The Importance of Shaft Alignment

by John Piotrowski

The most frequently asked questions by managers, engineers, foremen, contractors, and trades people concerning the subject of shaft (mis)alignment and its importance in maintaining industrial rotating machinery are discussed.

What exactly is shaft alignment?

In very broad terms, shaft misalignment occurs when the centerlines of rotation of two (or more) machinery shafts are not in line with each other. As simple as that may sound there still exists a considerable amount of confusion to people who are just beginning to study this subject when trying to precisely define the amount of misalignment that may exist between two shafts flexibly or rigidly coupled together. How accurate does the alignment have to be? How do you measure misalignment when there are so many different coupling designs? Where should the misalignment be measured? Is it measured in terms of ... mils, degrees, millimeters of offset, arcseconds, radians? When should the alignment be measured ... when the machines are off-line or when they are running?

In more precise terms, shaft misalignment is the deviation of relative shaft position from a collinear axis of rotation measured at the points of power transmission when equipment is running at normal operating conditions. To better understand this definition, let's dissect each part of this statement to clearly illustrate what's involved. The deviation of relative shaft position accounts for the measured difference between the actual centerline of rotation of one shaft and the projected centerline of rotation of the other shaft.

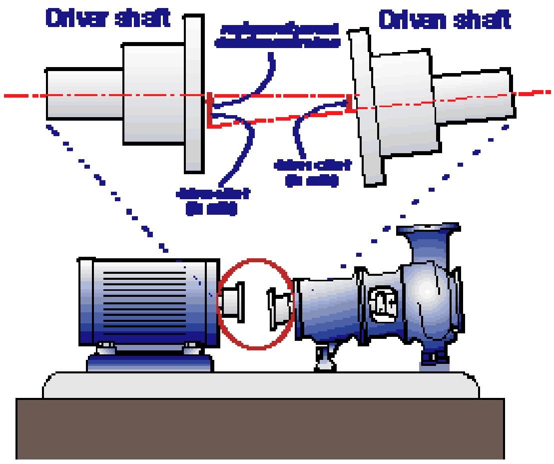

Figure 1. Typical misalignment condition.

Figure 1 shows a typical misalignment situation on a motor and a pump. For a flexible coupling to accept both parallel and angular misalignment there must be at least two points where the coupling can 'flex' or give to accommodate the misalignment condition. By projecting the axis of rotation of the motor shaft toward the pump shaft (and conversely the pump shaft rotational axis toward the motor shaft) there is a measurable deviation between the projected axes of rotation of each shaft and the actual shaft centerlines of each shaft where the power is being transmitted through the coupling from one 'flexing' point to another. Since we measure misalignment in two different planes (vertical and horizontal) there will be four deviations that occur at each coupling. In the example shown, notice that there is a horizontal deviation and a vertical deviation at the point of power transmission on the motor and a horizontal deviation and a vertical deviation at the point of power transmission on the pump. The goal of the person doing the alignment is to position the machinery casings such that all of these deviations are below certain tolerance values. A tolerance guide is shown in figure 2 that will help is establishing a goal for the people who are doing the alignment.

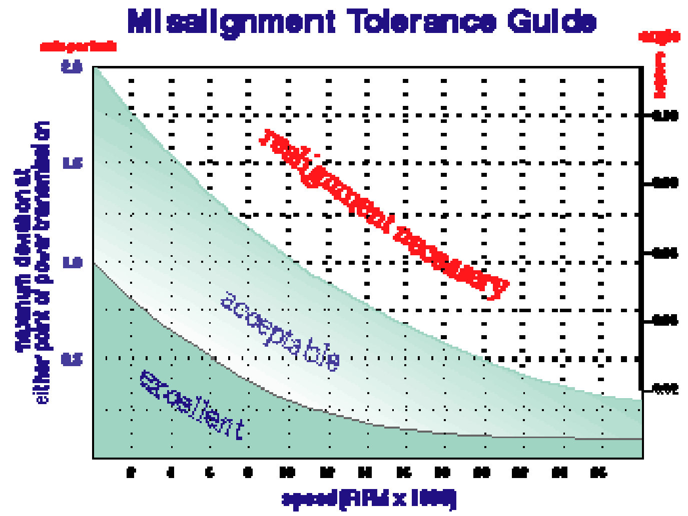

Figure 2. Shaft Alignment Tolerance Guide.

The last part of the definition of shaft misalignment is probably the toughest to achieve and usually the one aspect of alignment that is most often ignored. When rotating equipment is started, the shafts will begin to move to another position. The most common cause of this movement is due to temperature changes that occur in the machinery casings and therefore this movement is commonly referred to as hot and cold alignment. These temperature changes are caused by friction in the bearings or by thermal changes that occur in the process liquids and gases. Movement of machinery may also be caused by process reaction moments in attached piping or counter-reactions due to the rotation of the rotor, something similar to the forces you feel when you try to move you arm around with a spinning gyroscope in your hand.

What is the objective of accurate alignment?

Simply stated, the objective of shaft alignment is to increase the operating lifespan of rotating machinery. To achieve this goal, machinery components that are most likely to fail must operate within their design limits. Since the components that are most likely to fail are the bearings, seals, coupling, and shafts, accurately aligned machinery will achieve the following results ...

- Reduce excessive axial and radial forces on the bearings to insure longer bearing life and rotor stability under dynamic operating conditions.

- Minimize the amount of shaft bending from the point of power transmission in the coupling to the coupling end bearing.

- Minimize the amount of wear in the coupling components.

- Reduce mechanical seal failure.

- Maintain proper internal rotor clearances.

- Eliminate the possibility of shaft failure from cyclic fatigue.

- Lower vibration levels in machine casings, bearing housings, and rotors (*note ... frequently, slight amounts of misalignment may actually decrease vibration levels in machinery so be cautious about relating vibration with misalignment).

What are the symptoms of misalignment?

Misalignment is not easy to detect on machinery that is running. The radial forces transmitted from shaft to shaft are typically static forces (i.e. uni-directional) and are difficult to measure externally. Disappointingly, there are no analyzers or sensors that you can place on the outside of a machine case to measure how much force is being applied to the bearings, shafts, or couplings. Consequently what we actually see are the secondary effects of these forces will exhibit many of the following symptoms...

- Premature bearing, seal, shaft, or coupling failures.

- Excessive radial and axial vibration. (*Note ... tests have shown that different coupling designs exhibit different types of vibration behavior. It appears that the vibration is caused by the mechanical action that occurs in the coupling as it rotates).

- High casing temperatures at or near the bearings or high discharge oil temperatures.

- Excessive amount of oil leakage at the bearing seals.

- Loose foundation bolts.

- Loose or broken coupling bolts.

- Some flexible coupling designs run hot under misalignment conditions. If it is an elastomeric type, look for rubber powder inside the coupling shroud.

- Similar pieces of equipment are vibrating less or seem to have a longer operating life.

- Unusually high number of coupling failures or they wear quickly.

- The shafts are breaking (or cracking) at or close to the inboard bearings or coupling hubs.

- Excessive amounts of grease (or oil) on the inside of the coupling guard.

What happens to rotating machinery when it's misaligned a little bit, or moderately, or even ... severely?

The drawing shown in figure 3 illustrates what happens to rotating machinery when its misaligned. Albeit, the misalignment condition shown here is quite exaggerated, it tries to indicate that rotating machinery shafts will undergo distortion (i.e. bending) when vertical or lateral loads are transferred from shaft to shaft.

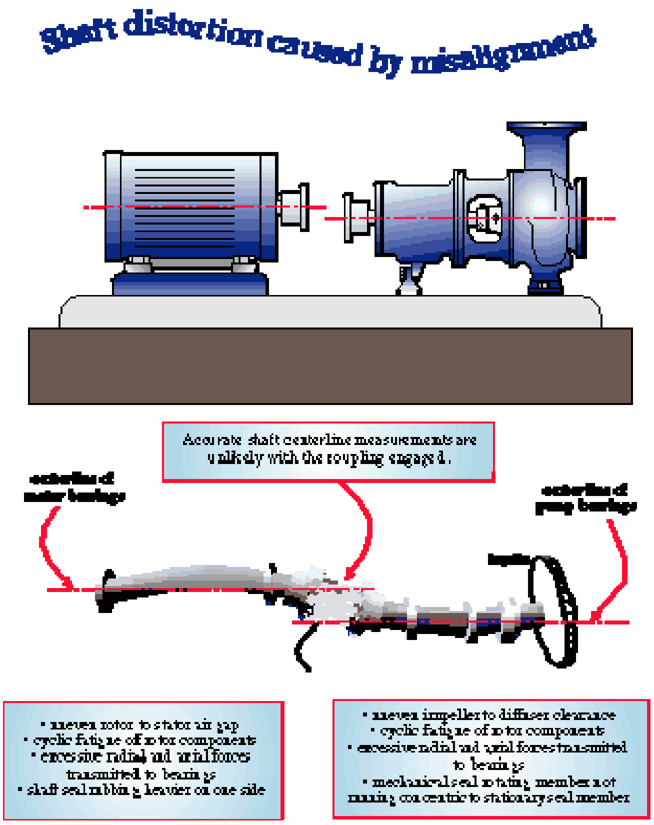

Figure 3. Shaft distortion due to excessive misalignment.

Please do not misinterpret the drawing! It is fully understood that flexible couplings do just what they are designed to do ... they flex to accommodate slight misalignment. But the shafts are flexible too, and as the misalignment becomes more severe, the more the shafts begin to flex also. Keep in mind that the shafts are not permanently bent, they are just elastically bending as they undergo rotation. Notice also that the pump shaft in this example is exerting a downward force on the inboard motor bearing as it tries to bring the motor shaft in line with its centerline of rotation. Conversely, the motor shat is exerting an upward force on the inboard pump bearing as it tries to bring the pump shaft in line with its centerline of rotation. If the forces from shaft to shaft are great enough, the force vector on the outboard bearing of the motor may be in the upward direction and downward on the outboard bearing on the pump. Perhaps the reason why misaligned machinery may not vibrate excessively is due in part to the fact that these forces are acting in the same direction. Forces from imbalanced rotors for instance, will change their direction as the 'heavy spot' is continually moving around as the shaft rotates, thus causing vibration (i.e. motion) to occur. Shaft misalignment forces do not move around, they usually act in one direction only.

The chart in figure 4 illustrates the estimated time to failure of a typical piece of rotating equipment based on varying alignment conditions. The term 'failure' here implies a degradation of any critical component of the machine such as the seals, bearings, coupling, or rotors. The data in this graph was compiled from a large number of case histories where misalignment was found to be the root cause of the machinery failure.

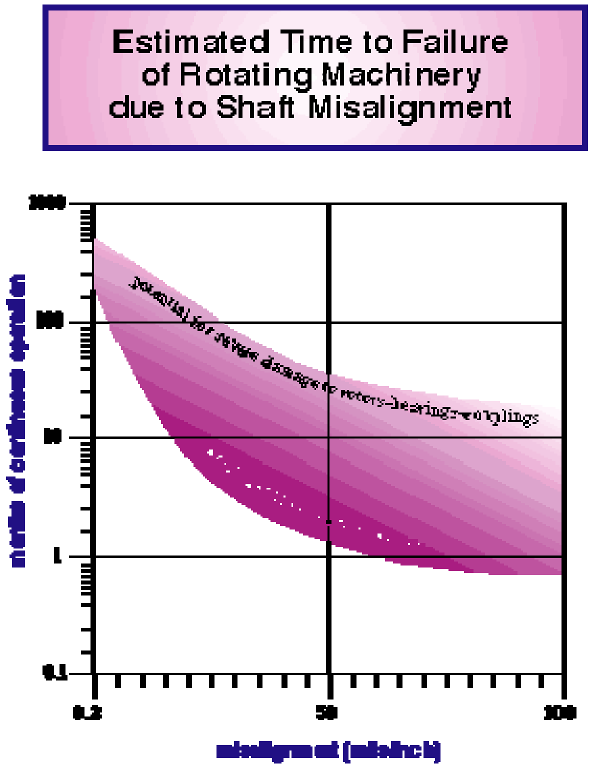

Figure 4. Estimated time to failure of rotating machinery due to various amounts of shaft misalignment.

How much time does it take to do each step in the alignment procedure?

There are eight basic steps in the overall alignment job.

1. Preparation - tools, people, training.

2. Obtain relevant information on the machine being aligned. Are there any special tools needed to measure the alignment or reposition the machines? Do the machines move from off-line to running conditions? If so, how much and ... do you have to purposely misalign them so they move into alignment when they're running?

3. Before you begin working on a machine remember ... Safety First! Tag and lock out the machinery.

4. Preliminary checks : runout, 'soft foot', coupling OK?, bearings OK?, foundation OK?, baseplate OK? Is the piping putting a strain on the machines?

5. Measure the shaft positions. Are they within acceptable alignment tolerance?

6. Decide who needs to be moved (which way and how much) and then physically reposition the machine(s) vertically, laterally and axially. After you've made a move, go back to step 5 and check to see that the machines really moved the way you hoped they did.

7. Install coupling and check for rotational freedom of drive train if possible. Install coupling guard.

8. Run and check the machinery.

How much time does it take to align machinery?

The graph in figure 5 shows the average amount of time taken to do steps 2 through 8. Step 1 is not on the graph since procuring all the necessary tools and training everybody who's involved can take a considerable amount of time to complete. As you can see, the two most time consuming tasks in the alignment process are ... performing the mechanical integrity checks and moving the machinery to align the shafts. It is not uncommon for accurate alignment to take from 3 to 8 hours, assuming everything goes just right!

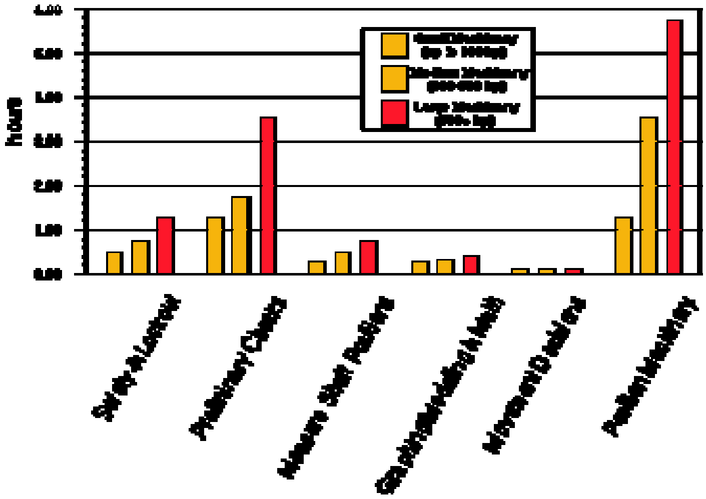

Figure 5. Estimated time to perform alignment steps.

How can I reduce the amount of time it takes to do alignment properly?

First, the people who are aligning the machinery have to know what they are doing and they have to have a goal to shoot for. They also require access to all of the tools needed to do the job and the tools must work properly. If your company purchased an expensive alignment measurement system that stays locked up in a cabinet, it's not doing anyone any good if they can't use it when they need it. It is also important to have an alignment system that can provide you with alternative movement solutions when repositioning the machinery.

The key to successfully aligning machinery comes from having the ability to arrive at a solution that is possible to perform and minimizes the required movement at the feet. Accurately calculating required movement at the machinery feet is useless if you can't move the machine the amount you're alignment system is telling you.

How often should alignment be checked?

As previously mentioned, rotating machinery can move around immediately after it has been started. This is fairly rapid movement and the shafts eventually take a somewhat permanent position after the thermal and process conditions have stabilized (anywhere from 2 hours to a week in come cases). However there are slower, more subtle changes that occur over longer periods of time. Machinery will slowly change its position for the same reason your driveway buckles, or your building foundation cracks. Settling of base soils underneath the machinery will cause entire foundations to shift. As the foundations slowly move, attached piping now begins to pull and tug on the machinery cases causing the equipment to go out of alignment. Seasonal temperature changes also cause concrete, baseplates, piping, and conduit to expand and contract.

It is recommended that newly installed equipment be checked for any alignment changes anywhere from 3 to 6 months after operation has begun. Based on what you find during the first or second alignment 'checkup', tailor your alignment surveys to best suit the individual drive trains. On the average, shaft alignment on all equipment should be checked on an annual basis. Don't feel too embarrassed as you read this because you're definitely not the only person who hasn't checked your machinery since its been installed.

How much money should I be spending on tools and training?

I guess a good rule of thumb is to invest 1% of the total replacement cost of all your rotating machinery on alignment tools and training on an annual basis. For example, if you have 20 drive trains in your facility valued at $5000.00 each (total $100,000.00) then you should invest $1000.00 on alignment every year. This expenditure should only cover tools and training and should not encompass the time and materials required to do alignment jobs.

How do I know if the contractors I hired to install my machinery are doing the alignment properly?

Include some clause in your contract that requires them to provide you with the initial alignment data, 'soft foot' conditions and the corrections made, shaft and coupling hub runout information, the final alignment data, the moves made on the machinery, and the final alignment tolerance. Don't be satisfied with and answer like ... "We used dial indicators" or "We used a laser".

Dial indicators and lasers don't move machinery, people do.

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