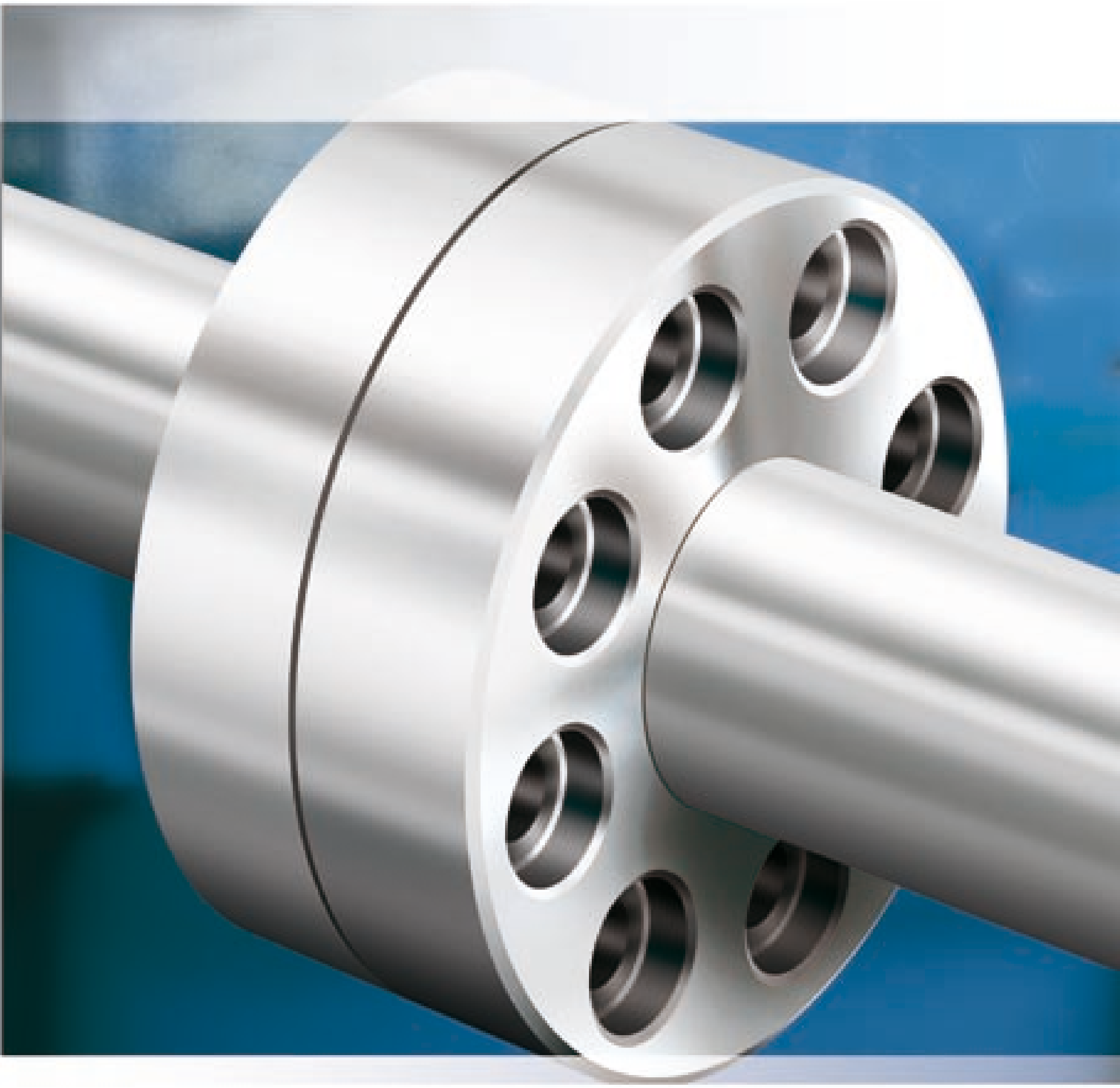
Shaft Alignment

A training handbook



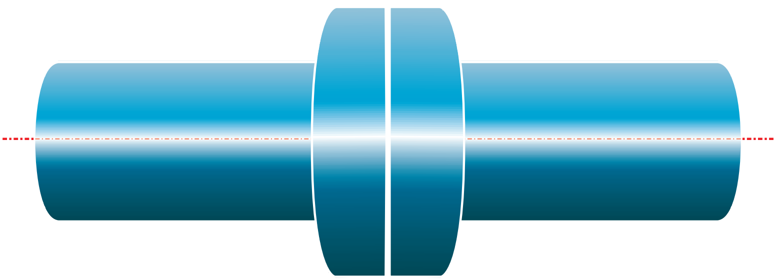
What is meant by shaft alignment?

Shaft alignment is the process whereby two or more machines (typically a motor and pump) are positioned such that at the point of power transfer from one shaft to another, the axes of rotation of both shafts should be colinear when the machine is running under normal conditions. Colinear means two lines that are positioned as if they were one line. Colinear as used in alignment means two or more centerlines of rotation with no offset or angularity between them.
As with all standard definitions there are exceptions. Some coupling types, for example gear couplings or cardan shafts, require a defined misalignment to ensure correct lubrication when operating.

In the above definition, "***at the point of power transfer***" refers to the fact that shafts have some form of catenary due to their own weight, and are strictly speaking not straight. Therefore the location where the alignment of the two shafts can be compared is only at the point of power transfer from one shaft to the next.

The term "***axes of rotation***" should not lead to confusing "shaft alignment" with "coupling alignment". The coupling surfaces should not be used to measure alignment condition since they do not represent the rotation axis of the shafts. To save manufacturing costs coupling surfaces are often only rough machined or in some cases not machined at all.

The accuracy of the fit of the coupling on the shaft is unknown
Rotating only one shaft and using dial gauges to measure the opposing coupling surface does not determine the axis of rotation of both shafts.



Rotating axes must be colinear during operation

"***Under normal operating conditions***" is an acknowledgement that the alignment condition can change when the machine is running. This can be for a number of reasons including thermal growth, piping strain, machine torque, foundation movement and bearing play. Since shaft alignment is usually measured with the machines cold, the alignment condition as measured is not necessarily the zero alignment condition of the machines.

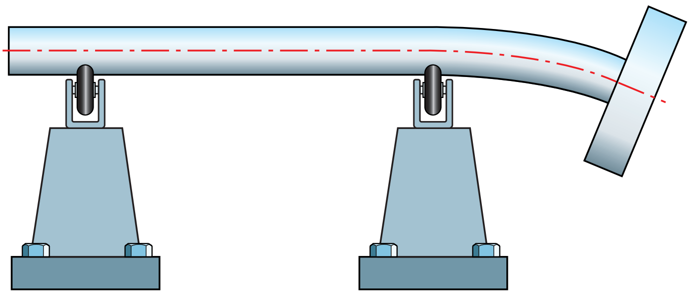
Alignment condition should be measured whilst turning the shafts in the normal direction of rotation. Most rotating machinery such as pumps, fans and motors, have arrows on the end casing showing direction of rotation.

Machinery catenary

The amount of shaft deflection in a machine depends upon several factors such as the stiffness of the shafts, the amount of weight between overhanging supports, the bearing design and the distance between the supports.

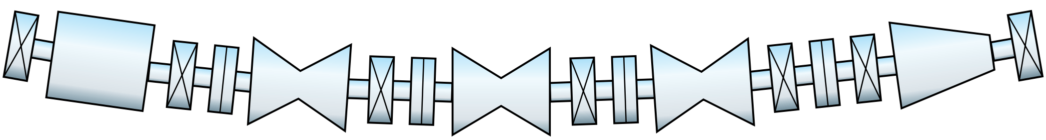
For the vast majority of close coupled rotating machines this catenary bow is negligible, and therefore for practical purposes can be ignored.

On long drive machine trains, (e.g. turbine generators in power generation plants or machines with long spacer shafts such as cooling tower fans or gas turbines, the catenary curve must be taken into consideration. In a steam turbine for example, the shafts are usually aligned to each other better than 1/100 mm, but the midpoint of the shaft in the centre could be as much as 30 mm lower than the shafts at both ends.



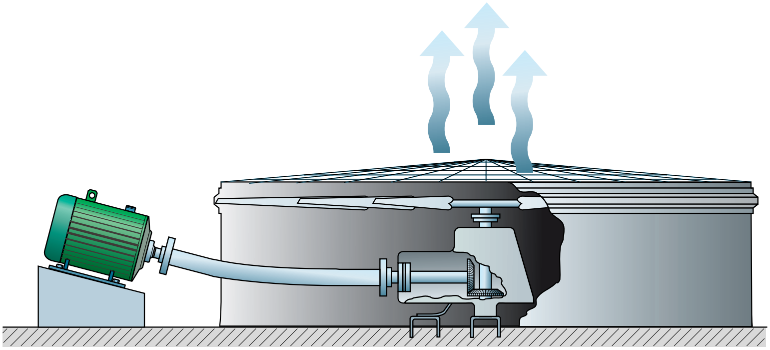
The natural bending of shafts under their own weight

Machine catenary

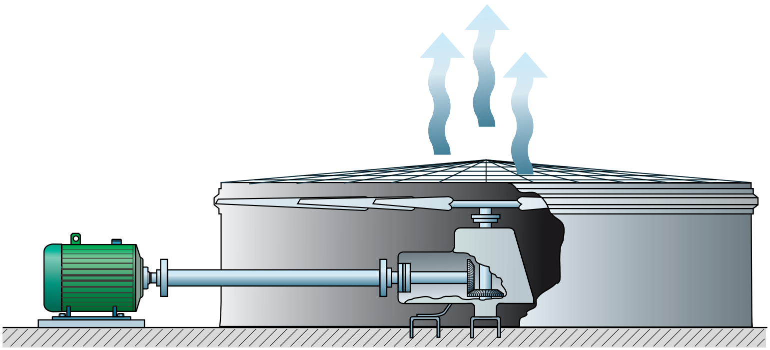


Operation above critical speed?

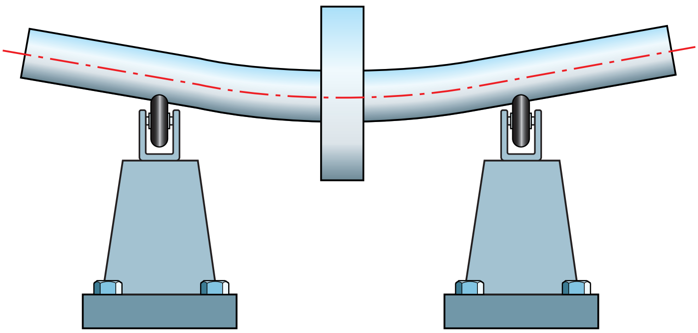
When a very long, flexible shaft begins to rotate, the bow of the shaft tries to straighten out, but will never become a perfectly straight line. It is important to understand that the axis of rotation of a shaft could very possibly run on a curved axis of rotation. In situations where two or more pieces of machinery are coupled together with one or more of the shafts rotating around a catenary shaped axis of rotation, it is important to align the shafts so that they maintain the curved centre-line of rotation.



Drive shaft operation below critical speed – align machine couplings to spacer couplings



Drive shaft operation above critical speed – align machine couplings to one another ignoring spacer

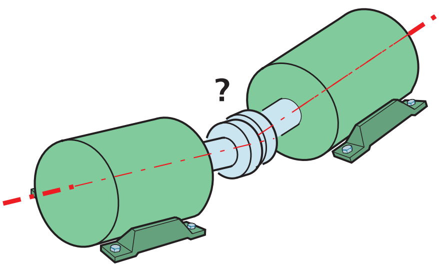


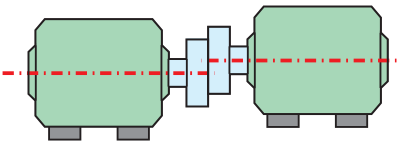
The natural bending of shafts under their own weight

Expressing alignment

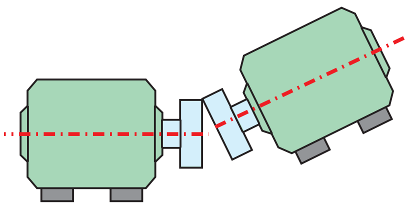
Alignment parameters

Since shaft alignment needs to be measured and subsequently corrected, a method of quantifying and describing alignment condition is necessary.
Traditionally alignment has been described in terms of dial indicator readings at the coupling face or position values at the machine feet. The measured values from both of these methods are dependent upon the dimensions of the machines. Since there are different methods for mounting dial indicators (e.g. reverse indicator, rim and face, double rim), the comparison of measurements and the application of tolerances can be problematic. Additionally the fact that rim indicator readings show twice the true offset and sign reversals must be observed depending on whether the indicator measures an internal or external, left or right coupling face or rim.
A more modern and easily understandable approach is to describe machine alignment condition in terms of angularity and offset in the horizontal (plan view) and vertical (side view). Using this method four values can then be used to express alignment condition.

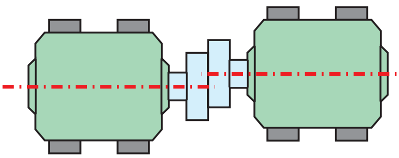




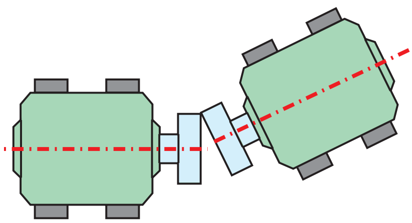
Vertical offset



Vertical angularity



Horizontal offset



Horizontal angularity

Angularity, gap and offset

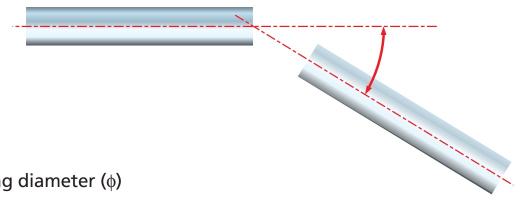
Angularity describes the angle between two rotating axes. It can be expressed directly as an angle in degrees or mrads, or in terms of a slope in mm/m or thous/inch. This latter method is useful since the angularity multiplied by the coupling diameter gives an equivalent gap difference at the coupling rim. And therefore, the angle is more popularly expressed in terms of ***gap*** per diameter. The gap itself is not meaningful, it must be divided by the diameter to have meaning. The diameter is correctly referred to as a "working diameter", but is often called a coupling diameter. The working diameter can be any convenient value. It is the relationship between gap and diameter that is important.

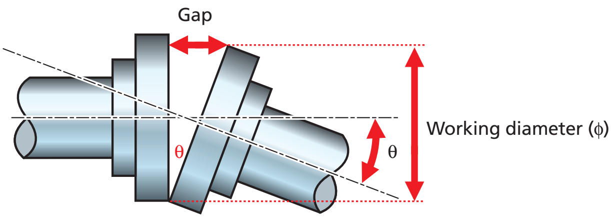
A 6 inch (152.4 mm) coupling open at the top by 0.005 inches (0.127mm) gives an angle between shafts axes of 0.83 mrads.

- For a 10 inch working diameter this corresponds to a gap of 0.0083 inches.
- For a 100 mm working diameter this corresponds to a gap of 0.083 mm.

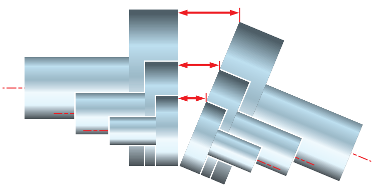
> - 1 mrad = 1 thousandths of an inch per inch
> - 1 mrad = 1 mm per meter

Relationship of angle (θ), gap and working diameter (ϕ)

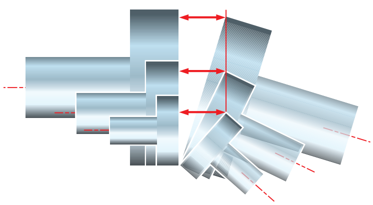




same angle - different gap

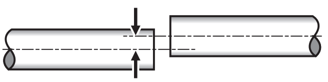


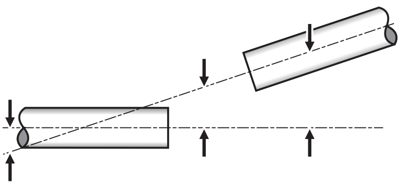
same gap - different angle

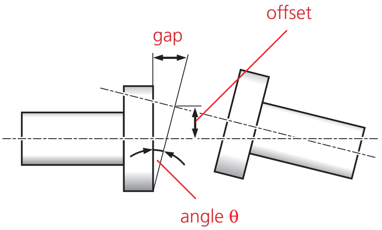


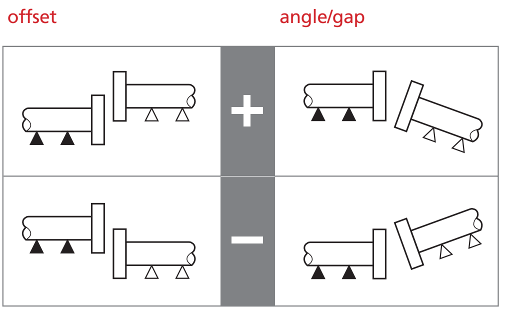
Offset describes the distance between rotation axes at a given point. Offset is sometimes incorrectly referred to as parallel offset or rim misalignment. Shaft rotation axes are however rarely parallel and the coupling or shaft rim has an unknown relationship to the shaft rotation axes.
For the same alignment condition, the offset value varies depending upon the location where the distance between two shaft rotation axes is measured. In the absence of any other instruction, offset is measured in millimetres or thousandths of an inch at the coupling centre. (This definition refers to short flexible couplings. For spacer couplings, offset should be measured at the power transmission planes of the coupling).

Short Flexible couplings
For ease of understanding, short flexible couplings are defined when ***the axial length of the flexible element or the axial length between the flexible element is equal or smaller than the coupling diameter***.
Machines with short flexible couplings running at medium to high speed require very accurate alignment to avoid undue loading of the shafts, bearings and seals.









Since the alignment condition is virtually always a combination of angularity and offset, and the machine has to be corrected in both vertical and horizontal planes, 4 values are required to fully describe the alignment condition. These are:

- Vertical angularity (or gap per diameter)
- Vertical offset
- Horizontal angularity (or gap per diameter)
- Horizontal offset

Unless otherwise specified the offset refers to the distance between shaft rotation axes at the coupling centre.

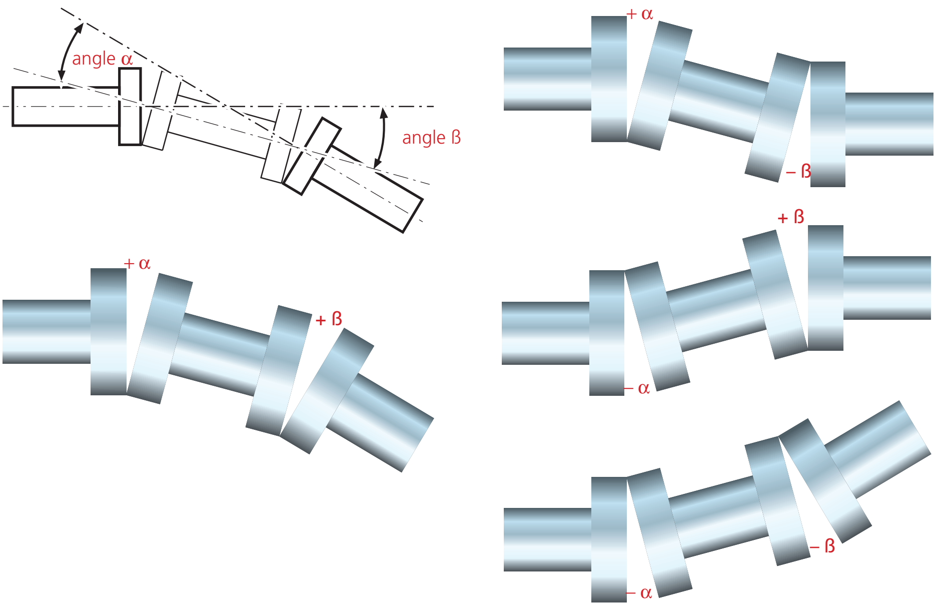
Spacer Shafts.

Spacer shafts are usually installed when significant alignment changes are anticipated during operation of the machine, for example due to thermal growth. Through the length of the spacer shaft, the angular change at the spacer shaft end remains small even when larger machine positional changes occur. The alignment precision for machines fitted with spacer shafts that have flexible elements at each end is not as critical as for machines that have short flexible couplings installed.

Four values are required to fully describe the alignment condition.

- Vertical angle α
- Vertical angle ß
- Horizontal angle α
- Horizontal angle ß

Angles are measured between the spacer shaft rotation axis and the respective machine rotation axes.



Offset B - offset A

As an alternative to the two angles α and ß the alignment can be specified in terms of offsets.

- Vertical offset B
- Vertical offset A
- Horizontal offset B
- horizontal offset A

The offsets are measured between the machine shaft rotation axes at the location of the spacer shafts ends. This is similar to reverse indicator alignment.

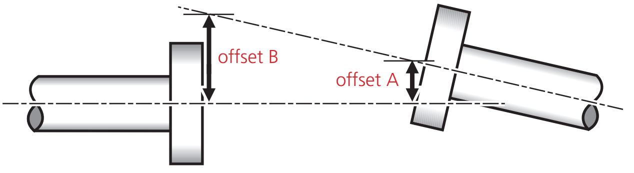
Alignment tolerances for flexible couplings.

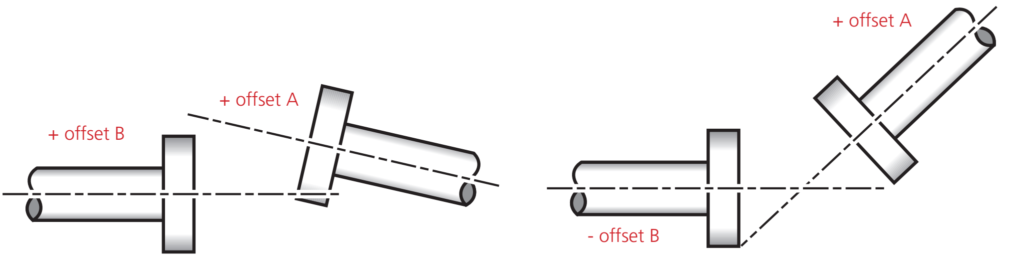
The suggested tolerances appearing in the appendix on page 99 are general values based upon over 20 years of shaft alignment experience at PRUFTECHNIK and should not be exceeded. They should be used only if no other tolerances are prescribed by existing in-house standards or by the machine manufacturer.

Consider all values to be the maximum allowable deviation from the alignment target, be it zero or some desired value to compensate for thermal growth. In most cases a quick glance at the table will tell whether coupling misalignment is allowable or not.

As an example, a machine with a short flexible coupling running at 1500 rpm. has coupling offsets of -0.04 mm vertically and +0.02 mm horizontally, both of these values fall within the “excellent” limit of 0.06 mm.

Angularity is usually measured in terms of gap difference. For a given amount of angularity, the larger the diameter the wider the gap at the coupling rim. The given tolerance lists values for coupling diameters of 100 mm or 10 inches. For other coupling diameters multiply the value from the table by the appropriate factor. For

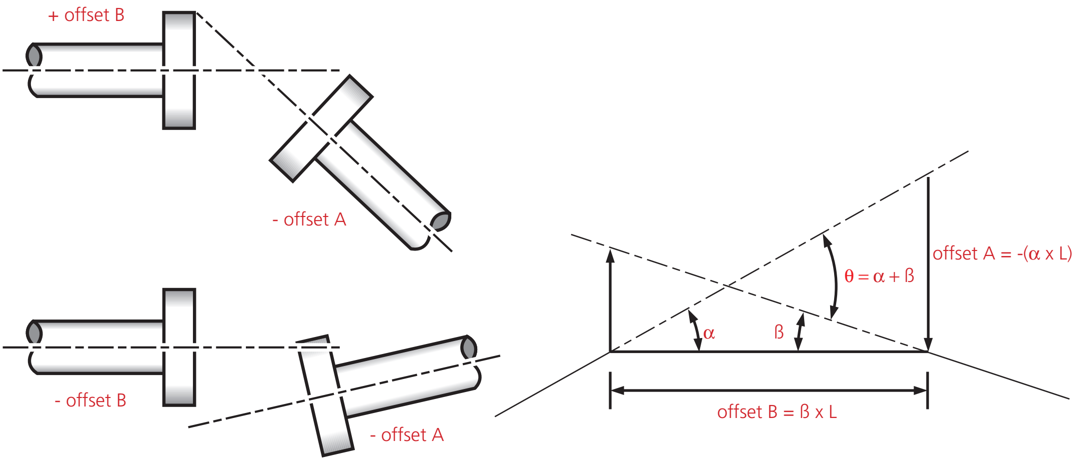




example, the maximum allowable gap for a machine running at 1500 rpm. with a coupling diameter of 75 mm is calculated as follows: At this diameter the maximum allowable gap would be; 0.07 mm x 75/100 = 0.0525 mm.
For spacer shafts the table gives the maximum allowable offset for either 100 mm or 1 inch of spacer shaft length. For example, a machine running at 6000 rpm with 300 mm of spacer shaft length would allow a maximum offset of 0.03 mm x 300/100 = 0.09 mm at either coupling at the ends of the spacer shaft.
Rigid couplings have no tolerance for misalignment, they should be aligned as accurately as possible.

Note

For industrial equipment the amount of misalignment that can be tolerated is a function of many variables including rpm., power rating, coupling type, spacer length, design of coupled equipment and expectations of the user with respect to service life. Since it is not practical to consider all these variables in a reasonably useful alignment specification, some simplification of tolerances is necessary.
Tolerances based on rpm. and coupling spacer length were first published in the 1970s. Many of the tolerances were based primarily on experience with lubricated gear type couplings. Experience has shown however that these tolerances are equally applicable to the vast majority of non lubricated coupling systems that employ flexible elements in their design.
In the previous table "acceptable" limits are calculated from the sliding velocity of lubricated steel on steel, using a value of 12 mm/sec for allowable sliding velocity. Since these values also coincide with those derived from elastomer shear rates they can be applied to short flexible couplings with flexible elements.
"Excellent" values are based on observation made on a wide variety of machines to determine critical misalignment for vibration. Compliance with these tolerances does not however guarantee vibration free operation



Coupling strain and shaft deflection

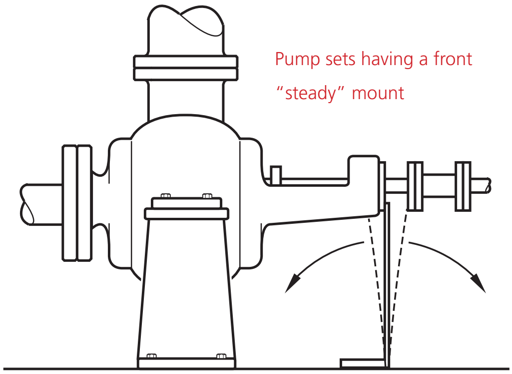
New readings do not agree with moves just made

When performing an alignment whether using dial indicators or laser optical systems, sometimes the readings following an alignment adjustment does not agree with the corrections made. One possibility is that coupling strain is bending the shaft, the machine mounts or the foundation. This has frequently been noticed particularly on pump sets which have a front "steady" mount.

In such an application, the flexible coupling element is radially quite rigid and can influence the alignment measurement. In situations like this, we advise splitting the coupling element to free the measured alignment from such external forces.

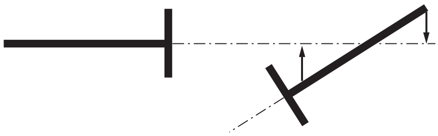
If not accomodated the net effect of influences such as noted above is that the new alignment is not only wrong but quite often has been made in the opposite direction to the required alignment correction.

In extreme cases coupling strain imposed by the newly aligned machines can bend shafts during operation. In most cases this bending will be minimal but sufficient to affect the measured axes of shaft rotation.

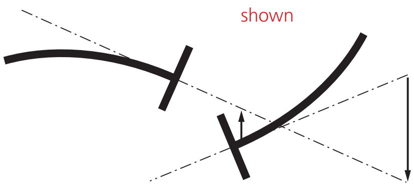


Pump sets having a front "steady" mount

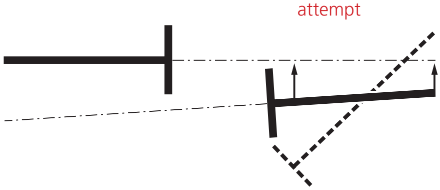
This is the alignment condition with shafts uncoupled



This is the measured alignment with the shafts coupled. Projected centrelines of rotation are shown



The moves are made as measured. There is less strain on the coupling now and the shafts will be properly aligned at the next attempt



Symptoms of misalignment

It is not always easy to detect misalignment on machinery that is running. The radial forces that are transmitted from shaft to shaft are difficult to measure externally. Using vibration analysis or infrared thermography it is possible to identify primary symptoms of misalignment such as high vibration readings in radial and axial directions or abnormal temperature gradients in machine casings, but without such instrumentation it is also possible to identify secondary machine problems which can indicate inaccurate shaft alignment.

- Loose or broken foundation bolts.
- Loose shim packs or dowel pins.
- Excessive oil leakage at bearing seals
- Loose or broken coupling bolts.
- Some flexible coupling designs run hot when misaligned. If the coupling has elastomeric elements look for rubber powder inside the coupling shroud.
- Similar pieces of equipment are vibrating less or have longer operating life.
- Unusually high rate of coupling failures or wear.
- Excessive amount of grease or oil inside coupling guards.
- Shafts are breaking or cracking at or close to the inboard bearings or coupling hubs.

Good shaft alignment practice should be a key strategy in the maintenance of rotating machines. A machine properly aligned will be a reliable asset to the plant, it will be there when it is needed and will require less scheduled (and unscheduled) maintenance.

Preparation is important

The first preparatory step toward successful alignment is to ensure that the machine to be aligned may be moved as required – this includes vertical mobility upwards (using proper lifting equipment, of course) and downwards, should the machine require lowering, as is frequently the case. This can be achieved by inserting 2 to 4 mm (0.08” - 0.16”) of shims beneath the feet of both machines on initial installation (we recommend shimming both machines initially so that changes in the foundation condition may later be compensated, if need be).

Horizontal positioning of machines is best performed using jack bolts or a simple ‘machine puller’ tool or hydraulic equipment, all of which allow fine control of movement in a slow, gentle and continuous manner. Methods such as hammers not only make exact positioning more difficult and can damage machines (by causing chatter marks on bearings), but the vibration could displace the alignment system during the Move function and therefore lead to less accurate monitoring of correction positioning.

Machine installation guidelines

The installation of machinery such as a pump, gearbox or compressor etc require some general rules to be followed.

- The driven unit is normally installed first, and the prime mover or motor is then aligned to the shaft of the driven unit.
- If the driven unit is driven through a gearbox, then the gearbox should be aligned to the driven unit and the driver aligned to the gear box.
- Basic checks should be carried out to determine the accuracy of the machine couplings, i.e. check for “run-out” (concentricity and squareness to the shaft centrelines) of coupling halves using a dial indicator, if possible (out of “true” coupling halves can cause out of balance problems!).
- Preparation of the machinery baseplate and machine mounting surfaces, feet, pedestals etc. is of paramount importance! Successful alignment cannot be easily achieved otherwise!
- Clean, dress up and file any burrs from mounting faces and securing bolt holes etc.
- Have quality shims available to align precisely and effectively.
- Before assembling the shaft alignment system/instrumentation to the machines, take a few minutes to look at the coupling/shaft alignment. Remember, your eyes are your first measuring system!
- Check that the pump/motor etc. is sitting square to the base plate. (Soft foot check) and correct as required – see following pages.
- Keep shims to a minimum i.e. no more than 3 shims maximum if possible under machinery feet/mounts.
- Correct alignment as required to ensure that, when the machinery is running, the machinery shafts are centred in their bearings and are aligned to manufacturers tolerances.
- Always check manufacturers alignment figures prior to commencing work! - temperature growth may require specific “cold” alignment offsets.
- Ensure that any pipework attached to machines is correctly supported but free to move with thermal expansion.