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Understanding Shaft Alignment: Thermal Growth

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Part two of a four-part series that will cover alignment fundamentals and thermal growth, and highlight the importance of field measurements through two case studies.

Machine conditions change from the time the machine is off line to when it is running under normal operating conditions. Some of these changes are due to process forces (e.g., fluid pressures, airflow, etc.). The most notable of these changes is the change in the temperature of the machine bearings and supports. This is called the machines thermal growth.

Thermal growth is the change in the length of a particular metal as a result of the change in temperature of that metal. Typically, when a metal bar is heated, it will get longer. These changes can be very small (0.0005 in.) or they can be very large, depending on the length of the piece of metal and its coefficient of linear expansion.

Formula for thermal growth

The formula used for this calculation is often referred to as the T x L x C formula. T represents the change in the materials temperature in degrees Fahrenheit, L represents the length in inches of the material, and C represents the materials coefficient of linear expansion. Different materials have different C values. Using the formula, we can anticipate the change in a machines shaft alignment based on the expected changes in machine temperature. Fig. 1 is a chart of the most common machine materials and their C values.

Consider the following example: A motor with a starting temperature of 70 F is perfectly aligned to the pump shaft it will be driving. For this exercise, the temperature of the pump will not change; however, the temperature of the motor will increase to 120 F under normal operating conditions. The motor end bells material is cast iron with a C value of 0.0000059. The distance from the bottom of the motor feet to the center of the shaft is 15 in. We now can calculate the change in position of the motor from off line to running by multiplying the T, L, and C values. T x L x C = growth (120 F â€“ 70 F) x 15 in. x 0.0000059 = 0.0044 in.

Based on this information, the motor will grow 0.0044 in. or 4.4 mils. If the growth of the motor is the same for both ends, the result will be a change in the offset alignment of 4.4 mils but the angular alignment will not change. This motor shaft should be aligned 4.4 mils lower than the pump shaft which will allow the machine to grow into an aligned condition.

Temperature changes unequally

That was a fairly simple example and does not accurately reflect what will happen to an actual machine. In reality, the temperatures of all the machine supports will change; however, they will almost never change equally.

Using the above machine example, consider the change in shaft alignment if the outboard end (OE) bearing temperature changed by 20 F and the drive end (DE) bearing temperature changed by 50 F. The drive end bearing would grow by 4.4 mils; however, the outboard bearing would grow only by 1.8 mils. The result will be a change in both the offset and angular alignment. If the motor feet are 20 in. apart, the change in the angular alignment will be 0.13 mil/in. [(4.4-1.8)/20 = 0.13] open at the top of the coupling. Changes in the temperature of machines from off line to running can have a significant impact on the shaft alignment.

These changes in the shaft alignment can be accommodated in a few different ways. One way is to align the machines to zero and then remove or add the amount of shim under the machine feet as determined by the temperature data. Another way is to gather the alignment data, graph the results, and predetermine the actual shim corrections based on the graph.

With today's modern laser alignment technology, accounting for thermal changes at the machine feet is actually a simple evolution. Most alignment systems on the market today have within them a function that allows the user to program the foot targets of the machine being aligned. For the previous example, the front foot target would be 4.4 mils and the back foot target would be 1.8 mils. After programming the determined foot target values at the machine feet, the user aligns the machines to zero on the display unit. The shaft alignment system will automatically calculate the required foot corrections to leave the feet at the prescribed positions. As the machine heats up, the shaft centerlines will grow into a properly aligned condition.

Gearboxes are difficult

Thermal changes in gearboxes can be especially difficult to calculate. Often the input shaft temperatures will be different from the output shaft temperatures. This causes the gearbox shaft alignments to change in the horizontal plane as well as the vertical plane.

Force-lubricated systems with an oil cooler also can have an effect on the final alignment condition of a machine. Higher oil temperatures out of the cooler will result in a hotter operating condition of the machine, therefore creating a more drastic change in the running alignment condition. A 10 F change in the operating temperature of a turbine from 105 F to 115 F can change the foot positions as much as 2-4 mils. The alignment condition of turbines and compressors that operate at very high speeds can be adversely affected by these relatively small temperature changes.

Pipe strain

Another condition that changes is the increase or decrease in temperatures of the suction and discharge piping attached to pumps and compressors. Some compressors may actually form ice on the suction end while the discharge piping is too hot to touch. Conditions such as these can force major changes in the operational alignment condition of machines.

While original equipment manufacturers might be able to anticipate the nominal changes in operating temperatures of a piece of equipment, they cannot accurately anticipate the effects of the piping configurations of the final machine installation or the changes in the temperature of the piping runs. Piping runs are typically very long and can have a tremendous impact on the change in the shaft alignment from off line to running condition. In addition, piping connections act as fixed (or restraining) points with respect to the tendency of machines to move/grow when on line. The effect of these fixed points on the final position of the machines is almost impossible to calculate or predict.

Depending on the piping configuration, these changes may be in the vertical plane or in the horizontal plane and are extremely difficult or impossible to accurately calculate based on the TLC formula above.

Consider two identical boiler feed pumps (BFP) as shown in Fig. 2. BFP #1 feeds boiler #1 which is 20 ft away and BFP #2 feeds boiler #2 which is 60 ft away. The length of the discharge piping on BFP #2 will be approximately three times longer than that on BFP #1. This will result in the two "identical" machines showing drastically different alignment changes from off line to running. A great deal of care must be taken when calculating the changes in the alignment condition of these machines. Just because two machines appear identical and serve the same function does not ensure they will exhibit the same operational characteristics.

Determining alignment changes

In the past, there have been several methods used to attempt to measure the changes in the shaft alignment of two or more machines. One of these methods involves measuring the changes in machine temperatures at each machine support and performing the target alignment based on mathematical calculations.

Another method relies on tooling balls mounted on machine bearings. Typically an optical transit (scope) is used to measure the off line positions of the tooling balls. Once the machine is at operating conditions, another set of measurements is made; the positional changes are compared to the "stationary" tooling balls. These changes are triangulated to calculate the change in the position of the shafts.

There is a variant to the above technique, the Acculign method, which involves installing tooling balls in the foundation as well as at the bearings. The distance between the fixed tooling balls (mounted in the foundation) and the bearing-mounted tooling balls is measured off line and then on line. Precise measurements of the distances and angles are required to make the calculations of the growth.

Doing hot alignment checks

Another way to gather this data is to perform a hot alignment check of the affected piece of equipment. The procedure for this is relatively simple. The machine is aligned off line and the results of the alignment are documented (horizontal angularity, horizontal offset, vertical angularity, and vertical offset). The machine then is placed on line and allowed to reach normal operating conditions. At this point, the machine is shut down and allowed to stop rotating.

The alignment system is remounted on the machine and the shaft alignment is remeasured and documented. Now the machine may be aligned hot by reshimming and repositioning the moveable machine as quickly as possible. One drawback of this method is that the machine will begin to cool as soon as it is shut down, adversely affecting the accuracy of the hot alignment check.

If the two sets of alignment readings were documented, a set of cold alignment targets can be calculated. Alignment results (hot) alignment results (cold) represents the change in the alignment condition of the machine from cold to hot. The alignment targets for this machine will be the opposite of the changes in the alignment parameters.

While this is currently a widely used method of hot-aligning machines, it will measure only the changes in the shaft alignment due solely to the changes in the machines temperatures. Discharge pressure, shaft torque, multiple machines operating in parallel, electrical loading of a generator, etc., also can play a large role in the change in the alignment condition from off line to running. These changes most often will be seen in the horizontal plane, but could affect the vertical alignment as well.

Yet another factor to consider is the location of the machine. If a machine is located indoors in a controlled environment, the operating characteristics should be relatively constant throughout the year. A machine that operates outdoors and is exposed to large changes in temperature also could exhibit extreme changes in its shaft alignment as the temperature changes (as in the change of seasons).

On line positional change measurements

One method used to measure the change in the alignment of two pieces of machinery is to document their bearing cap positions in both the horizontal and vertical planes relative to some fixed points in space while the unit is off line. After the data has been documented, the machine is started and placed on line. When the machine has reached its normal operating temperature, the positions of the bearing caps are measured again and compared to the points that are stationary. The movement of the machines and the changes in the shaft alignment then can be either calculated or graphed.

In the past, there have been problems obtaining on line readings using this method. A nominal amount of vibration can make an optical scale very hard to read through a transit or theodolite. Care must be taken that the scale is placed back in the exact location for each measurement at each point. Bearing caps are not typically precision machined on the outside surfaces. A very small deviation in the position of the detector can lead to a very large error if the surface that is being measured is not flat and smooth.

Modern laser-based measurement systems designed to measure flatness and surface parallel also can be used in this manner. One benefit of the laser-based positional measurement systems is that the data can be averaged, eliminating the potentially large errors when measuring machines that are running. When the laser beam strikes a vibrating detector surface the data will appear to bounce slightly. A simple function in the display unit will sample the data for the desired amount of time, locate the maximum and minimum values on the detector, and average the data accordingly. Since vibration, by definition, is cyclic and repeatable, very good results can be obtained.

Laser measurement systems

In the 1980s, a laser-based system became available that mounted to the drive end bearings of a machine to monitor the changes in the machines alignment from cold to hot or from hot to cold. Two laser transmitter/detectors are mounted on the stationary machine drive end bearing. One of these transmitter/detectors must be positioned in the 12 o'clock position (to monitor vertical changes) and the other must be positioned in the 3 o'clock position (to monitor horizontal changes). The transmitter/detectors are positioned coaxially with the stationary shaft centerline and level. Corresponding prisms are mounted on the moveable machine drive end bearing. They are positioned to reflect the laser beam back to the detectors mounted on the stationary machine.

The transmitter/detectors are hooked up to a computer running the measurement software. The user now can program the alignment monitoring equations into the software and have the system monitor all four alignment parameters simultaneously. The values are auto-zeroed and the data collection begins. When the machine is started and the alignment changes, it is recorded in the system software. When the machine reaches normal operation, the data collection is stopped and the alignment changes calculated. The results are displayed as a graphical trend.

The cold alignment targets will be opposite of the measured change in the machine alignment if the data collection was started when the machine was cold. If the cool down was monitored, the targets are equal to the values displayed in the software. While this system can be very effective for diagnosing alignment problems, it also can be very time consuming and frustrating to set up and monitor. Any change in the bracket position during the data collection will introduce errors into the results. This system also requires the user to purchase a PC to use for the data collection.

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COMMON MATERIALS AND THEIR C VALUES

Material	**C (in./in./F)**
Aluminum	0.0000126
Bronze	0.0000101
Cast iron	0.0000059
Copper	0.0000092
Mild steel	0.0000063
Stainless	0.0000074

Fig. 1. Different materials have different C values (coefficient of linear expansion).

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