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"Alignment of Movable Bridge Components"

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Machinery Alignment Considerations
In Design and Construction of Movable Bridges
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The purpose of this paper is to provide the engineer, owner and inspector with a guide to understanding the alignment of machinery components for movable bridges. We will not discuss the larger issue of the movable bridge as a machine, where the structural components are controlled through the mechanical and electrical systems. Some discussion in this paper will include their impact on, and relationship with the machinery system. The goal of improving understanding will be achieved by asking and answering a series of questions. To begin the discussion we will explore what alignment is and why it is important.

What is alignment?

When two machinery components are joined together for the purpose of transmitting power from one to the other, then issues of alignment come into play. While no machinery system is 100% efficient, the efficiency of the transmission of power is in direct correlation to the quality of the alignment between components. Poor alignment (misalignment) results in the following:

1) Financial waste, due to excessive power consumption
2) Premature bearing, seal, gear or coupling failure
3) Shaft failure due to cyclic fatigue
4) Excessive vibration, temperature and component loading

Alignment between components is usually considered as the relationship between ideal centers of shafts, the tooth to tooth contact in gear sets, the axial loading in bearings, and the interaction between components. While in our offices we design machinery systems to be in perfect alignment, in the real world this is a mere illusion. All machinery systems are misaligned to a degree. It is the contention of this author that it is the engineers responsibility to understand these realities and make account in our designs. In shafts and couplings alignment is generally defined in two ways, angular and offset (see figure 1).

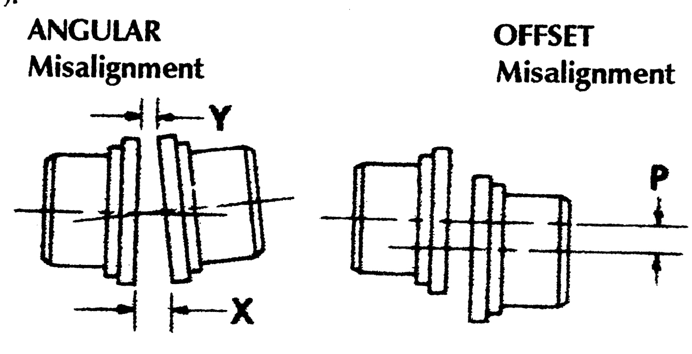
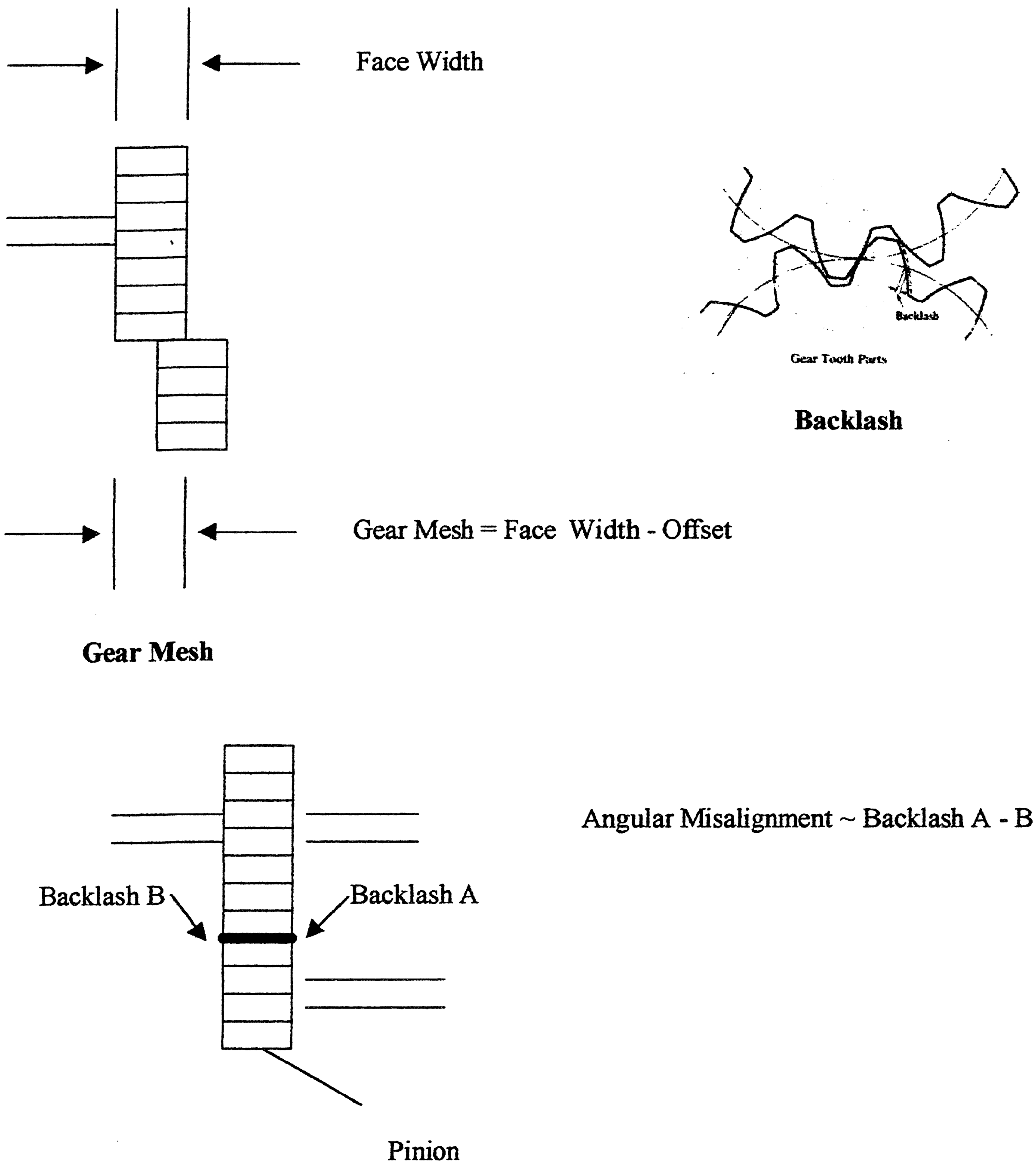


Figure 1

In gears, alignment is defined by gear mesh, backlash and angular misalignment or tooth contact (see figure 2).

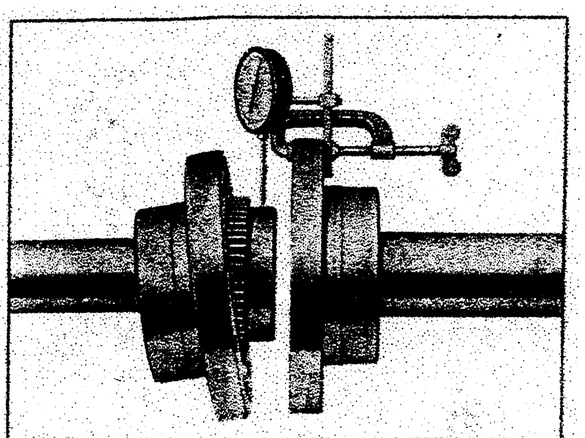


Angular Misalignment

Figure 2

How do you measure alignment between components?

The measurement of alignment between shafts is measured at the shaft end or interfaces (generally at couplings). The quality of alignment can be measured by the geometric relationship of coupling halves to be mated together. The specific techniques to perform these measurements vary. In this paper we will discuss the conventional techniques easily mastered by the engineer, owner or inspector. The first step in determining alignment between shafts is to measure offset alignment. For bridge machinery components, the measurements are made with a dial indicator and a magnetic base. Please note that if the contractor or inspector have not used a dial indicator or similar precision instruments during alignment, the alignment is probably not correct. The dial indicator is positioned on the shaft, which can most readily be slowly rotated. Note it is imperative that one shaft be rotated relative to the other to accurately measure alignment. Once the indicator is located on the rotating shaft, the indicator point is located on the non-rotating shaft or coupling. It is also important that the shaft or coupling surface be smooth and clean. Rotate the shaft with the indicator one revolution and note the angular position where the smallest reading is obtained. Set the indicator to a zero reading at this position. Rotate the shaft/indicator through one more revolution and record the angular position and value of the largest reading obtained. These shafts are offset misaligned by one half of the indicator reading (see figure 3).



1. Find angular position where Indicator has smallest reading, set to zero.
2. Rotate through one revolution and record highest reading
3. Offset misalignment is one half reading

Figure 3

Angular misalignment can only be checked once any offset misalignment has been corrected. Please note that a serious complicating factor in bridge machinery alignment is the LC6 fit requirements for fasteners connecting machinery components. The use of undersize temporary bolts is highly recommended until the proper alignment has been achieved and accepted. Only then should component mounting holes be reamed and final bolts installed. Extreme care must be taken in this effort to assure that the alignment is not altered particularly during the torquing of the fasteners. To measure angular misalignment either a dial indicator or feeler gauges are used. Generally feeler gauges are the preferred tool since the gaps to be measured are small (not allowing the probe of the indicator to be properly positioned). Measure the gap between the shaft or coupling end in four (90 degree apart) locations and record the readings (figure 4).

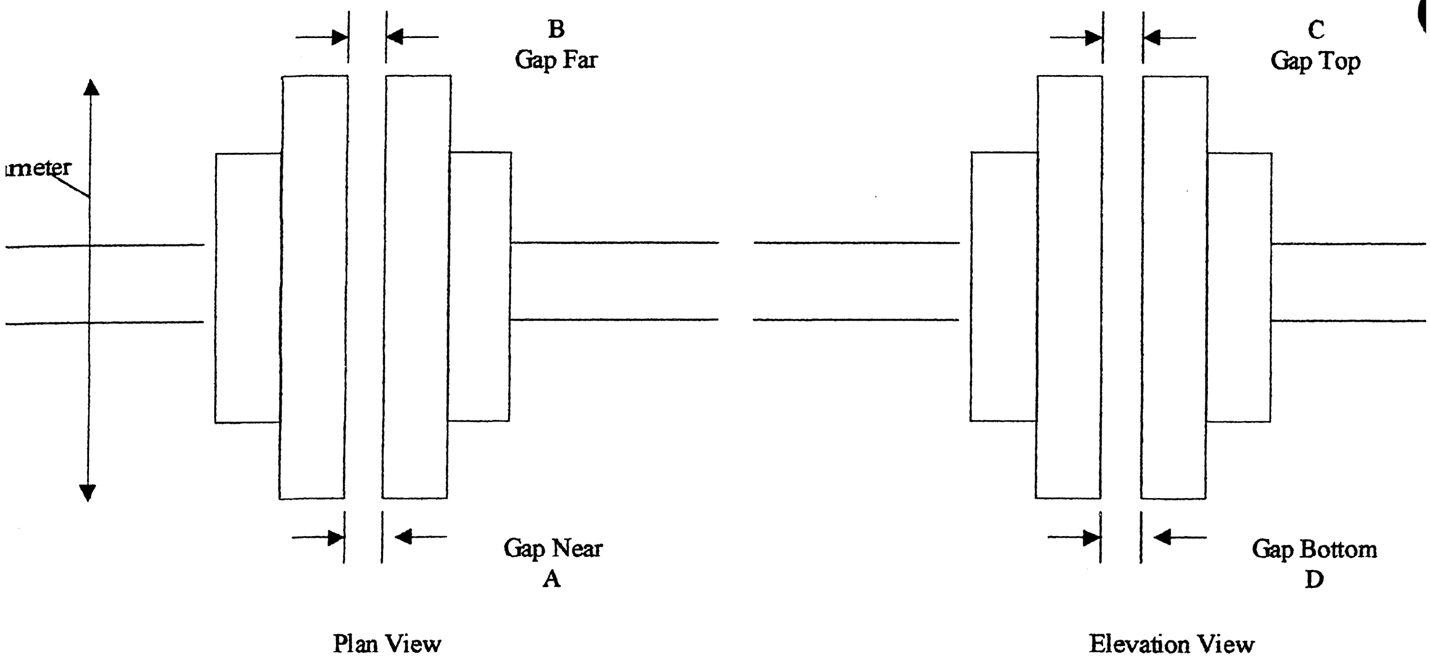
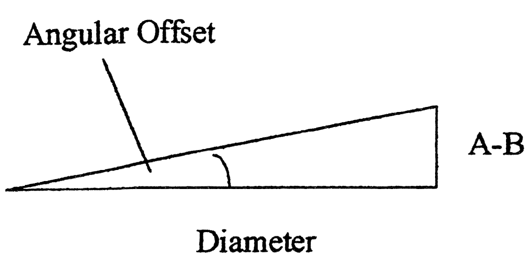


Figure 4

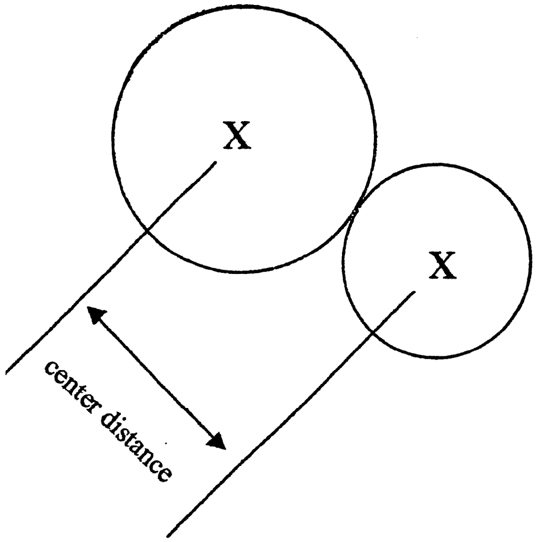
Take the readings by axis (see figure 4) and determine the differences, side A to B and side C to D. The angular offset will be in two axis and can be calculated using the following formula:

A-B = Plan View Angular Offset

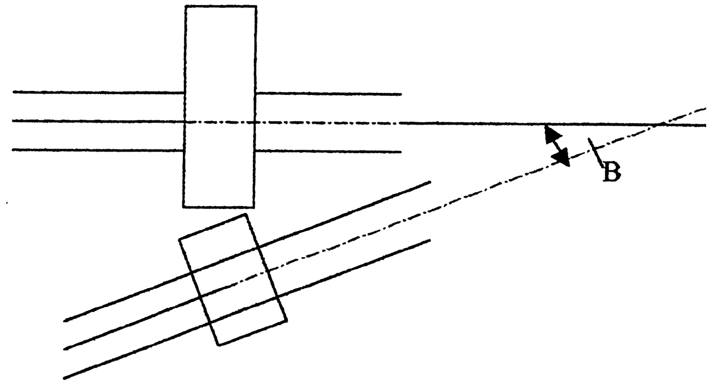


$$\text{Tan} = \frac{\text{A-B}}{\text{Diameter}}$$

Using geometry, the amount of adjustment in either plane A-B or C-D can be calculated. The measurement of alignment for gears is somewhat more complicated than for shafts. Three basic measurements must be made to determine if gears sets are properly aligned. The correct dimensional relationship for gears is determined by the shaft to shaft spacing (center distance) and the angular relationship of the two shafts (see figure 5).



Center Distance



Angular Relationship

Figure 5

The first measurement to be taken is the axial alignment between the two gears. In general, gear sets are designed such that one of the gears is slightly wider than to other, allowing for 100% mesh with the narrowest gear (see figure 2). Note that if the structure tends to have significant thermal expansion impacting gear geometry, the designer should consider this factor in the gear design. To measure the values simply measure the amount the narrowest gear is not engaged with the other gear. The next measurement to be taken for gear sets is the tooth contact. This measurement is related to the shaft to shaft angular misalignment. The measurement of tooth contact can be combined with the measurement of backlash, the other important measurement. A simple way to perform this measurement (figure 2) is to rotate one gear relative to the other until the teeth come into contact. Using a feeler gauge determine the gap between the mating teeth on each side of the gear set. These readings should be identical (to an accuracy of 0.001 inches). If they are not then the gears are misaligned. The difference in the readings over the width of the gear face can be used to calculate the amount of angular misalignment between shafts. This misalignment must be corrected before the backlash can be measured. Another technique used to measure tooth contact is to apply a contact material (Prussian blue) to the faces of one of the gears in the set and rotate the set of gears through a complete revolution. The contact material will be transferred to the mating gear; the amount of surface contact will be quite apparent by the amount of material transferred. This technique is often used to inspect gear sets where wear has occurred and as a final check for new installations.

Backlash is measured in the same manner as mesh was described above using feeler gauges. Rotate one of the gears until the teeth come into contact. Measure the gap at the backside of the teeth in contact. The measured value is the backlash. The engineer establishes the value of backlash at the time of design. A special note for inspectors. It is common practice for engineers to have the pitch diameter cut on the sides of the gear. This practice can lead to improper gear installation if these "pitch lines" are followed exclusively. The "Pitch Lines" are cut to an accuracy of hundreds of thousands on inches where as the actual alignment requires accuracy of just a few thousands of an inch.

What is considered acceptable misalignment?

As mentioned previously, perfect shaft alignment is difficult if not impossible to achieve. While the goal should always be perfection, reality dictates that acceptable values should be specified. The following discussion will be in context of shafts and gears as previously discussed. Shafts are the simplest case, while gears must meet the requirements of shafts; they must also meet their own special requirements. Shafts are generally connected through couplings. Various designs of coupling allow for greater amounts of misalignment. As an example:

Falk 1040 T10
- 12 mils (0.012 inches) of offset misalignment
- 1/4 degrees of axial misalignment

Falk 1040 G51 (Single Engagement)
- 0 mils (0.000 inches) of offset misalignment
- 1/2 degrees of axial misalignment

It would seem that if two shafts were aligned within the coupling tolerances all is well and no future problems would occur. In Movable Bridges, significant flexural and thermally induced motion occurs within the structure. These motions significantly impact machinery alignment characteristics. If two shafts are aligned to the coupling manufacturer's allowable alignment specifications, it is safe to assume that a significant portion of the couplings operating life will be beyond the manufacturer's recommendations. The author recommends that during installation, shafts should be aligned to have misalignment about 1/5 the manufacturer's recommendations. For gears, all installation parameters must be set to the engineer specifications. The typical installation parameters for gears are expressed as backlash, gear mesh, and tooth contact. The backlash is generally expressed as a range of values (example 0.022 to 0.025 inches). Gear mesh and tooth contact are expressed as a percentage (example 90%). It is generally the gear alignment that will dictate shaft alignment requirements.

How do I set Alignment goals for the machinery system?

It is important for designers and field engineer of Movable Bridges to calculate installation tolerances as part of the design. A typical bridge machinery installation is described by figure 7 below.

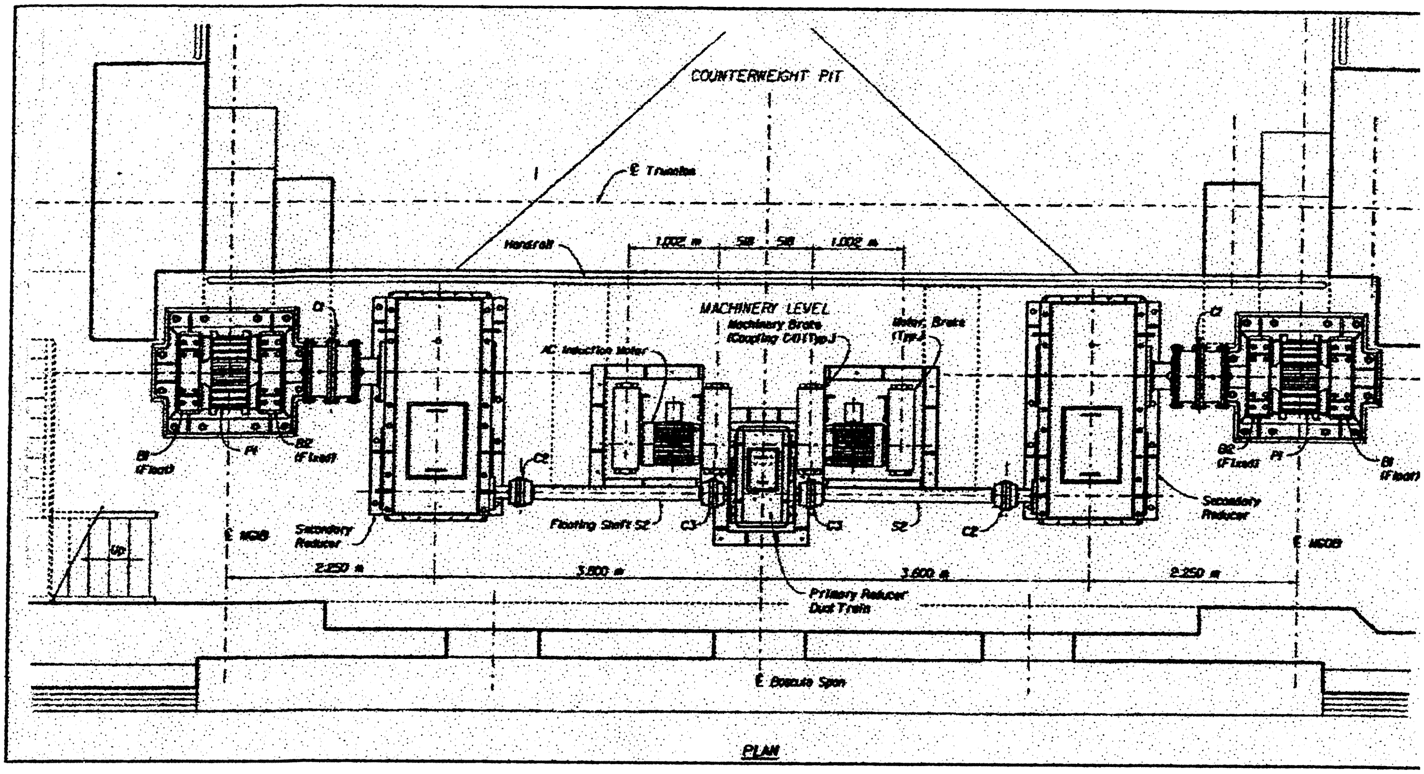


Figure 7

In the above configuration the pinion shafts would be installed first. The gears would be aligned per the engineer's requirements. The ends of the pinion shafts will represent two fixed points that the remaining machinery must be aligned to. The designer should assume that these points are located in space within the structural designer's tolerances and construction realities. The machinery designer must design the machinery/ shafting to meet the realities of these potentially unknown locations. Referring to figure 7, it is possible based upon shaft lengths and coupling selection to determine the allowable misalignment between the pinion shafts and the central reducer. Figure 8 describes the calculation used:

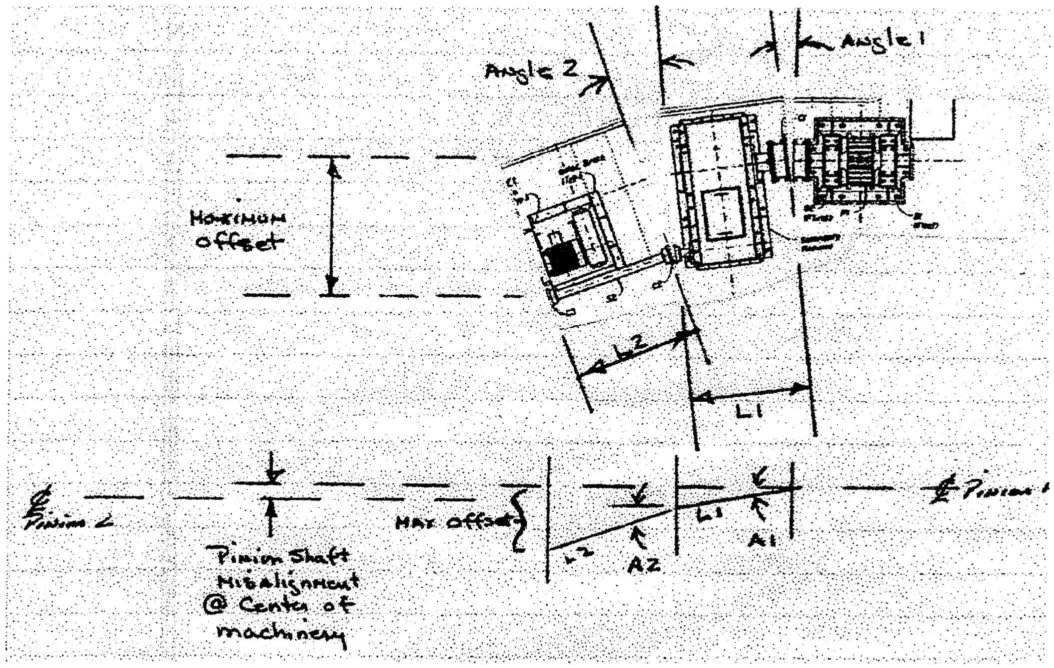


Figure 8

This calculation describes the maximum allowable misalignment for a proposed design not accounting for thermal, vibration or other effects. The machinery designer must work with the structural engineers to set appropriate construction tolerances for critical components. One practical check to ensure that proper machinery alignment is even possible is to specify the measurement of pinion shaft to pinion shaft axial alignment before rack and pinion shaft installation is completed. These checks are easily made using laser alignment equipment at the appropriate construction stage.

What are the symptoms of improper alignment?

Misalignment is easily identified in extreme situations but is quite difficult to spot in marginal situations. In extreme cases the symptoms are:

1) Excessive machinery noise
2) Binding of shafts
3) Couplings are hot after operation
4) Coupling failures
5) Excessive oil or grease leakage from bearings
6) Vibration of machinery components (particularly shafts)
7) Loose mounting bolts
8) Extreme or rapid wear of gears (plastic deformation of teeth)
9) Presence of rubber powder in shrouds of elastomeric bearings
10) Significant rises in bearing case temperatures during operation.

When machinery systems are operating properly, they are virtually silent (Hydraulic power units excepted). A noisy bridge generally has machinery alignment problems and is cause to begin a more thorough investigation. The design standards for Movable Bridge machinery are so robust that vibration should be completely absent from all machinery components during operation (new installation). If vibrations are felt by laying ones hand on machinery components, then a potential problem probably exists. These vibrations generally will have a frequency related to the specific component in question. As an example, binding is generally a once per revolution, where as improper alignment often has a period twice the rotational frequency.

In existing installations misalignment can be detected by monitoring the wear of bearings and gears. Since misalignment causes shaft bending and hence excessive bearing loads, abnormal wear in sleeve bearings is easily measured. The backlash in gear sets can also be measured and recorded. If these measurements are recorded over time and compared, a pattern will emerge. Movable Bridges are machines and should be considered as such. In plant operations it is common to monitor equipment utilization and condition. A simple technique to monitor the equipment health is to annually measure and record component (bearing clearance) measurements.

What do I do if Misalignment exists?

In new installations, the machinery should not be accepted until the misalignment is corrected. In extreme cases, this has resulted in complete reinstallation of the machinery system. In existing installations, misalignment is generally the result of component (bearing) wear. The steps to be taken to identify the source (s) of the misalignment are:

1) Inspect all gears for plastic deformation, severe wear, abnormal wear patterns
2) Inspect all bearings, measuring clearances, for signs of wear
3) Inspect all couplings

It is not uncommon to find sleeve bearings with excessive clearance. The correct clearance for sleeve bearings based upon shaft size are:

Shaft size	Clearance	
	Under 600 rpm	Over 600 rpm
2″ to 3″	0.002″ to 0.004″	0.003″ to 0.006″
3″ to 4″	0.002″ to 0.005″	0.004″ to 0.007″
4″ to 5″	0.003″ to 0.005″	0.004″ to 0.008″
5″ to 6″	0.003″ to 0.006″	0.005″ to 0.009″
6″ to 7″	0.004″ to 0.006″	0.005″ to 0.009″
7″ to 8″	0.004″ to 0.006″	0.006″ to 0.010″

Figure 9

A simple technique to inspect bearing clearances is to use a feeler gauge and measure the gap (usually at the top of the shaft) between the shaft and the bearing liner, see figure 9.

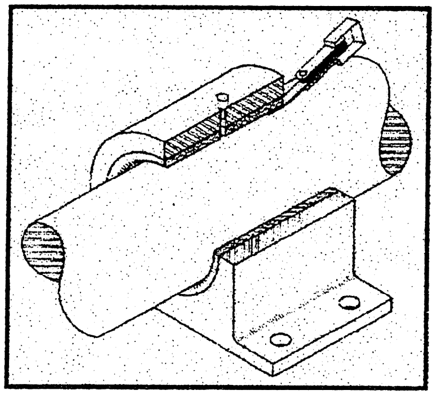


Figure 10

If excessive clearances are detected, they should be corrected immediately. The result of excessive bearing clearance is addition cyclic fatigue loading of the shafts due to bending and improper gear set alignment. The misalignment resulting at the gear sets also increases gear tooth loading as indicated in the table for span gear Load distribution factors. Note that the factor increases from 1.7 to 2.2 (30% increase for a 6" gear if full face contact is lost).

Table 8.3.12 Load-Distribution Factor K_m and C_m for Spur Gears*

Characteristics of support	Face width, in			
	0–2	6	9	16 up
Accurate mountings, small bearing clearances, minimum deflection, precision gears	1.3	1.4	1.5	1.8
Less rigid mountings, less accurate gears, contact across full face	1.6	1.7	1.8	2.2
Accuracy and mounting such that less than full face contact exists		Over 2.2		

*An approximate guide only. See AGMA 218.01 for derivation of more exact values.
SOURCE: Darle W. Dudley, "Gear Handbook," p. 13–21, McGraw-Hill, New York, 1962.

Figure 11

The wear rate for mechanical components is an exponential function. Once a limit to wear has been exceeded the rate of wear becomes very rapid. Movable Bridges are generally inspected annually. It is quite possible that an engineer could interpret bearing wear to be excessive, but not extreme, and have a catastrophic machinery failure before the next inspection. In order to guard against such occurrences, an annual inspection of all bearing clearances should be made and their values recorded and compared year to year. As bearings wear, they can be adjusted simply by removing shims to establish proper clearance. This activity if rigorously followed will extend the life of the machinery system significantly.

Conclusion

Movable Bridges are machines, which integrate structures with mechanical and electrical systems. In order for these systems to function properly over their design life and beyond, it is important that engineers and owners understand some simple inspection techniques. The techniques indicated in this paper combined with the simple act of recording and comparing data year to year will greatly enhance bridge machinery service life. The design criteria for movable bridge machinery is extremely conservative. With proper monitoring and appropriate corrective action it should not be unreasonable for bridge machinery systems to function well beyond the 30-year design life.

References

1. Machinery's Handbook 25th Edition, Industrial Press, Inc., New York, New York.
2. Mechanical Drivers, Power Transmission, 4th Edition, National Technology Transfer, Inc., Englewood, Colorado.
3. Coupling Installation Publication 458-834, The Falk Corporation, Milwaukee, Wisconsin.
4. Marks' Standard Handbook for Mechanical Engineers, 9th Edition, McGraw Hill Book Company, New York, New York.