REVERSE ALIGNMENT—UNDERSTANDING CENTERLINE MEASUREMENT

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ABSTRACT

Shaft alignment is a key factor in reducing vibrations and increasing reliability in rotating equipment. The most popular method of measurement is "reverse alignment." This method is often considered so complicated that many users have developed step by step worksheets, plotting boards, programmable calculators, and computer-aided laser devices that can guide the aligner through the procedure without a real understanding of the fundamentals of alignment. A need for a good understanding of the reverse method of measurement prompted this presentation.

The focus herein is to show how misalignment affects the rotor's behavior. Using a back to basics graphical method, it is shown how to visualize the shaft centerlines that enable the aligner to use logic for the easiest and best move. Calculation of thermal growth and how to select an allowable tolerance is also discussed.

Hot alignment is presented by showing different online monitoring systems as well as how to misalign cold so that the shafts will be colinear during operation.

An alignment trainer is used to demonstrate how an actual alignment is made.

INTRODUCTION

In today's high tech world, lasers can project a light beam with accuracy of 1/10 mil, and computers that can quickly calculate the amount of misalignment. To better apply this high tech, the aligner should understand the logic of the measurement and where to set the shaft for the proper cold position.

A back to basics approach to shaft alignment is presented. By observing the coupled shafts in the form of centerlines, one can visualize how it will respond to thermal movement, and how misalignment affects the rotor. It is more far-reaching than merely aligning a coupling to a coupling.

WHAT IS REVERSE ALIGNMENT?

Reverse alignment is the measurement of the axis, or centerline, of one shaft to the relative position of the axis of an opposing shaft centerline. This measurement can be projected the full length of both shafts for proper positioning there is a need to allow for thermal movement. The measurement also shows the position of the shaft centerlines at the coupling flex planes for the purpose of selecting an allowable tolerance. The centerline measurements are taken in both horizontal and vertical planes (Figure 1).

WHY REVERSE ALIGNMENT?

Proper alignment is required to reduce the amount of flexing in the coupling. When power is being transmitted from a driver to a driven unit, radial and axial stresses are induced by the sliding or bending of the flexible coupling. These stresses greatly affect the health of all connected equipment. To better understand, misalignment must be examined.

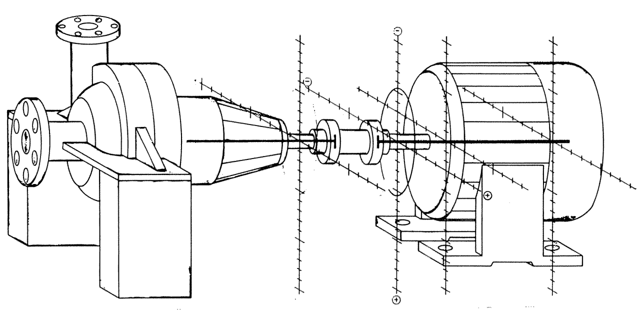


Figure 1. Centerline Measurement both Horizontal and Vertical

MISALIGNMENT

Shaft misalignment is the deviation of relative shaft position from a colinear axis of rotation, measured at the points of power transmission when the equipment is at normal operating conditions.

Misalignment is defined as angular, parallel, and combination angular and parallel (Figure 2).

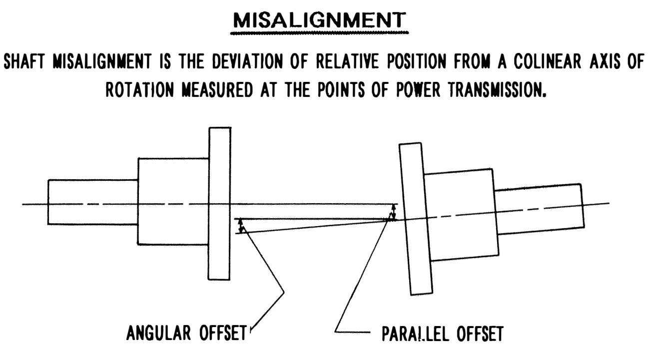


Figure 2. Misalignment Defined.

A misaligned gear coupling, Figure 3, shows how the coupling sees misalignment statically. It is shown in Figure 4 how the gear teeth slide back and forth when the shafts are rotated. This axial response to misalignment also occurs in disc pack, diaphragm, and elastomer type couplings.

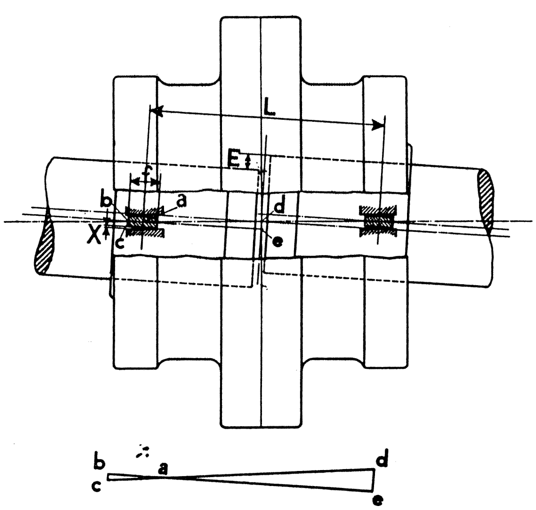


Figure 3. Misaligned Gear Coupling.

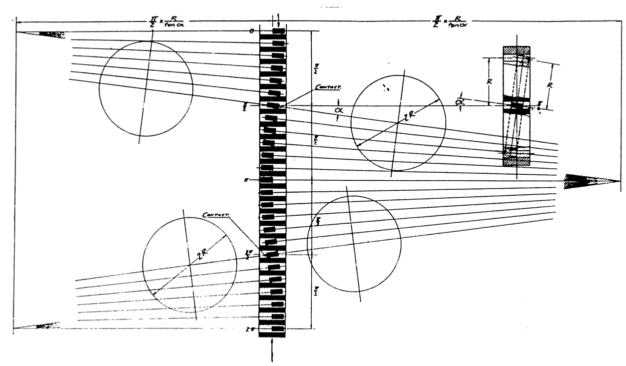


Figure 4. When Rotated Gear Teeth Side Axially.

Misalignment has many negative effects on equipment. Consider one, the geometry of misalignment (Figure 5).

The differences in diameter of the flexing element in Figure 6 show that the axial forces from misalignment can be greater on a disc pack coupling where the flexing diameter is larger than that of

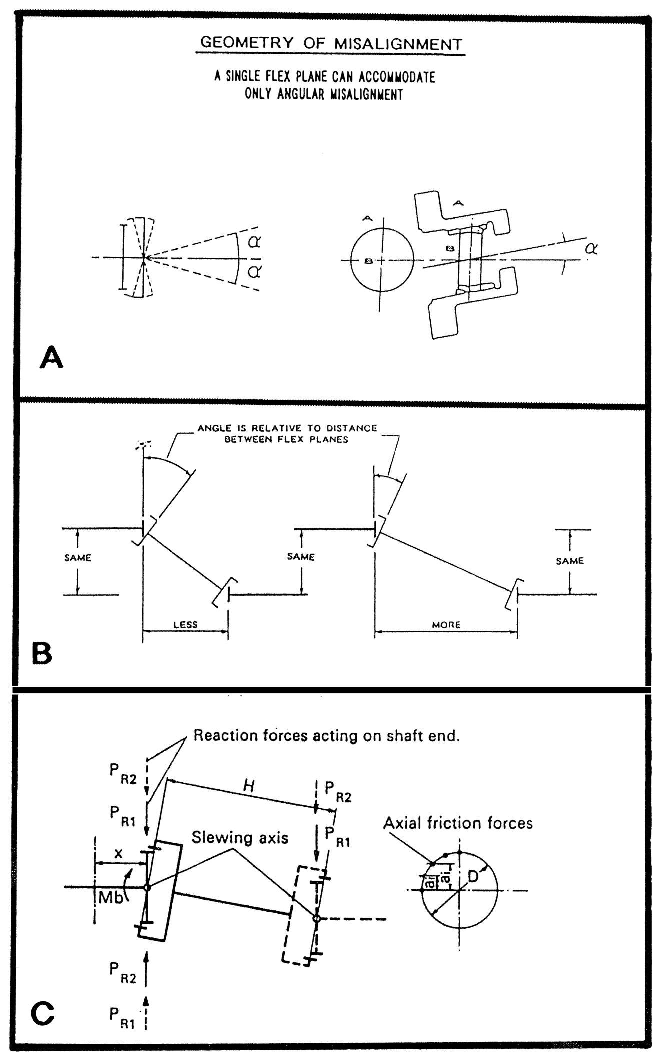


Figure 5. Geometry of Misalignment. A) A single flex plane can accommodate only angular misalignment; B) The angle is relative to distance between flex planes; C) Reaction forces acting on shaft end are relative to flexing diameter.

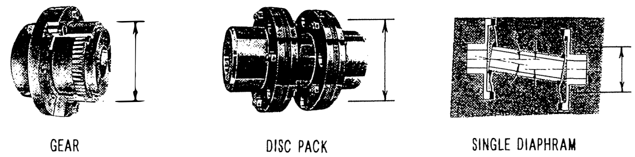


Figure 6. Axial Forces Are Relative to Diameter of Flex Planes.

a gear type coupling. On a single diaphragm coupling, the flexing element diameter is even smaller. Coupling stiffness is a factor in axial forces.

CRITERIA FOR ALIGNMENT TOLERANCE

The first alignment tolerances were dictated by the coupling manufacturer, by how much misalignment his coupling could take before it locked up. This was expressed in degrees of angle. This is shown in Figure 7 as the tilting movement of the gear tooth.

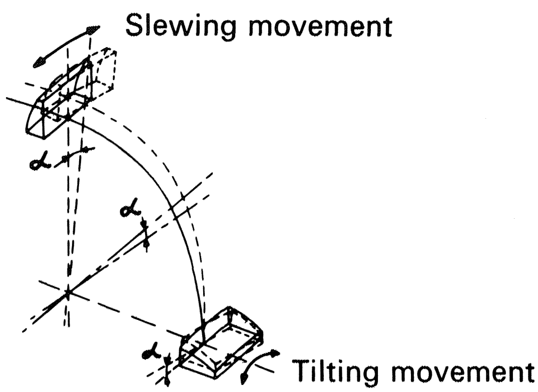


Figure 7. Movement inside Coupling.

The next coupling user tolerance was how much of the slewing movement (Figure 7) or sliding velocity the lubrication could stand before it fatigued. This slewing or bending movement also fatigues metallic discs and elastomer elements.

The speed of the equipment is a factor in setting an allowable tolerance. The amount of flexing, bending, or sliding times the rpm dictates the fatigue factor.

HOW MISALIGNMENT AFFECTS THE ROTORDYNAMICS

Axial forces excite or intensify the residual unbalance in an overhung rotor. The mode shape of a typical overhung rotor is shown in Figure 8. The axial movement caused by misalignment at the coupling end is transmitted down the shaft, causing the force of the residual unbalance to move back and forth, altering the length of the moment at the rate of 1.0 × rpm. This axial movement can make misaligned overhung rotors very difficult to balance.

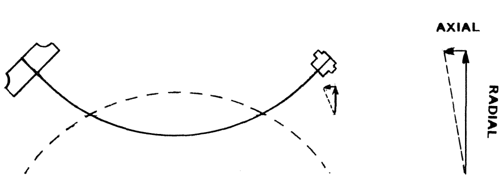


Figure 8. Misalignment Forces (1x, 2x, 3x, and 4x) Complicates (1x) Balancing.

RADIAL RESPONSE TO MISALIGNMENT

When misalignment occurs between two or more machines, there is a preload direction that is very important to the vibration data received. There are several ways of observing the machines response to misalignment.

Machinery with Hydrodynamic Bearings

Using an orthogonal pair of noncontact probes, one can measure the shaft's centerline movement, or orbit, for diagnostic purposes. One can observe preloading by the position of the rotor running in its bearings. The deflection of the circular orbit to an ellipse indicates the preload direction (Figure 9).

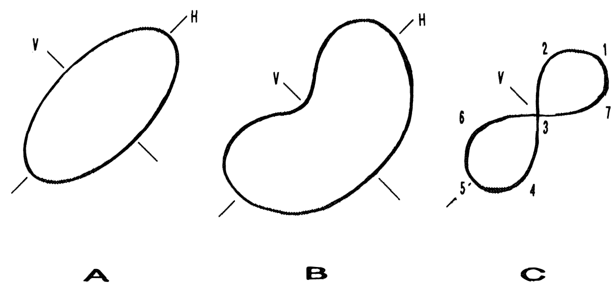


Figure 9. Orbit.

The orbit of a turbine driving a pump during startup is shown in Figure 9(a). As the temperature and loads increase, the preload direction influenced by the improper allowance for thermal movement is shown in Figure 9(b). When normal operating temperature was achieved (which was severe in this incident, with near 1/4 in offset) the orbit, Figure 9(c), evolved into a "figure eight pattern" giving a 2 × vibration response. All misalignments do not cause figure eight orbits; however, they do distort the normally circular/elliptical pattern of orbits. In this incident, the turbine shaft did break.

Machinery with Rolling Element Bearing

Data taken from the casing can be used to determine the amount of energy transfer (vibration) transmitted from the rotor to casing. Using a handheld vibration meter, lower vibration readings will be seen in the direction of most misalignment. The preload from misalignment restrains the vibration in the direction of the shaft-to-shaft misalignment. This generally coincides with high axial (and 1 × and 2 ×, depending on the phase angles) readings. It has a "false" indication to many that the vibration is "improved." Always measure in two planes, 90 degrees apart.

Severe amounts of misalignment can cause rotor deflections leading to bows, even breaking shafts or failing bearings quickly.

SELECTING AN ALLOWABLE TOLERANCE

Considering all the information about misalignment and how it affects the machinery, one might decide that all equipment should be perfectly colinear when running. But how perfect is perfect? Since this is not always economically feasible, a tolerance must be selected to allow the aligner some guidelines to know when the equipment is aligned well enough.

An excellent guideline for tolerance of most equipment up to, say 10,000 rpm, is 0.0005 in deviation from colinear for each inch of distance between the flex planes.

An example of a tolerance window with 8.0 in between the flex planes and 0.004 in above and below the fixed centerline is shown in Figure 10. Therefore, when the adjustment has been made, and the moveable centerline falls within the tolerance window, the alignment is satisfactory. When considering thermal movement, the machine should be set so that it does not grow out of the tolerance window.

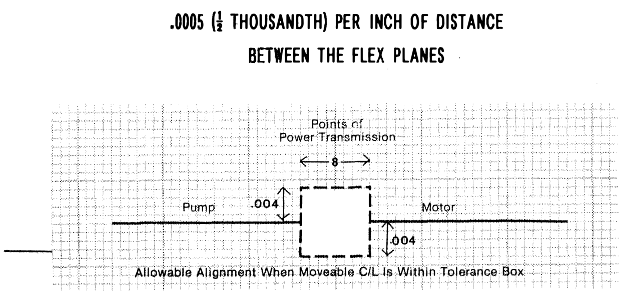


Figure 10. Alignment Tolerance.

This tolerance is probably too close for general purpose pumps, but if one always aligns to this, the next time it is checked, one will be able to see if there have been settling foundations, pipestrain, poorly adjusted pipe hangers, etc.

It is not difficult to obtain these tolerances. Since the unwanted loads (thermal and other) are difficult to predict, the tighter tolerances give a margin of safety.

The procedure is normally worked in reverse order. The actual movements are measured and then applied to the cold set positions to determine the reverse indicator readings required. First, measure or predict; next, adjust the desired cold position (DCP) from the hot operating line (HOL); and finally, apply the alignment tolerance after the field movements begin.

HOW?

Again, reverse alignment is the measurement of one axis to the relative position of an opposing axis. This measurement will be made by using dial indicators that measure in 0.001 in (Figure 11).

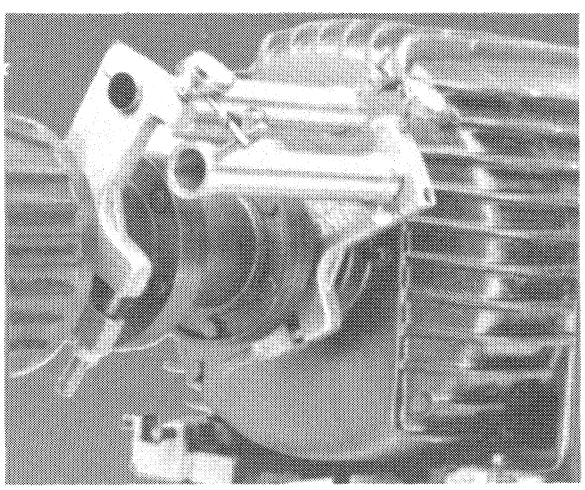


Figure 11. Reverse Alignment Brackets. Note indicator aimed directly toward centerline.

The graphical illustration of a single dial indicator sweep is shown in Figure 12.

This illustration shows the true arc of measurement (the centerline of the opposing shaft to be 0.004 in lower and 0.002 in to the right of the centerline of the shaft being measured).

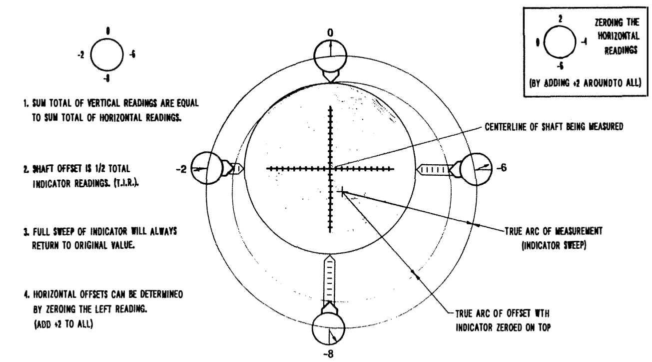


Figure 12. Graphical Illusion of Single Dial Indicator Sweep Logic (RIM).

The most important factors to remember about the logic of the indicator sweep are:

- The plus and minus sign show direction
- The number value shows how far (distance)
- The offset is 1/2 total indicator reading (TIR)

HOW TO GRAPH PLOT

A scaled representation of the shaft's centerline can be created by using square grid graph paper. Each horizontal square will represent 1.0 in. Each vertical square will represent 0.001 in.

Graph Scale $\updownarrow$ = 0.001 in
$\leftrightarrow$ = 1.0 in

The machine must be viewed in the same manner that it appears on the graph paper. This view with the fixed machine on the left, moveable machine on the right, will remain the same, both vertically and horizontally (Figure 13).

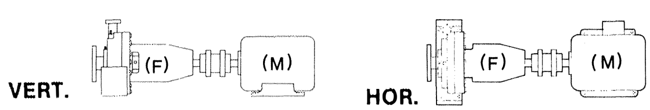


Figure 13. View Is Same Vertically and Horizontally.

GRAPH SCALE

The machine is measured and recorded on the graph (Figure 14).

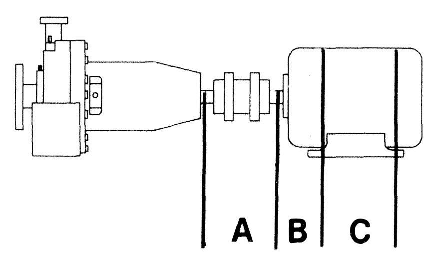


Figure 14. Measurement. A) Distance between indicators; B) Distance to front foot; C) Distance to back foot.

As previously stated about the logic of the dial indicator, the plus and minus signs tell direction. Therefore, it is important to always zero and read in the same manner every time, to be able to tell the relationship of the moveable centerline to the fixed centerline.

In all examples in this text, for the vertical move (Figure 15), the indicators are zeroed on top and read on the bottom. For the horizontal move (Figure 16), the indicators will be zeroed on the far side and read on the near side.

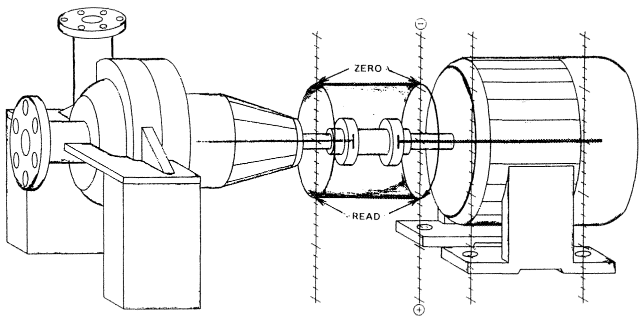


Figure 15. For Vertical Reading. Both indicators are zeroed at top and read at bottom.

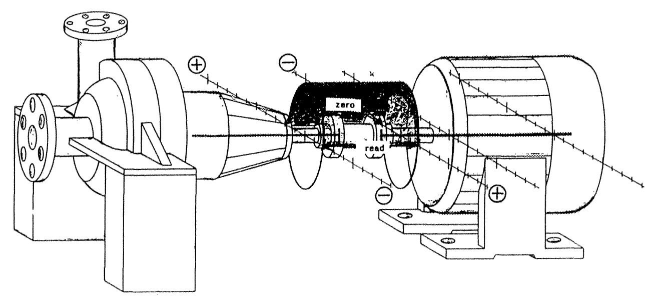


Figure 16. For Horizontal Reading. Both indicators are zeroed on far side and read on near side.

When the indicators are zeroed and read in this manner, the plus and minus signs relate the position of the moveable centerline to the fixed centerline.

To simplify the graphical procedure, the plus and minus signs should be included on the graph to tell direction. Shown in Figure 17, the sign's position will be the same both vertically and horizontally.

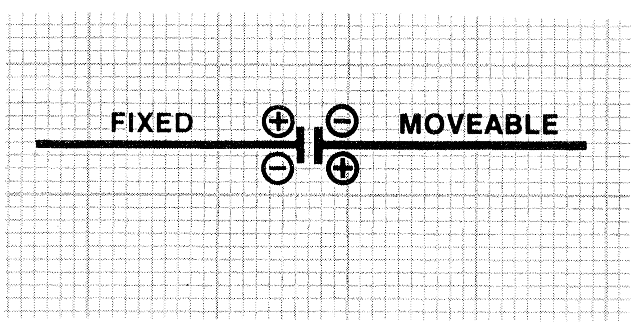


Figure 17. Relationship of Indicator Signs.

CALCULATING THE VERTICAL MOVE

The example for vertical move (Figure 18) shows that the indicators were zeroed on top and read at the bottom. The fixed indicator read -12. This means that the moveable centerline is 0.006 in (1/2 of indicator reading) from being colinear on the plus side of the line. The moveable indicator reads -18. This means that the moveable centerline is 0.009 in away from being colinear on the minus side of the line. When the line is extended, it shows the position of the moveable centerline at the front foot and the back foot of the motor.

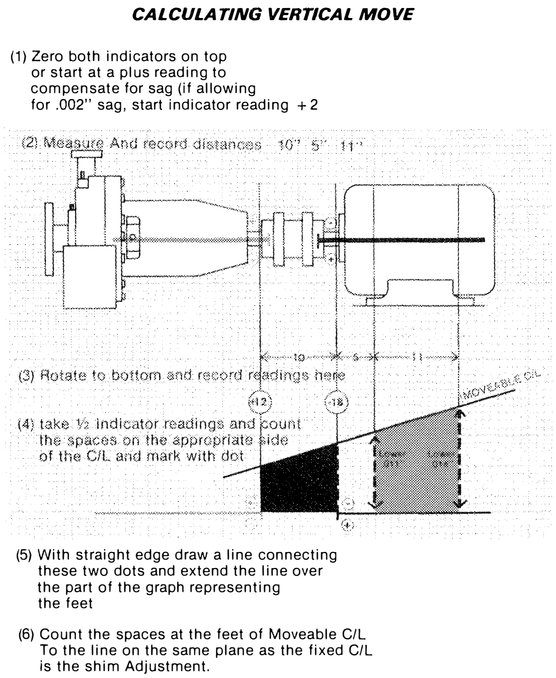


Figure 18. Calculating Vertical Move.

CALCULATING THE HORIZONTAL MOVE

The graph plot for the horizontal move is shown in Figure 19. It shows that when the aligner has the knowledge of centerline measurement and uses the logic of the indicator sweep, the horizontal move can be simplified.

The plus and minus signs tell direction, and the numerical value tells how far. The aligner can turn the indicator face to 1/2 the reading, then adjust the motor to the proper direction until both indicators read zero.

THERMAL MOVEMENT

Most machinery must be misaligned cold so that the shafts will be colinear during normal operating conditions. A good way to estimate thermal movement is by multiplying the coefficient of thermal expansion of the material by the distance (shaft centerline to base) by the difference in temperature change.

Demonstrated in Example 1 (Figure 20) is how to plot when the centerline mounted pump does not move, but the motor is estimated to rise 0.003 in.

Proper alignment is to set the motor shaft (desired cold position) 0.003 in lower than the pump shaft (hot operating line). One can see that a +6 and -6 final reading on the indicators is a much better alignment than zero, zero readings.

ONLINE MONITORING

Other factors can cause machine alignment not to respond as expected. Some of these are pipestrain, settling foundations, improperly adjusted pipe hangers, etc.

PRELIMINARY HORIZONTAL MOVE

SCALE ↔ = 1"
↕ = .001"

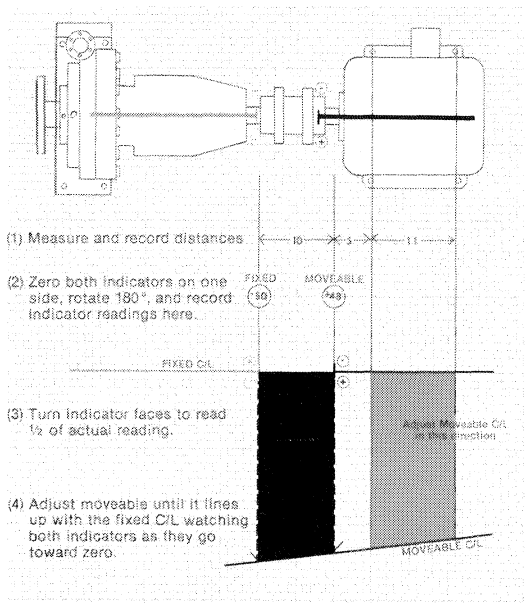


Figure 19. Horizontal Move.

THERMAL MOVEMENT

EXAMPLE 1.
Pump stays the same, motor grows .003" at both feet.

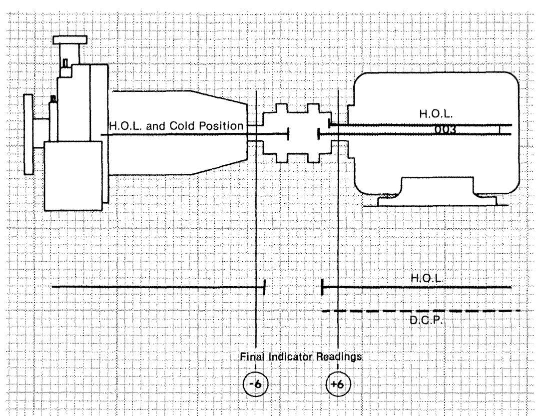


Figure 20. Example 1.

There are several online monitoring systems that can measure the case/bearing housing position. Other systems can measure shaft movement during operations, e.g., water stands or coupling deviations. How to plot when the pump will rise 0.001 in at the front reference point and 0.004 in at the back reference point is shown in Example 2 (Figure 21). The motor will rise 0.003 in at both back and front reference points.

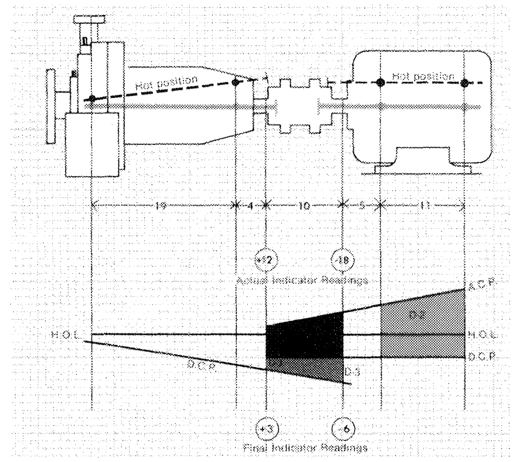
In order for the shafts to be colinear (hot operating line) during operation, they must be set lower (desired cold position—DCP). A reading is taken that shows the actual cold position (ACP). The difference between the ACP and the DCP at the indicator points of measurement can be projected to the motor feet. This shows the amount of shim adjustment.

Example 2.
Pump will rise .001" at front reference point, .004" at back reference point.
The motor will rise .003" at both reference points.

Step 1. Calculate thermal movement from ambient to running position.

2. Set up graph using H.O.L. as target and layout D.C.P.

3. Use ½ indicator reading at the fixed D.C.P. to layout the A.C.P. of the motor. (D1)



H.O.L. - Hot Operating Line.
D.C.P. - Desired Cold Position.
A.C.P. - Actual Cold Position.

D-1 - ½ indicator readings taken from the projected C/L of the fixed.
D-2 - Total shim adjustment.
D-3 - Final indicator reading.

Figure 21. Example 2.

This example shows that when proper alignment is achieved, the indicator readings should be + 3.0 on the fixed and - 6.0 on the moveable.

SUMMARY

- Rotating equipment can be dynamically sensitive to axial and radial forces.
- Aligning shafts centerlines, not couplings.
- Alignment tolerance is based on the equipment, not coupling.
- The indicator sign tells which side of the centerline; the number tells now far.
- Misalign cold so that machine is aligned when operating.

CONCLUSION

The economic objective is to improve machine reliability. Accurate alignment is critical in maintaining peak performance. A good understanding of the measurement and the logic of where to position the shaft is most important to all persons concerned with the operations of the equipment (engineers, mechanics, contractors, and managers). Since the alignment is constantly changing because of settling foundations, deteriorating pipe hangers, the changing out of piping components, etc., too much emphasis cannot be placed on this maintenance task.

The need to observe orbits of shaft motion is strong. The need to observe DC gap voltage changes of journals relative to their bearings is strong (eccentricity plots—manual or otherwise).

The focus herein has been to explain the reverse method of measurement and how misalignment affects the rotordynamics. These are only a few aspects of the complete alignment procedure.

FINAL THOUGHT

One can use a laser with accuracy up to 1.0 mil in 14 ft. One can use two sets of aligning equipment at $20,000/set. One can use special guages at eight points on each casing. One can use water stands on each shaft end [1] and each corner [2]. One can use instrumented couplings with telemetry—or whatever. However, when it gets down to the correction in the field, one must get down to hard rock fundamentals. The cold alignment will be done with measuring devices in the field by machinists, technicians, and/or engineers. Several know how to determine the moves. Very few know how to move the machines graciously and accurately! Piotrowski recently said, "People, not lasers and dials, move equipment!" [3].

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