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THE ROAD TO RELIABLE PUMPS

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ABSTRACT

The purpose of this paper is to take a "back to basics" look at installation issues that affect pump reliability. Topics of hydraulic fit, baseplate installation, shaft alignment, and piping alignment will be discussed.

INTRODUCTION

In today's marketplace, the company that can manufacture a product at the lowest price and maintain or improve quality will be the company that survives. From a mechanical perspective, the best contribution to achieving and maintaining a low price position is to minimize maintain cost. A large portion of maintenance budgets are spent on pumps. If plant pump life can be improved, every dollar saved is a contribution to the bottom line. For this reason, most top tier companies are working to achieve a mean-time between-repairs (MTBR) of 60 months or better.

Like any investment, something cannot be gotten for nothing. In order to improve pump life there must be upfront investment in qualified manpower, properly selected equipment, and properly installed equipment. Obtaining top tier MTBR requires paying attention to the details during the selection and installation process. For existing pumps, shortcomings in selection and installation are hard to overcome. Improvements in bearing designs, seal designs, or lubrication improvements are relatively easy to implement. Issues relating to hydraulic fit, pipe strain, or poor baseplate installation require great effort to justify and correct. Whether dealing with existing or new equipment, understanding and utilizing the basic concepts of sizing and installing pumps will pave the way to achieving long-term pump reliability. The remainder of the paper will discuss concepts for proper hydraulic fit, foundation design, baseplate design, grouting techniques, shaft alignment, and pipe alignment.

HYDRAULIC FIT

The cornerstone of a reliable pump system is assuring that the pump is a good hydraulic fit. That may seem very obvious, but the fact is that most pumps operate far from their best efficiency point (BEP). There are many reasons for that fact. In older plants, the service conditions have either increased or decreased over the years due to rate increases or different product slates. In many existing plants, as well as new plant construction or upgrades, the end user or engineering company destined the pump for a life of subpar operation at the specification stage.

The Law of Unintended Consequences is always at play during the specification stage. Every party involved is trying to do the right thing. The pump data sheet is the mechanism used to convey the process requirements from the pump user to the pump supplier. Every pump data sheet has a space for normal flow capacity and rated flow capacity. At both flow points, the required developed head from the pump will at least be the same. The rated flow capacity is generally an "it's possible" number. If a series of circumstances all line up, it is possible the pump will have to provide the rated flow capacity. Add a "fudge" factor to make sure the pump will absolutely provide the flow, and the outcome is a data sheet entry for normal flow that is fairly accurate and a rated flow capacity that is well off the mark. The Law of Unintended Consequences hits home with the selection of the pump.

The pump supplier has no choice but to select a pump that will develop the higher rated flow capacity at the required developed head. If the pump was selected based on the normal flow rate, any required flow in excess of the normal flow would not meet the necessary developed head. The outcome is a pump selected with hydraulics that is not optimized for normal operation. Take for example a pump with a normal flow requirement of 80 gpm at 120 ft of developed head, and a rated capacity of 160 gpm. Figure 1 reflects the pump curve for this example. The pump will operate the majority of the time at a point well to the left of the BEP. The unintended consequences are that the pump system's reliability will suffer.

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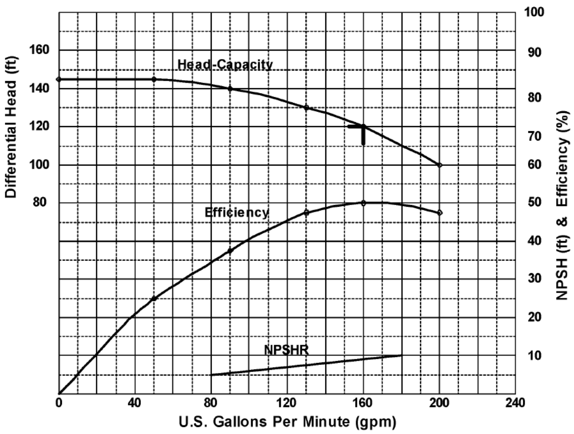

Figure 1. Pump Hydraulic Curve.

New Pump Applications

For new construction and upgrades, the machinery folks and the process folks need to talk. In most cases, neither party understands the design constraints the other is working with. If the only form of communication is the pump data sheet, poor choices are guaranteed to happen. There are legitimate conditions where the normal and rated flow requirements have a large spread. There are tools available to deal with these circumstances, and they will be discussed later with the subject of existing pump applications. By the same token, there are many situations where the rated flow and pressure requirements reflect nothing more than a possibility or a hedge against the unknown.

Using a few simple guidelines for selecting the pump will satisfy both the machinery reliability criteria and relieve the process folks of the need to hedge their service conditions. Pump hydraulics should be selected using impeller diameters that are roughly 75 percent of the available range, and the baseplate should be designed to accommodate one larger motor frame size. Using these two design criteria during the selection process will provide the hydraulic flexibility necessary to respond to unknowns in the piping design or adjustments in the process. The thought process that the rated flow is a one shot attempt at covering all possible scenarios can be replaced with factor-free estimates for rated flow. This will help to minimize the range between normal flow and rated flow, and provide a more accurate hydraulic envelope for pump selection.

Existing Pump Applications

Existing pump applications provide a different set of opportunities. In this day and age, several tools are available to help identify poor hydraulic fits, and several tools to help solve the problem. If a pump is experiencing poor reliability, one of the first questions to answer is whether the pump is right for the service.

Most plants have some type of system that stores historical process data. This system will provide a wealth of information about pressure and flow conditions over a selected time interval. Somewhere in the piping system is a pressure or flow control valve that dictates where the pump operates on its hydraulic curve. Generally, the control valve receives its instruction from a pressure indicating controller (PIC) or a flow indicating controller (FIC). The output from the PIC or FIC is actual process readings, and these readings are stored in a process historian database (PHD). By retrieving this trended data over a day, month, or year, a clear picture of the actual hydraulic requirements of the pump can be made. The flow or pressure data will show a range of operation. Comparing these data to the pump hydraulic curve will show how close to the BEP the pump is operating.

If the operating data has a range that is within 15 percent of BEP, chances are the reliability issues experienced by the pump are not hydraulic related. On the other hand, if the operating range falls outside the 15 percent range, it is at least worth investigating. It has been proven, and written about, numerous times that as the operating point moves further to the left of the BEP, shaft, seal, bearing, and recirculation issues come into play.

When reviewing the actual process data, it is not uncommon to find two or more distinct operating points or ranges. This may indeed be the normal and rated operating points, providing the pressure and flow requirements are different. The operating points may represent different product slates or turndown in the unit output. Regardless of the reason, if the pump routinely operates up and down its hydraulic curve, reliability will be affected.

Variable Speed Drives

One of the best tools for satisfying both pump reliability and multiple operating points is the variable speed drive. Great improvements have been made in variable speed drive (VSD) technology over the last few years. It is now possible to use direct motor torque as the controlling parameter with an alternating current (AC) motor, as opposed to frequency and voltage. This improves the response time and accuracy of both torque and speed. More importantly, "internal" shaft parameters are used for control response rather than "external" parameters like frequency and voltage. In addition to VSD improvements, most of the pump companies now offer control systems that utilize these drive platforms in conjunction with control algorithms suited specifically for pumps. These systems provide great flexibility for resolving pump hydraulic issues on new or existing applications.

The best way to illustrate the use of a VSD for resolving pump reliability issues is through an example. In the eyes of a chemical engineer, a distillation column is a great tool for making several different products. Depending on the product slate, the poor pump at the bottom of the column can see a wide variance in flow conditions. For example, Product A is produced 75 percent of the time, and requires the pump to provide 70 gpm at 120 ft. Product B is produced 25 percent of the time, and requires 160 gpm at 120 ft. This example ends up with a hydraulic curve similar to Figure 1. Using a VSD will allow taking a completely different approach to the application.

Most pump services have an installed spare. If each pump had a VSD with pump logic, they could be linked together for communication. Figure 2 shows the pump curve at different speeds. Product A would require one pump to operate at 1760 rpm (curve 3), and be right at BEP. For Product B, the VSD could start the second pump, and both pumps would operate at 1800 rpm (curve 4) to provide 80 gpm 120 ft for each pump. This would satisfy service requirements for Product B and still allow each pump to operate at the BEP. Because the VSD controls from measured shaft torque, and communicates with each other, the two pumps will work together and function as one.

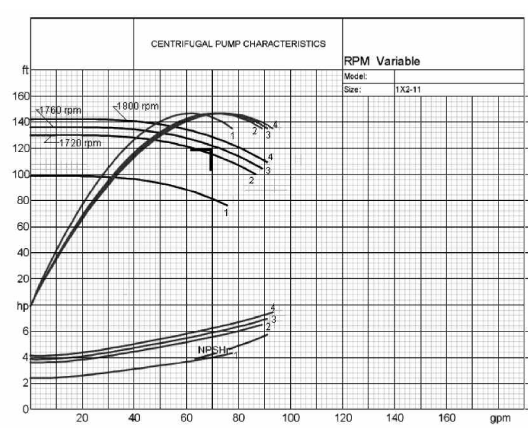

Figure 2. Pump Curve at Different Speeds.

PUMP BASEPLATE INSTALLATION

A proper installation involves many facets: good foundation design, no pipe strain, proper alignment, just to name a few. All of these issues revolve around the idea of reducing dynamic vibration in the machinery system. Great design effort and cost is expensed in the construction of a machinery foundation, as can be seen in Figure 3. The machinery foundation, and the relationship of F = ma, is extremely important to the reliability of rotating equipment. Forces and mass have a direct correlation to the magnitude of vibration in rotating equipment systems. The forces acting on the system, such as off-design operating conditions, unbalance, misalignment, or looseness, can be transient and hard to quantify. An easier and more conservative way to minimize motion in the system is to utilize a large foundational mass.

Figure 3. Example of Foundation Design Effort and Cost.

The cornerstone to a proper installation, and reduced vibration, is determined by how well the machinery system is joined to the foundation system. The baseplate, or skid, of the machinery system must become a monolithic member of the foundation system. Machinery vibration should ideally be transmitted through the baseplate to the foundation and down through the subsoil. "Mother Earth" can provide very effective damping (frequency attenuation) to reduce equipment shaft vibration. Failure to do so will result in the machinery resonating on the baseplate, as shown in Figure 4.

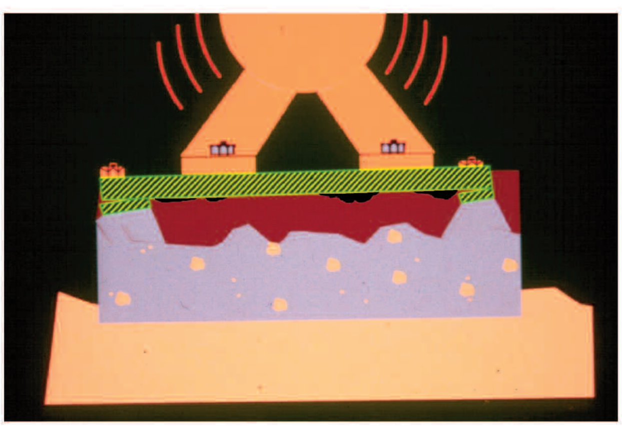

Figure 4. Machine Resonating on Baseplate.

There are several different grouting methods used for joining the pump system to the foundation system. These various techniques will be discussed later in the paper. Regardless of the method used, the foundation must be properly designed and prepared, and the baseplate must be properly leveled.

Foundation Design

Through years of empirical evidence, the rule of thumb has been developed that the foundation mass should be three to five times the mass of the centrifugal equipment system. Additional foundation design considerations are as follows:

- The foundation should rest on solid or stabilized earth completely independent of other foundations, pads, walls, or operating platforms. A minimum of 3000 psi steel reinforced concrete should be used.
- The foundation should be adequately designed to support the pump. Foundation mass for centrifugal pumps should be at least three times the mass of the pump, driver, and baseplate. Reciprocating pump foundation mass should be at least five times the pump system mass.
- The foundation should be designed to avoid resonant vibration conditions originating from normal excitation forces at operating speed or multiples of the rotating speed.
- The pump, gearbox (if used), and driver rest on a common foundation.
- The foundation is designed for uniform temperatures to reduce distortion and misalignment (boiler feed-water pump applications).

New Concrete Preparation

Freshly poured concrete must be allowed to cure before installing the pump baseplate. Moisture will ruin the bond between the epoxy grout and concrete interface, even the small amount of moisture from green concrete. It is a good practice to run an ASTM-157-80 Concrete Shrinkage Test to determine when the shrinkage drops to a minimum. This will indicate the end of the chemical reaction of the cement and water, which causes the concrete to cure. If no shrinkage test is run, the following rules of thumb for cure time should be used:

- Standard concrete (five bag mix) 28 days
- Hi-early concrete (six to seven bag mix) 7 days

An additional test for moisture can be made by taping a one foot square piece of plastic garbage bag over the new concrete and allowing it to set overnight. If there is moisture on the underside of the plastic bag the next day, the concrete is not ready for the placement of epoxy grout. Repeat the test until there is no moisture. Unprotected cured concrete will absorb moisture from rain, so give it the moisture test also.

During the placement of concrete for the pump foundation, samples of the concrete should be taken to make slump and compressive strength tests. During a routine compressive strength test for a 600 hp pump, a 3000 psi concrete mix, which passed the slump test, cracked at 1400 psi. The foundation was chipped out and the job started over at the expense of the concrete supplier. The concrete mix had been in the truck too long and additional water was added to pass the slump test. This retempering of the concrete made it much weaker.

Old Concrete Preparation

Old concrete has already cured and does not present the problem of determining moisture content as with new concrete, unless it rains. A visual check for foundation cracks must be made. All oil soaked concrete must be chipped away and all cracks repaired. It is a good practice to trepan a test core of the old concrete and run a compressive strength test. If the compressive strength is under 3000 psi, the foundation should be replaced.

Surface Preparation

The concrete must be chipped to remove the cement rich concrete (called laitance) from the top of the foundation and expose the aggregate. Removing the laitance provides a strong

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concrete/epoxy grout bond. Surface preparation is performed by chipping away the laitance with a light duty pneumatic hammer and a sharp pointed chisel. *Do not use a jack hammer* as that may crack the foundation. Chip away at least the top 0.50 inch of concrete until all laitance is removed and the aggregate is exposed (Figure 5). Chamfer all the foundation edges at least 2.0 inches at a 45 degree angle (Figure 6). This removes stress risers, and provides a wedge of epoxy grout to grip the sides of the foundation and prevent edge lifting of the grout.

Figure 5. Exposing Aggregate.

Figure 6. Chamfering of Foundation Edges.

Once chipping is completed, surface must be blown clean with oil free air and kept dry. *Moisture and oil are the main enemies of good epoxy grout/concrete bonding*. A good practice is to keep the chipped foundation completely covered with plastic until the last possible minute.

Anchor Bolt Preparation

The purpose of the anchor bolts is not to hold the baseplate in place. The purpose is to keep the interface of the concrete and epoxy grout in compression. Anchor bolts should have 10 to 15 times the bolt diameter of free bolt length for proper stretch to develop the designed compressive force. When properly torqued, the anchor bolts will hold the concrete foundation, epoxy grout interface, and the baseplate together in compression, and form one monolithic block. If epoxy grout is allowed to grip the anchor bolt, the bolt will break at the grout surface, even when tightened to the design torque. To prevent breakage, the anchor bolts must be isolated from the epoxy grout. This requirement must be met at the foundation design stage and might require the use of bolt sleeves in the concrete. If sleeves are used, they must be filled with a nonbinding material such as sand or flexible foam to prevent the epoxy grout from filling the sleeves and bonding to the anchor bolt. If sand is used, the top of the sleeve must be sealed with silicon caulk or an all-purpose sealing and caulking compound as the epoxy grout will flow into the sand. The exposed length of anchor bolt from the top of the concrete to the bottom of the baseplate should be wrapped with sealing and caulking compound or one layer of weather stripping and one layer of duct tape. The method most used by the authors is a 0.25 inch thick layer of sealing and caulking compound applied around the anchor bolt and sealed to the concrete and baseplate (Figure 7). This method may also be used on the jack screws so they can be removed when the grout has cured.

Figure 7. Wrapped Exposed Length of Anchor Bolt.

Baseplate Adjustment and Leveling

There are four methods used to support the pump baseplate while the grout is poured and cured. Figure 8 illustrates the use of single, double, or parallel wedges, jack screw, and shim pack to adjust or level the pump baseplate. Over the years, the jack screw method has become the adjustment technique of choice (Figure 9). This method allows for quick elevation changes, and more importantly the jack screws can be completely removed after the grout has cured. The baseplate should be 100 percent supported by the grout, with all leveling devices removed. Stainless steel circular pucks, cut from 2 inch diameter bar stock, can be used to prevent the points of the jack screw from digging into the concrete and altering the level. Grind the sharp edges of the circular pucks to remove any stress concentration points. Use just enough tightening force, approximately 45 ft-lbs, on the jack screws and anchor bolts to hold the baseplate in position until the grout has been poured and cured.

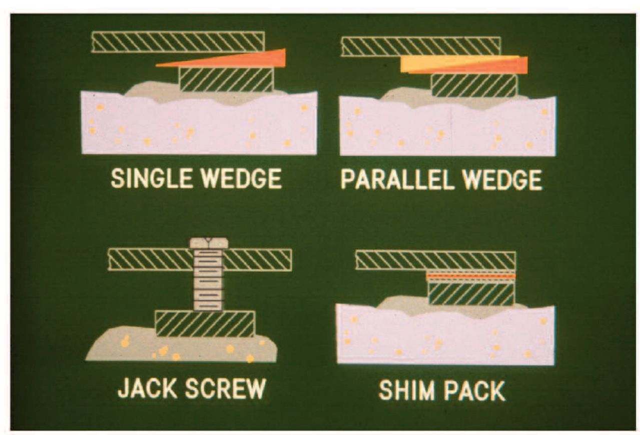

Figure 8. Four Most Common Methods Used to Level Pump Baseplates.

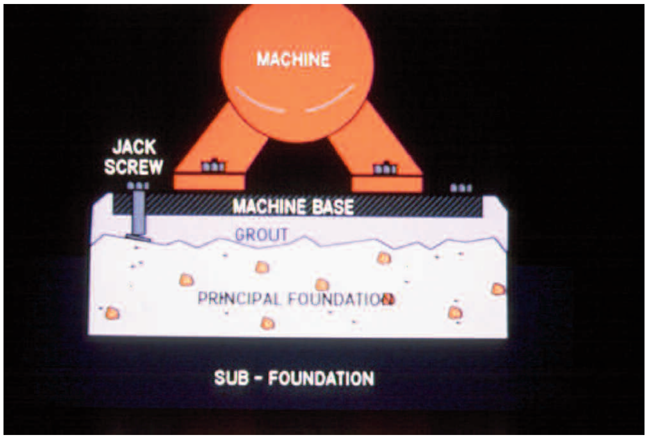

Figure 9. Jack Screw Method of Adjustment.

Leveling the baseplate in the field requires that the mounting surfaces be flat. However, the concept of flatness and level has become confused. Flatness cannot be measured with a precision level, and unfortunately this has become a common occurrence today. A precision level measures slope in inches per foot, and flatness is not a slope, it is a displacement. In the field, flatness should be measured with a ground bar and a feeler gauge, as shown in Figure 10, not with a level. Once the mounting surfaces are determined to be flat (0.002 inch) and coplanar (0.002 inch to 0.005 inch), the baseplate can be properly leveled. This confusion has caused many baseplates to be installed with the mounting surfaces out of tolerance for both flatness and level.

Figure 10. Measuring Flatness with Ground Bar and Feeler Gauge.

Flat and coplanar mounting surfaces make field leveling of the baseplate very easy. The best method is to use a precision level for each mounting surface. This will give a clear picture of the position of the baseplate to absolute level. The level must also fit completely inside the footprint of the mounting surface to read properly. If the level is larger than the mounting surface, use a smaller level or a ground parallel bar to assure that the ends of the level are in contact with the surface.

With the levels in position, adjust the jack bolt and anchor bolt system to the desired height for the final grout pour, typically 1½ to 2 inches for epoxy grout. With the grout height established, the final adjustments for level can be made. The baseplate should be leveled in the longitudinal or axial direction first, as shown in Figure 11, then in the transverse direction, as shown in Figure 12. The tolerance for level is 0.0005 inch per foot of baseplate length, not to exceed 0.010 inch total.

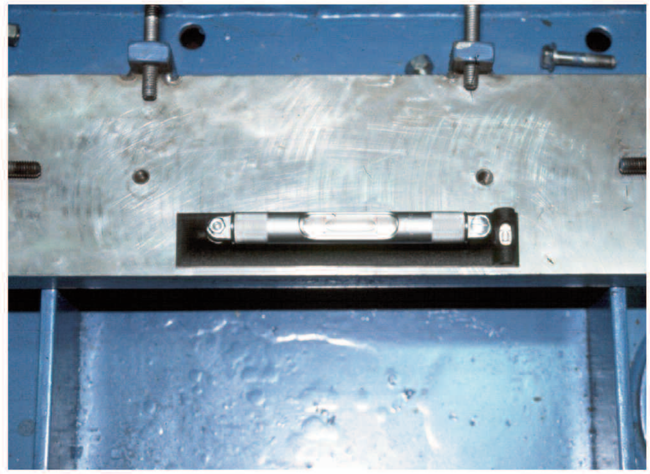

Figure 11. Level Baseplate in Axial Direction First.

Figure 12. Level Baseplate in Transverse Direction Next.

Baseplate Surface Preparation

Before grouting techniques are discussed, the subject of surface preparation for the underside of the baseplate needs to be addressed. Just as the surface of the foundation must be chipped and free of contaminates to provide good bonding, the baseplate underside must meet the same criteria.

Epoxy grout systems have very good bonding properties, typically an average of 2000 psi tensile to steel, but surface preparation and primer selection greatly affect the bond strength. The underside of the baseplate must be cleaned, and the surface must be free of oils, grease, moisture, and other contaminates. All of these contaminates greatly reduce the tensile bond strength of the epoxy grout system.

The type of primer used on the underside of the baseplate also affects the bond between the epoxy grout and the baseplate. Ideally, the best bonding surface would be a sandblasted surface with no primer. This is not feasible for conventional grouting methods, so a primer must be used, and the selection of the primer must be based on the tensile bond strength to steel. The epoxy grout system will bond to the primer, but the primer must bond to the steel baseplate to eliminate the formation of voids. The best primers will be epoxy based, and have minimum tensile bond strength of 1500 psi. Other types of primers, such as inorganic zinc, have been used, but the results vary greatly with how well the inorganic zinc has been applied.

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Figure 13 shows the underside of a baseplate sprayed with inorganic zinc primer. The primer has little or no strength, and can be easily removed with the tip of a trowel. The inorganic zinc was applied too thick, and the top layer of the primer is little more than a powdery matrix. The ideal dry film thickness for inorganic zinc is 3 mils, and is very hard to achieve in practice.

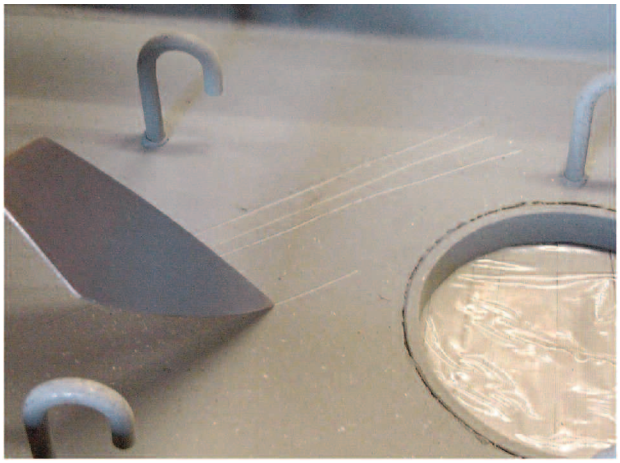


Figure 13. Underside of Baseplate Sprayed with Inorganic Zinc Primer.

The consequences of applying epoxy grout to such a primer are shown in Figure 14. This is a core sample taken from a baseplate that was free of voids for the first few days. As time progressed, a void appeared, and over the course of a week the epoxy grout became completely disbonded from the baseplate. The core sample shows that the inorganic zinc primer bonded to the steel baseplate, and the epoxy grout bonded to the inorganic zinc primer, but the primer delaminated. It sheared apart because it was applied too thick, and created a void across the entire top of the baseplate. As a best practice, the baseplate underside should be blasted to a 3 mil profile using SP-10 near white criteria, and within four hours be painted with a minimum 1500 psi tensile bond epoxy primer to a 4 mil dry film thickness (DFT).

Figure 14. Core Sample Showing Primer Delamination.

Grouting Techniques

The traditional approach to joining the baseplate to the foundation has been to build a liquid tight wooden form around the perimeter of the foundation, and fill the void between the baseplate and the foundation with either a cementitious or epoxy grout. There are two methods used with this approach, the two-pour method, shown in Figure 15, or the one-pour method, shown in Figure 16.

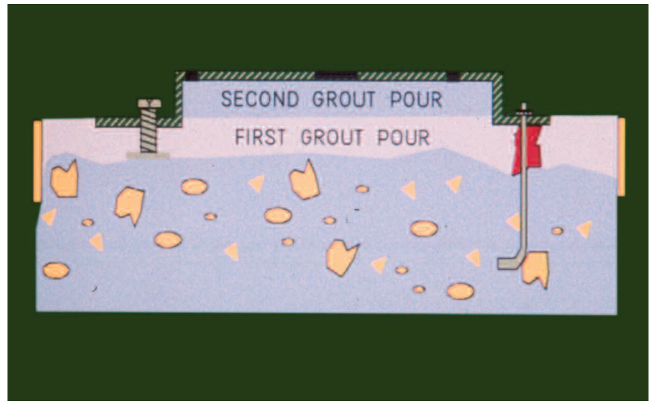


Figure 15. Two Pour Grout Form for Pump Baseplate.

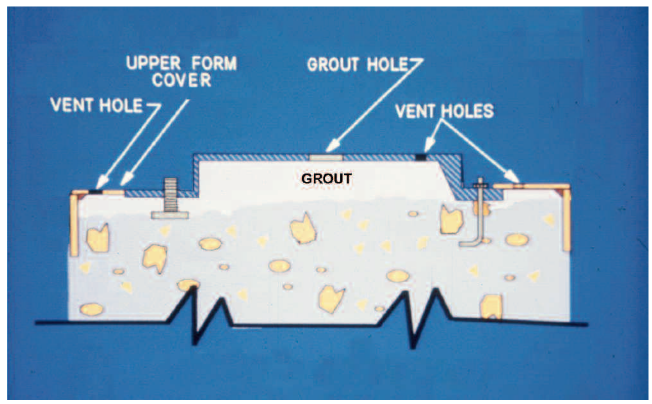


Figure 16. Single Pour Grout Form for Pump Baseplate.

The two-pour method is the most widely used, and can utilize either a cementitious or epoxy grout. The wooden grout forms for the two-pour method are easier to build because of the open top. The void between the foundation and the bottom flange of the baseplate is filled with grout on the first pour, and allowed to set. A second grout pour is performed to fill the cavity of the baseplate, by using grout holes and vent holes provided in the top of the baseplate.

The one-pour grouting method requires a more elaborate form building technique, but does reduce labor cost. The wooden grout form now requires a top plate that forms a liquid tight seal against the bottom flange of the baseplate. The form must be vented along the top seal plate, and be sturdy enough to withstand the hydraulic head produced by the grout. All of the grout material is poured through the grout holes in the top of the baseplate. This pour technique requires good flow characteristics from the grout material, and is typically used for only epoxy grout applications.

For either of these grouting methods, the baseplate must be equipped with pour holes and vent holes in the deck plate. The vent holes are an important part of the process to eliminate voids, or air pockets, at the interface between the grout material and the bottom of the baseplate. Whether the void is one inch deep, or one-thousandth of an inch deep the desired monolithic support system has not been achieved. Voids inhibit the foundation system from dampening resonance and shaft generated vibration.

Other provisions also need to be made to allow grout flow through the cross braces. The design criteria are as follows:

- All cross bracing on the underside of the baseplate must have a 2 inch × 6 inch wide opening to allow for grout flow.

• Pour holes, or grout holes, must be a minimum 5 inch diameter, and be provided in each bulkhead compartment.

• Vent holes (½ inch diameter) must be provided for each bulkhead compartment at all corners, high points, and perimeter edges of bulkhead. Perimeter vent holes in baseplate must be on 18 inch minimum centers. Any angle iron or "C" channels added for stiffeners will require vent holes on both sides.

• Radius all sharp corners on baseplate flanges, minimum 1 inch radius.

Pregrouted Baseplates

Over the last several years, a third option for baseplate installation has been utilized with the pregrouted baseplate. There are significant cost savings to be realized by pregrouting, but there are also technical reasons. Depending on the rigidity of the baseplate design, the epoxy grout cure during a traditional pour can actually distort the mounting surfaces. This "pull down" phenomenon has been proven by finite element analysis (FEA) modeling and empirical lab tests jointly performed by the lead author's company, a major grout manufacturer, and a major petrochemical company.

All epoxy grout systems have a slight shrinkage factor. While this shrinkage is very small, typically 0.0002 inch/inch, the tolerances for flatness and level of the mounting surfaces are also very small. The chemical reaction that occurs when an epoxy grout is mixed together results in a volume change that is referred to as shrinkage. Chemical cross-linking and volume change occurs as the material cools after the exothermic reaction. Epoxy grout systems cure from the inside out, as shown in Figure 17. The areas closest to the baseplate / grout interface experience the highest volume change.

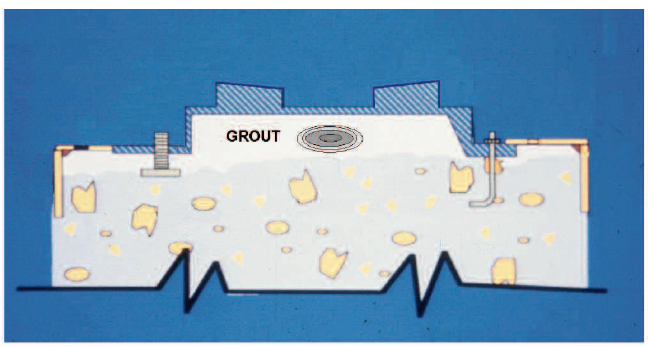


Figure 17. Epoxy Grout Systems Cure from the Inside Out.

Baseplates with sturdy cross braces are not affected by the slight volume change of the grout. For less rigid designs, the bond strength of the epoxy grout can be stronger than the baseplate itself. Referring back to Figure 17, after the grout has cured, the motor mounting surfaces become distorted, and are no longer coplanar. Tolerances for alignment and motor soft foot become very difficult to achieve in this scenario.

To eliminate the pull-down effect, the process of pregrouted baseplates has been developed. The term "pregrouted baseplate" sounds simple enough, but the process involves far more than flipping a baseplate over and filling it with grout. A proper pregrouted baseplate will be stress-relieved, blasted and primed on the underside, properly filled with grout material, completely cured, and then machined. This process will provide complete bonding of the epoxy grout to the baseplate underside, contain zero voids, and provide mounting surfaces that are flat, coplanar, and colinear within the required tolerances.

The final field grouting step will be performed much like a traditional two-pour method, but after the first pour the installation is complete.

Grout Forms

As mentioned above, wooden grout forms must be attached to the foundation sides to contain the grout during the pour process. The form must be of a heavy-duty design. Unlike concrete, epoxy grouts are designed to flow, and will apply substantial forces to the form boards. Forming material should be a minimum of 0.75 inch thick grade one plywood with 2 inch × 4 inch bracing. *If in doubt, make it stout*. All surfaces coming in contact with the epoxy grout must receive three coats of paste wax to prevent bonding to the wood. Allow time for the wax to penetrate into the wood and dry before applying the next coat.

Forms are to have ¾ or 1 inch × 45 degree chamfer strips at all vertical corners and at the top elevation surface of the grout. The forms must be liquid tight, using room temperature vulcanizing (RTV) sealant at all joints and at the mating surfaces of the foundation.

Form design for a two-pour method is essentially an open top form, as shown in Figure 18. Waxed form boards are attached to all four sides of the foundation, chamfer strips are installed, and all joints are sealed with caulk. The only dimensional consideration is to assure that the top of the form board is higher than the bottom baseplate flange. Grout is poured into the open spaces of the form, to fill the void between the concrete and the baseplate flanges. The forms are not used for the second pour of the baseplate cavity. Figure 19 shows another example of an open top form. This picture actually shows the final pour of a pregrouted baseplate, but the forming requirements are the same.

Figure 18. Form Design for a Two-Pour Method.

Figure 19. Another Example of an Open Top Form.

One-pour grout forms require a top plate be installed in the areas that were left open for the two-pour process. The top plate, shown in Figure 20, is attached to the sides of the grout forms and the top of the baseplate flanges. The top plate must be sealed liquid tight. Vent holes (d inch diameter) are drilled in the top form on 18 inch to 24 inch centers to allow air to escape as the grout flows from the center of the baseplate to the edges.

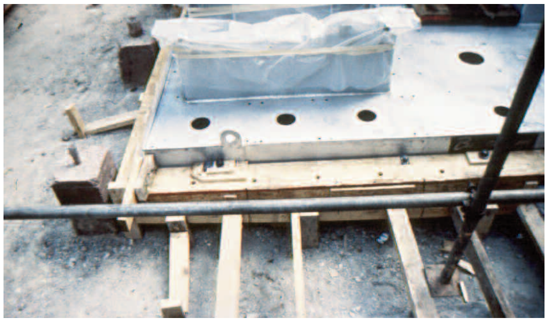


Figure 20. The Top Plate for a One-Pour Grout Form.

Epoxy Grout Placement

The pump baseplate is ready for grouting after the following last minute checks are made:

- Baseplate under surface is free of oil, dirt, or moisture.
- Concrete surface is clean, free of oil, dirt, and moisture.
- Anchor bolt sleeves are filled with nonbonding material.
- Exposed surfaces of anchor bolts are covered with sealing and caulking compound.
- Jack screws are lubricated with never-seize for easy removal.
- Circular steel plates are under each jack screw point.
- Vent holes are in correct locations and unobstructed.
- Forms in contact with grout are properly waxed (three coats).
- Grouting materials are in unopened containers, dry, and stored at 70°F to 80°F for 24 hours prior to placement.
- Sufficient quantities of grout materials are on hand at the site to complete the pour. (Add 15 percent to calculated grout requirement.)

Epoxy grouts have a narrow temperature range for mixing and placement. This range is from 50°F to 90°F for best pot life, flow ability, and curing. Low temperature grout pours will require that the foundation and baseplate be covered and heated. In hot weather, direct sunlight can greatly elevate surface temperatures. Construct a temporary shelter over the baseplate to provide shade at least 24 hours before grout placement.

There are two ways to mix the grout: in a wheelbarrow with a mortar mixing hoe or in a motorized mortar mixer. Both methods work well, but for larger grout jobs (five units or more) the motorized mixer should be used. When using a motorized mixer, limit the mixer blade speed to a maximum of 30 rpm. A typical motorized mortar mixer is shown in Figure 21.

Figure 21. Typical Motorized Mortar Mixer.

The grout should be mixed in accordance with the manufacturer's instructions. However, the following are some helpful tips that can be utilized to make the job go smoothly. The liquid components of the epoxy grout system must be mixed together prior to placement in the motor mixer. The resin and hardener should be combined and mixed in the container provided by the manufacturer. A jiffy mixer is the best tool for mixing the liquid components of the grout. Shown in Figure 22, this mixing blade is designed to mix without entraining air.

Figure 22. Mixing Blade of a Jiffy Mixer.

The liquid components should be added to the mortar mixer before any aggregate is added to the drum. By adding the aggregate to the liquid, all the aggregate will "wet-out" quickly. Adding the liquid to the aggregate makes a clumpy mess.

A unit of epoxy grout usually consists of liquid hardener and resin, and five bags of aggregate. The manufacturer will usually allowone bag of aggregate to be "cut" from the standard mix to improve flowability. *Do not cut more aggregate than is allowed by the manufacturer*. The aggregate is not just a bag of rock. There are specific ratios of components in the aggregate, and one of those components is "fines." The purpose of the fines is to capture entrained air and keep it in the grout matrix. Approximately one gallon of air is entrained in each bag of aggregate. Without adequate quantities of fines, the entrained air will bubble out of the matrix during the curing process, rise to the surface of the grout, and form air pockets right at the baseplate interface. In essence, voids will form after the grout has been placed.

During the grout placement process, the objective is to create a "wall" of grout that will displace the air in the open cavities of the baseplate, and push it through the vent holes in the deck plate. The best way to produce this "wall" of grout is to use a head box and stand pipes with the pour holes. Figure 23 shows an example of this. In this case, the one-pour method is being used, and the grout is dumped directly from the mixer to the head box. The better epoxy grout systems have excellent flow characteristics, and will flow all the way to the far end of the baseplate. By maintaining a grout level in the head box, the "wall" of grout will progress down the length of the baseplate, displacing all the air in the cavities. In Figure 24, the progression of the grout can be seen in the grout pour holes. Also notice that the vent holes in the top plate of the grout form have been covered with duct tape. As the formed area of the foundation fills with grout, all the air will be displaced through the vent holes. Grout will extrude out of these holes, but duct tape can be used to cover these holes and continue on.

Figure 23. Head Box and Stand Pipes to Produce "Wall" of Grout.

Figure 24. Progression of the Grout in Grout Pour Holes.

Another placement technique is to pour the grout directly into the stand pipes placed over the pour holes (Figure 25). This technique is typically used during the second pour of the two-pour process. In either case, a grout level is maintained in the head box or stand pipe until grout escapes out the vent holes (Figure 26). The hydraulic head helps to sweep air bubbles to the vent holes, and provides a void-free grout job. The "grout mushrooms" that form at the vent holes can be left in place until the grout gets tacky. At that point, remove the head box, pipe stands, "mushrooms," and clean up all grout spills.

Figure 25. Another Placement Technique.

Figure 26. Maintaining Grout Level.

Form Removal

Wait 24 hours before removing the grout forms and three days before removing the jack screws. Clean the thread lubricant from the jack screw holes with a degreaser and fill the holes with epoxy, RTV, or liquid rubber to seal out moisture and oil. After the jack screws have been removed, torque all the anchor bolts to their designed load.

Repairing Grout Voids

Proper attention to the grouting process should all but eliminate the formation of voids under the baseplate. Nevertheless, if voids do appear, they must be properly repaired. Lightly tap the top of the baseplate with a hammer to locate the voids. Voids sound much higher in pitch than the rest of the surface. Draw the outline of the void on the baseplate with a magic marker. After the void has been defined, drill multiple 0.250 inch holes into the periphery of the void. Install a self-tapping grease fitting into one of the holes. The other holes should be used as vents to prevent the lifting of the baseplate as unfilled epoxy grout is pumped into the void with a grease gun (Figure 27). It is good practice to put a dial indicator at the center of the void, held by a magnetic base mounted on the void free section of the baseplate. If there is a 0.003 inch rise in the dial indicator, stop pumping the epoxy until the indicator goes to zero. Pump the unfilled epoxy grout into the void until the void is filled and grout runs out the vent hole(s). Remove the grease fitting and allow the grout to cure.

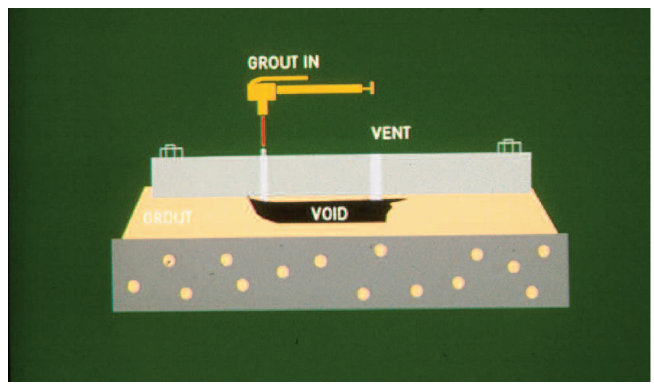


Figure 27. Using Vents When Pumping Grout into Void with Grease Gun.

MECHANICAL SHAFT ALIGNMENT

Mechanical shaft alignment is a key component in the pump installation process. Taking two or more shaft systems, and essentially making them operate as a single unit, is the principle behind mechanical alignment. The very best technique for learning how to align is to physically perform the work with an experienced person. Shaft alignment in its simplest form is geometry and visualization; mastering both requires practice.

It is impossible to completely cover the subject of mechanical shaft alignment in an abbreviated format, but the basic principles and techniques can be discussed.

Preparation for Alignment

The first thing to be done is to check and clean the machined mounting surfaces. Remove all burrs, paint, and rust and hone the surfaces with a fine honing stone. As discussed above, check the mounting surfaces for flatness, coplanar, and absolute level. If the baseplate was properly installed, these checks will meet tolerance. Any deviations from the tolerances will need to be corrected by field machining. Warped or skewed surfaces make alignment very difficult. The feet on both the pump and driver must be cleaned and honed before placing them on the mounting surfaces. The motor feet will need to be checked for "soft-foot."

Soft-foot is an elevation discrepancy between the motor feet. Figure 28 illustrates the two types of soft-foot: parallel and angular (also called tapered or skewed). Parallel soft-foot is caused by one or more of the mounting feet having a different elevation (noncoplanar) but remaining parallel to the mounting surfaces. This type of soft-foot is the easiest to correct because shims can be added to fill the gap and provide 100 percent contact. Angular soft-foot is caused by machining problems or stress relieving of the casting. Angular soft-foot is hard to correct with shims. Most often the motor is remachined to correct the problem.

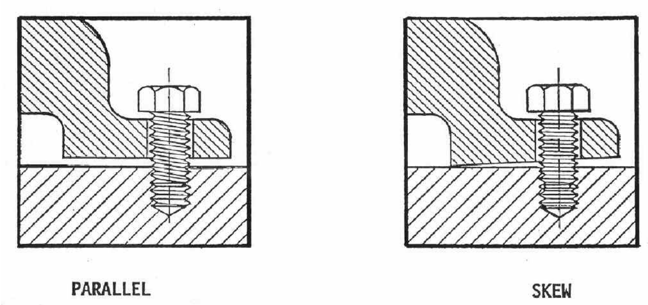


Figure 28. Types of "Soft Foot."

To check for soft-foot, all the hold-down bolts must first be firmly tightened. Each motor foot will check independently, by placing a dial indicator close to the hold-down bolt. Zero the dial indicator, loosen the bolt, and record the indicator reading for that location. Retighten the bolt, and the indicator reading should go back to zero. Repeat the process for each bolt location. Soft foot readings should be equal or less than 0.002 inch. If readings fall outside this range, use a feeler gauge to determine if the displacement is parallel or angular. Parallel soft-foot can usually be corrected by adding shims equal in thickness to the indicator readings. It is not uncommon to have the same or similar soft-foot reading at diagonal corners of the motor. In this case, a little math is required to fix the problem. Figure 29 illustrates how to correct diagonal soft-foot.

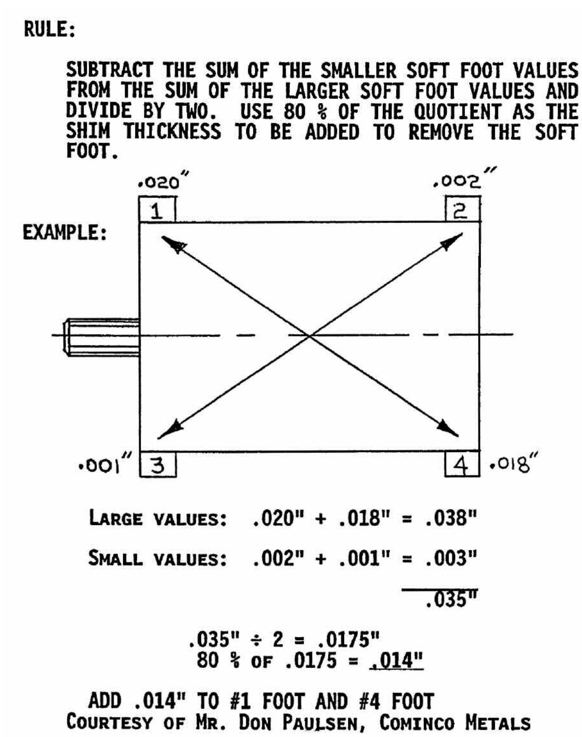


Figure 29. Soft Foot Shim Correction Formula.

Before alignment can begin, orientation must be established by choosing which piece of rotating equipment is the "fixed" and which is the "moveable." The fixed, or stationary, equipment should be the one that has the biggest piping problem, like a pump or steam turbine. Motors are generally picked as the moveable, or adjustable, equipment and, in the case of a steam turbine driver, the pump is the moveable. Once the steam turbine piping is correct, leave it alone! There are cases where a gearbox is the fixed equipment and the driver/driven pieces of equipment are designated as moveable.

Types of Misalignment

There are three types of shaft misalignment: parallel, angular, and a combination of the two. Parallel misalignment occurs when the shaft centerlines extend to infinity without intersecting (Figure 30). Angular misalignment is shown in Figure 31, and is defined by the intersection of the moveable centerline at the center of the fixed coupling hub face. It is rare to find pure parallel or angular misalignment on rotating equipment, but the combination of both parallel and angular misalignment is very common. Figure 32 shows the combined parallel/angular misalignment, which occurs when the extension of the moveable centerline intersects the fixed centerline at any location other than the fixed coupling hub.

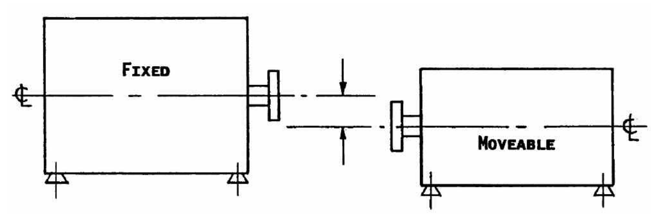


Figure 30. Parallel Misalignment.

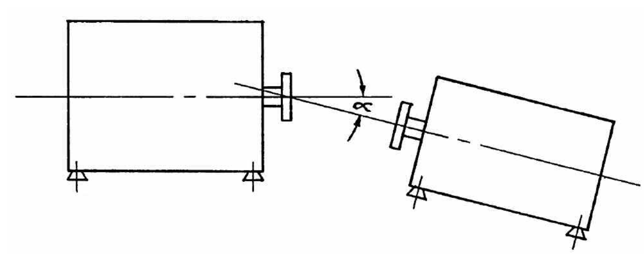


Figure 31. Angular Misalignment.

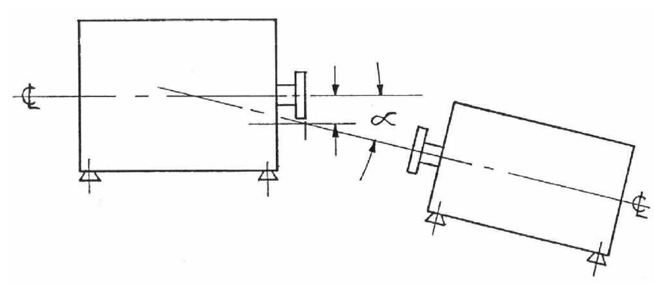


Figure 32. Parallel and Angular Misalignment.

Alignment of Rotating Equipment

Taking physical measurements of the relationship between two shafts can be accomplished in several different ways and there are good reasons for using each method. Some of the most popular methods are listed below.

- Straight edge and feeler gauge
- Dial indicator face and rim
- Reverse dial indicator
- Laser alignment

In the "olden days," when pumps were sealed with packing, the straight edge and feeler gauge were the prime tools for shaft alignment. The straight edge was used to correct parallel misalignment and the feeler gauge corrected angular misalignment. A careful millwright could align a pump within 0.015 inch to 0.020 inch with this method, which was acceptable for packed pumps. Today most pumps are sealed with mechanical seals requiring shaft alignment tolerances below 0.002 inch. However, the straight edge and feeler gauge method is still an excellent way to rough align shafts to bring the misalignment within the range of the dial indicator.

The face and rim dial indicator method is a popular way of aligning shafts and has been used for many years. One indicator is mounted on the rim or outer diameter (OD) of the coupling hub to read parallel misalignment and one indicator is mounted on the coupling hub face to read angular misalignment. This technique is an excellent choice when only one shaft is able to turn, or when the shaft ends are very far apart, such as cooling tower fans. The rim and face method should not be used for applications with axial shaft float, such as electric motors with sleeve bearings. One thing to remember when using this technique, when making shim correction calculations, is to always divide the OD readings by two. OD readings represent the total indicated run-out (total indicated reading, TIR), and are twice the actual centerline displacement. Face readings, on the other hand, are used at their full value.

The reverse dial indicator method has become very popular for aligning rotating machinery because of its accuracy. This method uses two indicators mounted on the OD of each coupling hub, so it can be used on sleeve bearing applications. The indicators describe two points in space that, when joined by a straight line, define the parallel and angular misalignment of the moveable shaft centerline to the fixed shaft centerline. Since all reverse indicator readings are OD readings, they must be divided by two when making shim correction calculations.

Both the rim and face and reverse dial alignment methods require the use of dial indicators and mounting brackets to take measurements. As the brackets extend the indicators out to the opposite shaft, the brackets will deflect or "sag." The amount of sag is a function of the length of extension. Sag is an error in the dial indicator reading caused by the force of gravity pulling down on the bracket/indicator system. When the indicator is zeroed at the top of the coupling hub, the gravitational error is subtracted out. As the indicator is rotated to the bottom, the indicator goes through the neutral position and sags below the neutral position the same amount as at the top. The sag of the bracket system must be measured and accounted for in the shim calculations. However, sag only affects the vertical readings. Horizontal, or side to side, readings are not affected by sag.

Sag can be measured by mounting the alignment brackets and indicators on a rigid piece of pipe in the same arrangement as on the rotating equipment shafts. With the indicators at the top position, zero the indicators and rotate the pipe 180 degrees. The readings on the indicators are the amount of sag that must be corrected for. The full indicator reading is used as the sag value. Some bracket manufacturers will provide a chart for determining bracket sag versus the length of extension.

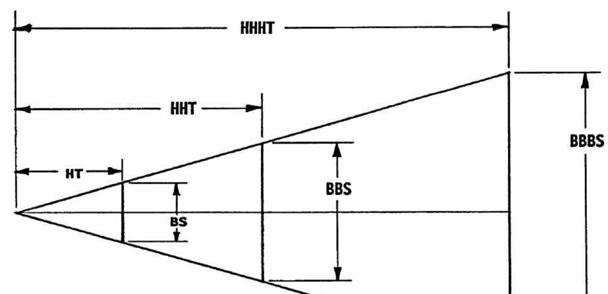
Sag can be compensated for during the shim correction calculations or by setting the indicator at a positive value equal to the sag reading when the indicator is at the top position. If the indicator is at the bottom position, which is the case with some alignment brackets, set the indicator at a negative value equal to the sag reading. A positive reading occurs on the dial indicator when the stem is pushed in. A negative reading occurs when the stem goes out, or extends.

The last alignment method listed is the laser. The use of the laser alignment system has become very popular, but has also contributed to the deficit of alignment skills. Most companies have purchased numerous laser systems, in spite of the $20,000 plus price tag, in hopes of improving plantwide alignment. The purchase of a laser system does not reduce the need for alignment training. Maintenance personnel need to understand the basics of shaft alignment prior to using the laser. It may sound like the authors are against laser systems and that is not true, let us just use them for the right reasons.

There is no sag in a laser system so it can be used over long distances and will also perform the soft-foot checks without the use of indicators. The system will record the readings, calculate shim changes, and provide a printed report for permanent records. It is an excellent tool in the hands of a well-trained millwright. One caution though, it is very important that the operator position the laser computer in the correct orientation or the alignment moves will be made in the wrong direction.

Methods for Calculating Shim Changes

All alignment calculations are based on the "height to base" relationship of a scalene triangle as illustrated in Figure 33. The point of the triangle represents the location of the dial indicator on the fixed coupling hub for a reverse indicator setup. The distance, "HT," is the location of the indicator on the moveable coupling hub and the distance, "BS," defines the slope of the triangle's sides. "HHT" and "HHHT" are the locations for the inboard and outboard hold-down bolts, respectfully. Inboard (IB) is defined as the position closest to the coupling hub, and outboard (OB) is defined as the position farthest from the coupling hub. The dimensional relationships illustrated by the triangle can be vertical or horizontal, depending on the perspective. The vertical relationship would be perceived as a "side view," and the horizontal relationship would be perceived as a "top view."



$$\frac{HT}{BS} = \frac{HHT}{BBS} = \frac{HHHT}{BBBS}$$

Figure 33. Base-to-Height Relationship in Scalene Triangle.

There are three methods to calculate corrective moves at the inboard and outboard feet of the moveable equipment:

1. Graphically using a plotting board or graph paper,

2. Hand calculations using formulas, or

3. By using a computer program.

Regardless of the method used, the same process is used for determining both vertical shim changes and horizontal positional changes.

The graph, or plotting board, method is an excellent way to visualize the alignment process. To illustrate the graph method, see the worksheet in Figure 34. Using the reverse dial method to obtain shaft readings, the measurements for the stationary and adjustable equipment are recorded every 90 degrees. The horizontal readings are zeroed-out on one side, and divided by two for the horizontal misalignment. The vertical readings take into account the bracket sag, which was determined to be .004 inch. Looking at the vertical readings, the indicator at the stationary machine (plane S) reads −.008 inch and the reading at the adjustable machine (plane A) is

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+.0005 inch. To interpret the readings, remember that a positive number means the indicator stem was pushed in, and for the negative reading, the stem moved out. At plane S, the indicator stem moved out (−) .008 inch. For that to happen, the bracket extension on the adjustable machine is lower than the stationary machine by .008 inch. At plane A, the indicator stem moved in (+) .0005 inch, meaning the adjustable machine is higher than the stationary by .0005 inch.

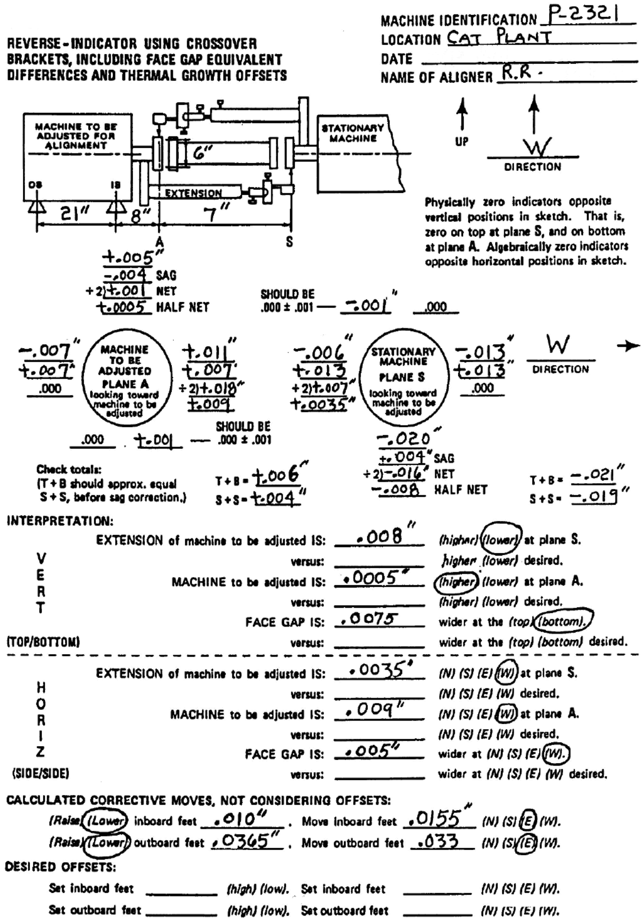

Figure 34. Graph Method Used to Visualize Alignment Process.

The horizontal interpretation is obtained in the same manner, but the diagram in Figure 34 is viewed as a top view rather than a side view. Notice that the direction arrow for "up" is the same as "west."

As with the scalene triangle mentioned above, the distances between the indicators and the hold-down bolts need to be used to complete the triangle. Looking at Figure 34, the distances are 7 inches, 8 inches, and 21 inches, respectively. With this information it is now possible to graphically plot the relationship of the adjustable machine to the stationary machine.

Figure 35 shows a plotting board depiction of the vertical shaft position. The x-axis is measured in inches, and represents the dimensions between the indicators and the hold-down bolts. The y-axis is measured in thousands of inches, and represents the indicator readings. The same scale must be used on the x-axis as the y-axis; in this example scale C is used. The red zero-axis line represents perfect alignment. The example of the vertical alignment shows that the adjustable machine is above the zero line, and will need to be lowered for perfect alignment. Using the graph method, the vertical correction, or shim adjustment, can be taken directly from the graph. To achieve vertical alignment, the IB feet will need to be lowered .010 inch and the OB will need to be lowered .037 inch.

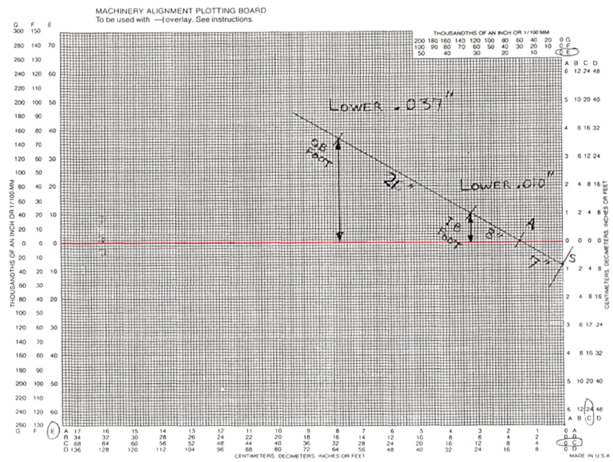

Figure 35. Plotting Board Depiction of Vertical Shaft Position.

These same corrections can be determined by using formulas. Figure 36 shows the formulas used to determine alignment corrections using the reverse dial method. Again, these formulas can be used for either vertical or horizontal corrections; only the perspective of top view or side view changes. One difference with the formulas is the reference point of the "axial" dimensions. The indicator on the fixed, or stationary, machine is used as the zero reference point for axial dimensions.

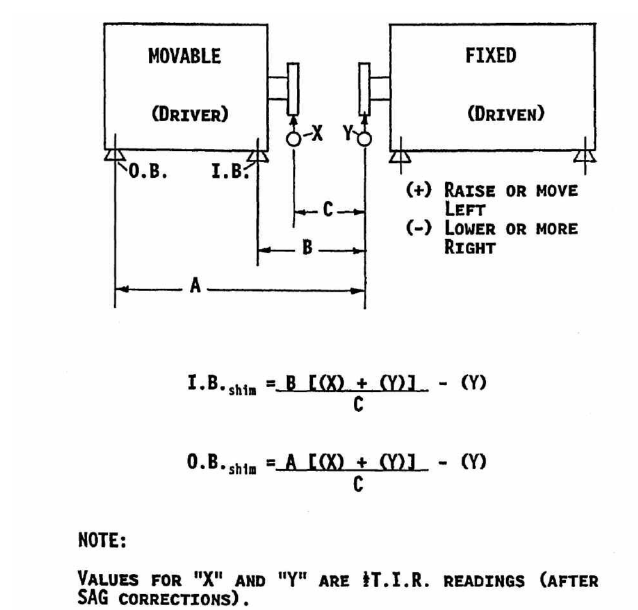

Figure 36. Reverse Indicator Shim Calculation Formulas.

Using the same numbers from the graph example:

- A = 36 inches, B = 15 inches, C = 7 inches
- X = −.0005 inch, Y = −.008 inch

To determine the vertical correction:

- IB = (15 inches [(−.0005 inch) + (−.008 inch)] / 7 inches) − (−.008 inch)
- IB = −.0182 + .008 inch = −.010 inch (lower)
- OB = (36 inches [(−.0005 inch) + (−.008 inch)] / 7 inches) − (−.008 inch)
- OB = −.0437 + .008 = −.036 inch (lower)

There are several computer programs available that combine the graphical display of the graph method with the perceived accuracy of the formulas. As a point of reference, one of these programs was used to obtain vertical corrections for the example problem. The results were:

- IB = −0.0102 inch (lower)
- OB = −0.0357 inch (lower)

Notice how close the solutions are; a maximum difference of 0.0013 inch. The pocket computer with alignment and balancing programs cost $1000 as compared to $55 for the plotting board. Plotting boards never require calibration and the batteries never need charging!

Alignment Tolerances

Once the alignment process is in progress, one must know when to stop. If one continues to make shim changes to obtain perfect alignment, time and money are being wasted. In most cases perfect alignment is not what we want. Journal bearings and gear coupling require a small amount of eccentricity for proper lubrication. There are several different tolerance criteria that can be applied, but a good rule of thumb is .0005 inch per inch of shaft separation. Figure 37 contains a graph for acceptable alignment tolerances based on speed and shaft distances. Please notice that the rule of thumb alignment of 0.0005 inch per inch of shaft separation gives acceptable alignment up to 14,000 rpm. Most of the rotating equipment aligned is below 5000 rpm.

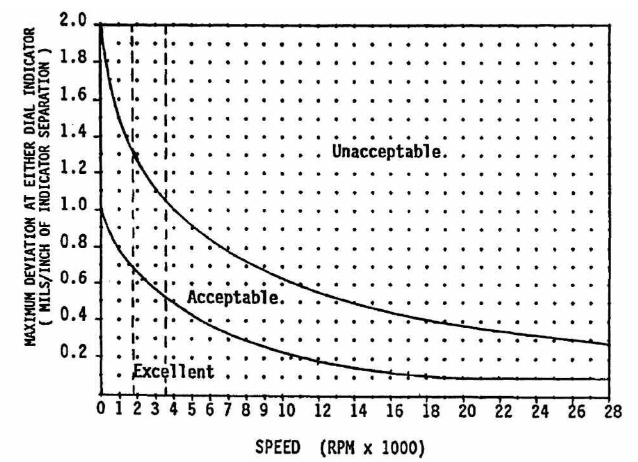

Figure 37. Guideline for Alignment Tolerances.

PIPE ALIGNMENT

Even if the pump has the perfect hydraulic fit, was correctly installed, and has excellent shaft alignment, it can still be doomed to a life of failure because of piping alignment.

Suction and discharge piping can induce high stress and nozzle loads to the pump casing if not properly installed. Mechanical seals and bearings both have stationary components that are directly affected by these loads and stresses. Pipe stress analysis is a science unto itself, and is highly recommended, especially in applications with large temperature changes. However, there are many pumps in service that endure severe pipe strain due to simple neglect of basic principles. While most pump designs allow for some nozzle loads, *the pump is not a pipe support*. Keep the pipe off the pump. At ambient temperatures, when maintenance work or new installation is being performed, the piping should be concentric, parallel, and have proper axial spacing in relation to the pump nozzles.

Figure 38 shows the concept of concentricity. The pipe flanges are to be fit, such that the bolts can be inserted into the pump nozzle holes with finger pressure only. No spud wrenches or "come-a-longs" are to be used to align flange holes.

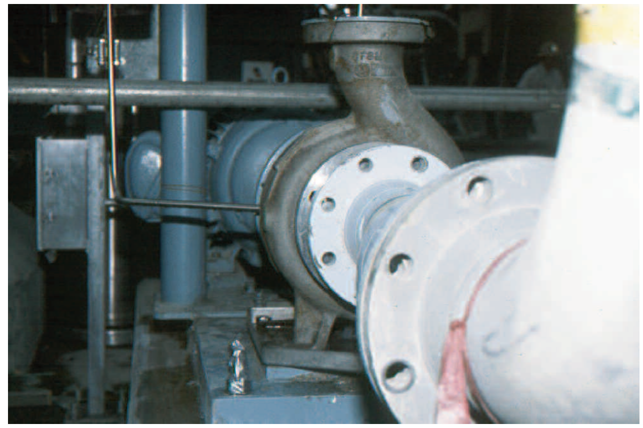

Figure 38. Concept of Concentricity.

Parallelism of the flange gasket surface should be limited to .002 inch per inch of nominal pipe size, with a maximum of .030 inch. Figure 39 illustrates the concept of parallelism. Pipe sizes under 3 inches are flexible enough to allow 0.008 inch maximum out-of-parallelisms on the gasket mounting surfaces. Vertical inline pump flanges under 3 inches can have a maximum out-of-parallelism of 0.020 inch without causing shaft alignment problems.

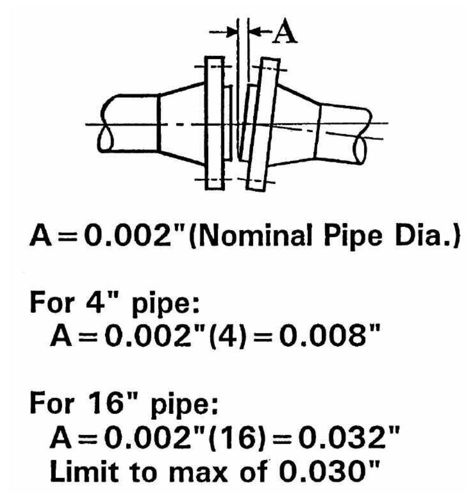

Figure 39. Concept of Parallelism.

Figure 40 shows a poor example of axial spacing. The gap between the pipe flange and the pump nozzle should be no more than the gasket thickness, plus .062 inch.

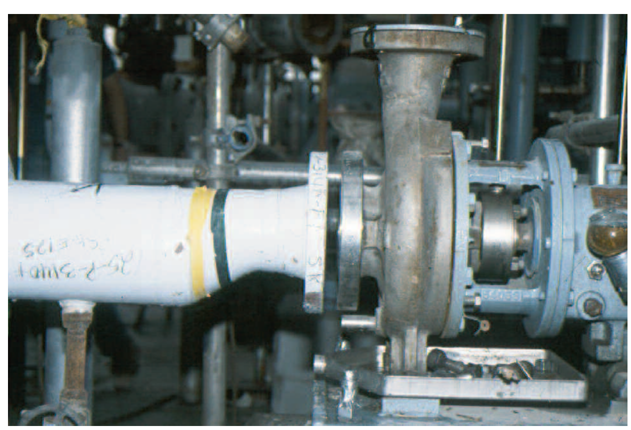

Figure 40. Poor Example of Axial Spacing.

In addition, the following are steps that can be taken to minimize the effects of pipe strain on the pump:

- The last 20 feet of piping to the pump suction and discharge flanges should be installed after the pump is grouted and aligned. Both suction and discharge piping flanges, with gaskets, should be four-bolted to the pump flanges and the piping field-fitted back to the pipe headers.
- Dial indicators should be installed from the driver to the pump to monitor movement when the piping is bolted up. The maximum acceptable movement is 0.002 inch.
- Modify existing flange tightening procedures to the following. Tighten the flange bolts to 1/3 the design torque using a crisscross pattern. This reduces the possibility of cocking the flanges and causing shaft movement. Make a second pass on the bolts tightening them to b their design torque in a crisscross pattern. The bolts are then tightened to the designed torque level in a crisscross pattern. A final bolt torque is made in a circular pattern.

CONCLUSION

The goal of achieving top tier reliability of 60 months MTBR is very attainable, but it requires much more than just utilizing the latest pump design. Paying attention to the details is the key to success. Hydraulic fit, baseplate installation, shaft alignment, and piping alignment all play a vital role in the total effort of achieving top tier performance.

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