \cos\theta}{2}$$

Substituting into F_r

$$F_r = \frac{W}{2 \times \sin b \times \tan b} \Rightarrow F_r = \frac{W \times \cos b}{2 \times \sin^2 b} \Rightarrow F_r = \frac{-W \times \cos\frac{a}{2}}{2 \times \sin^2\frac{a}{2}} \Rightarrow F_r = \frac{-W \times \cos\frac{a}{2}}{1 - \cos a}$$

$$a = 202° \Rightarrow F_r \cong \frac{W}{10}$$

$$a = 207° \Rightarrow F_r \cong \frac{W}{8}$$

$$a = 240° \Rightarrow F_r = \frac{W}{3}$$

$$a = 255° \Rightarrow F_r \cong \frac{W}{2}$$

$$a = 283° \Rightarrow F_r \cong W$$

$$a = 320° \Rightarrow F_r \cong 4 \times W$$

$$a \to 360° \Rightarrow F_r \to \infty$$

Equation 5 Calculating Thread Grip

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