Using Tilting-Pad Journal Bearings in Hydroturbine Generators

The tilting-pad type of journal bearing offers several advantages in the operation of a hydro generator. Understanding how this type of bearing works and the practical aspects of its design and use can be helpful in both plant operations and generator rehabilitation.

By Stanley Abramovitz

Of the hydroelectric generators I've inspected over the years, about half of them were equipped with the tilting-pad type of guide and shaft support journal bearings. However, I've found that hydroelectric plant operators and equipment designers often do not have a full understanding of the practical aspects of the design, operation, and potential problem areas associated with this type of bearing. Gaining a better understanding of these aspects can be useful in analyzing a bearing failure, preventing a serious failure by inspecting and possibly modifying bearing components at the first sign of bearing distress, and selecting or designing a new bearing.

Journal Bearings: Making a Case for the Tilting-Pad Type

The most familiar, and perhaps the most useful, of all bearings is the journal bearing. The most common type of journal bearing is the one in which a sleeve of bearing material is wrapped partially or completely around a rotating shaft, or journal, and is designed to support a radial load. This type of bearing is commonly used in both small and large rotating machines. Depending on the machine's operating conditions, the bearing will have various bore surface configurations and grooving designs.

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Another type of journal bearing, the tilting-pad type, consists of a number of curved bearing pads that are free to pivot or rock independently of one another. This type of journal bearing has several advantages compared to the sleeve-type. First, this type of bearing can be made to be self-aligning, so that the pad surfaces can align themselves to the surface of a misaligned shaft. (Shaft misalignment is a harmful condition that, if not accommodated by the bearing, reduces the amount of load the bearing can reliably support.) Second, higher load capacity can be expected from this type of bearing owing to the efficient cooling of the lubricant between pads. Third, with radially adjustable pivots, the diametrical clearance between shaft and bearing surfaces can be closely controlled, both for rotor dynamic considerations and to increase fluid film stiffness for shaft centering. Finally, unlike sleeve-type bearings, the diametrical clearance of tilting-pad journal bearings can be easily changed to correct excessive clearance that causes high shaft runout.

In many cases where I have observed a hydroturbine tilting-pad journal bearing operating marginally or failing, the problem typically stemmed from basic design factors such as number of pads, pad surface curvature, pad-to-shaft surface clearance, and bearing size for the operating load. By becoming more aware of the way tilting-pad type journal bearings are designed, how they operate, and what causes problems, hydropower plant personnel will be better prepared to ensure successful operations and/or modifications to machines with these types of bearings.

How the Tilting-Pad Bearing Works

The tilting-pad (pivoted-pad) bearing contains a number of segmented pads (shoes) placed around the shaft. Each pad is supported on a pivot, and is free to tilt in the circumferential direction of shaft rotation so that a hydrodynamic fluid film pressure between the shaft and pad surfaces can be developed. As the shaft rotates within the bearing, the fluid pressure in each pad develops a ring of radial forces. Design of the tilting-pad type journal bearing is based on plane hydrodynamics bearing theory.[1,2,3]

Individual pads are either centrally pivoted or offset in one particular direction of shaft rotation. A centrally pivoted pad is most common and can be used in situations where both directions of shaft rotation are needed (i.e., in reversible machinery such as pump-turbines and generator-motors). Also, centrally pivoted pads cannot be improperly assembled for the wrong direction of shaft rotation. On the other hand, if an offset pivoted pad is assembled for the wrong direction of shaft rotation, the bearing performance is sharply reduced and may even result in a failure.

When oil is used as the lubricant for a tilting-pad type journal bearing, the steel pads normally are surfaced with a good bearing material such as a babbitt, which is a tin- or lead-based alloy containing copper and antimony. When low viscosity corrosive liquids such as water are used as the lubricant, materials such as elastomers or laminated phenolics

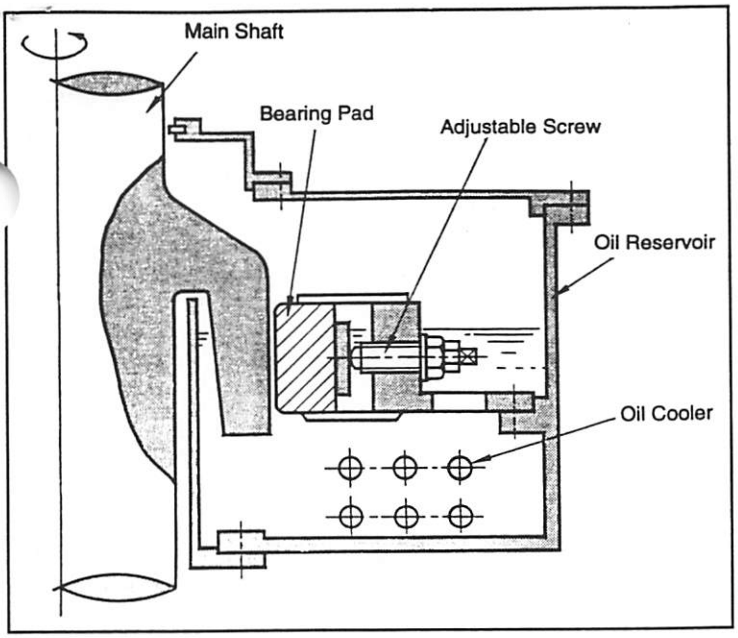


Figure 1: In this section view of a large tilting-pad journal guide bearing for a vertical hydroturbine-generator, the pad is supported by, and pivots on, a spherically ended jack screw. All pads can be adjusted for proper diametrical clearance at the assembly.

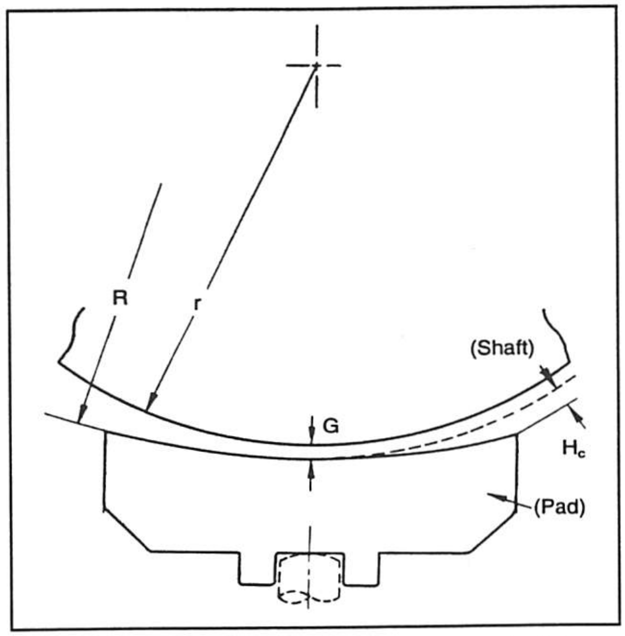


Figure 2: This figure shows the clearance between the tilting-pad bearing pad and shaft surfaces. The "machined-in" pad clearance (R-r) is greater than the bearing clearance (G) in order to form a pad surface crown of height H. The ratio of the bearing-to-pad clearance is termed "bearing preload" and is necessary for proper bearing operation.

often are used to surface the pads. To provide lubrication, the pads are either fully submerged in the lubricant reservoir, or partially submerged with angled pumping grooves in each pad surface to provide full pad lubrication. Where relatively high oil film temperatures are expected, owing to high loading and/or high shaft rpm, an external pumping system is used to provide cool lubricant to each pad surface.

Using the Tilting-Pad Journal Bearing in Various Configurations

Tilting-pad journal bearings are used in both vertical and horizontal and inclined large hydroturbine-generators as well as in small machines.

For large vertical hydroturbine-generators, one advantage of the tilting-pad bearing over the sleeve-type bearing is that it can be made to accommodate some amount of shaft misalignment. Where large pad loads are not expected, the hardened pivot design can be a flat surface against a spherical surface, allowing for freedom of the pad to pivot radially and axially in all directions. Care should be taken so that the contact stress and deformation of the pivot is not so high that pad movement is restricted.

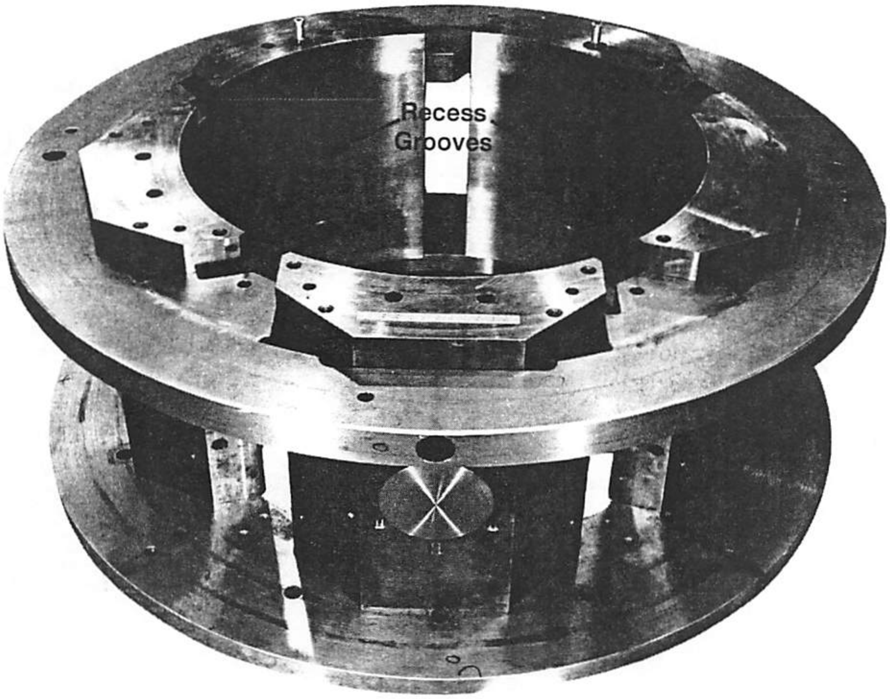
If a tilting-pad type of journal bearing is used in a large vertical hydroturbine, the large diameter and large number of pads may make it difficult to machine the housing and pads to a diametrical clearance within a specified tolerance. (A typical large tilting-pad guide bearing in a vertical hydroturbine operating at 85 revolutions per minute (rpm) has 20 adjustable pads in a 100-inch-diameter circle.) Therefore, pads typically are rested on hardened, spherically surfaced jack screws so that they can be adjusted independently for the proper diametrical clearance. (See Figure 1).

In large vertical guide bearings, the bearing's pad surface curvature in relation to the shaft curvature is critical. This is because of the relatively light bearing loads and the corresponding low film temperatures, which may have an insufficient thermal effect to correct a pad curvature that is inadequately designed for the operating conditions. In addition, many large vertical units are pump-turbines, which are operated in both directions of rotation. Consequently, proper pad surface curvature is needed for optimum development of a hydrodynamic fluid film separating the shaft and pad surfaces under both directions of rotation. Therefore, machining the proper pad surface curvature during original manufacture of the hydroturbine generator is vital.

For inclined turbine-generators, bulb turbine-generators, and horizontal tubular- or S-turbine-generators, a tilting-pad type journal bearing has many advantages. For example, the flexibility of tilting-pad bearings with regard to diametrical clearance and misalignment tolerance is a key advantage.

As compared to large vertical guide bearings where bearing loads are light, bearings in horizontal machines must be capable of carrying a relatively large radial load. Two pads normally support the major portion of the load; therefore, the design of their pivots to minimize deformation is important to ensure that the pads are free to pivot and maintain their location. I have seen a situation where, despite analysis indicating a satisfactory oil film thickness, the bearing performed marginally and experienced occasional failures. The journal load was high, and changing from a spherical pivot to a cylindrical pivot design reduced the deformation and eliminated the problem.

In general, journal bearings for horizontal and inclined hydroturbine-generators range from about 20 inches to 36 inches in shaft diameter with speeds of about 60 to 120 rpm, and can use anywhere from three to eight pads. Even though the major shaft load direction may be on one pad or between two pads, there can be uploads due to transient impeller forces. Therefore, seemingly unused pads around the shaft are necessary, and should be considered in design. In some large bulb turbines, three spaced tilting-pad bearings share the total shaft load so as to reduce structural deflections, shaft deflections, and



This tilting-pad journal bearing is designed for a 48-inch-diameter horizontal shaft. The five pads are all adjustable. The two pads with the recess grooves in their bearing surfaces primarily support the shaft. Lubricant pressure and flow is fed to the recesses from an external source to hydrostatically lift the shaft during starting and stopping. (Photo courtesy Kingsbury, Inc.)

journal bearing loading. The middle journal bearing is adjusted at assembly and checked again later for any relaxation of its radial location.

For applications in turbine-generators where bearing loads are high and the shaft surface velocity is relatively low (low speed/small diameter), the hydrodynamic fluid film thickness separating the bearing surfaces may be too small or just marginal for reliable operation. An externally pressurized hydrostatic system can be designed to separate the pad and shaft surfaces, independent of shaft speed. The hydrostatic hydraulic system supplies high-pressure lubricant at a constant volume to reliefs on the pad surface. This system can be used for full-time operation or as a hydrostatic lift during turbine starting and stopping when there is insufficient shaft speed to develop a hydrodynamic film or for rotating the shaft in air to check clearances.

As a hydrostatic bearing example, a pump-turbine with a 30-inch-diameter shaft was supported at one end on a tilting-pad journal bearing. The bearing was designed to operate hydrodynamically in an oil bath, although a hydrostatic oil lift system was a part of the design, needed only during starting and stopping. After an oil bath leak starved and failed the bearing, a routine reanalysis of the bearing design showed it to be marginal. Because the hydrostatic lifts at the two supporting pads were already in place, only the hydrostatic bearing system had to be improved to make it more reliable for full-time operation. This was done by upgrading certain hardware and increasing oil flow to develop a more conservative film separation during continuous operation.

For small hydroturbine-generators, a tilting-pad journal bearing can be purchased "off-the-shelf" for a reasonable price. Again, in this application, the tilting-pad type of bearing offers several advantages. It can be self-aligning to give maximum load capacity. And, it is inherently stable and can be designed to be free from oil film instability. This is especially important in small vertical machines.

A Review of Bearing Design Considerations, Problem Areas

Pad surface curvature, general pad design, hydrostatic lift, and vibration of the turbine all affect how the tilting-pad journal bearing operates. Understanding these various factors can be useful in trouble-shooting problem areas.

Pad Surface Curvature

The effect and importance of pad surface curvature is perhaps the least understood and yet one of the most important design characteristics of the tilting-pad journal bearing. The curvature of the pad surface effectively can create a "crowning" of the pad surface relative to the shaft surface, as illustrated in Figure 2.

Bearings with improper pad surface curvature may have been supplied that way, deformed during operation, or incorrectly reconditioned. As an example, a large vertical hydroturbine used a tilting-pad guide bearing for its 96-inch-diameter shaft. During a maintenance outage, some of the pads' surfaces were reconditioned. Shortly after the rehabilitation, these pads began running hot and failed. The problem was solved by correcting the curvature of the pad surfaces.

As part of a scheduled maintenance shutdown inspection, pad surface curvature should be routinely checked. Aside from improper initial curvature, there could be permanent distortion caused by relaxation of the pad prior to manufacturing as a ring and being cut into segments. Large bearing pads can be inspected by fitting them against the turbine shaft and measuring the amount of curvature with feeler gage strips.

The machined-in pad surface radius is a design parameter that significantly affects load capacity and film stiffness and temperature. Because the pad surface radius can be made independent of the bearing radius (which is the sum of the shaft radius plus radial clearance), the relationship between these two radii is an important design consideration. In situations where this relationship was not properly considered during bearing design, it has been a primary cause of the bearing running hot or failing.

The ratio of the assembled bearing clearance to the machined-in pad clearance establishes the pad surface crown, defined as H_c. This ratio is used to define the term "preload," which describes the relationship between these two clearances. Preload is calculated using the following equation:

Equation 1:

$$\text{Preload} = 1 - G/(R-r)$$

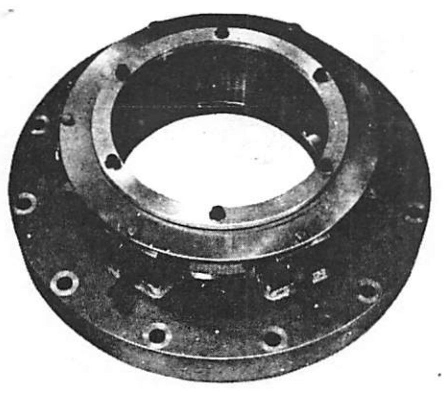
where:

G = the radial assembled bearing clearance, measured when the shaft is concentric;

R = the pad "machined-in" radius; and

r = the shaft radius.

In practice, preload values can range from 0.3 to 0.7. A value of 0.5 (where the pad radial clearance is twice that of



This tilting-pad journal bearing is for a 15-inch-diameter vertical shaft. The six pads are adjustable using the jack screws, shown in the foreground. (Courtesy Kingsbury, Inc.)

the bearing radial clearance) can be used as a reasonable guide for checking a bearing. Although shaft eccentricity influences the preload, using the preload equation and the values shown provides a good practical check of the design.[4]

A preload value of 0—where the radial pad and bearing clearances are the same resulting in a "flat" pad (no crown)—could cause a deterioration in bearing performance, particularly when the pads are centrally pivoted. Thermal "unwrap" (flattening) of the pad surface due to the thermal gradient across the pad thickness can help to produce the needed curvature, but it may be insufficient or occur too late to prevent failure.

General Pad Design

Hydropower plant personnel should be aware of a condition called "spragging," which is a pad instability, sometimes audible, where the leading edge of the pad touches or gets close to the journal surface. This can occur in applications involving light loads, such as in vertical guide bearings with relatively high speeds (surface velocity) and low viscosity lubricants, and usually is caused by too little or no preload. In most cases, a generous amount of preload will prevent or eliminate this instability. Relieving the leading edge of the pad with a generous radius also can control spragging.

As in steel-backed, babbitt-surfaced thrust pads, attention to babbitt bonding is important in segmented journal bearing pads, not held as a sleeve in a shell. During inspection, hydropower plant personnel should use dye penetrant testing to check for cracks and porosity of the babbitt surface and 100 percent ultrasonic inspection to check the quality of the babbitt bond to the steel surface.

Some turbines about 35 years and older have journal pads where the babbitt is mechanically dovetailed, with no chemical bonding to the steel pad surface. The dovetails may cause a problem owing to variable babbitt thickness. The surface can become wavy because of high film temperature and the variable expansion of the babbitt. Also, if there is no chemical bond, oil can find its way under the babbitt and distort the pad surface.

A case in point was where there was overheating and wiping of the babbitted pad surfaces of a guide bearing in a large vertical hydroturbine. The telltale burnishing and wiping marks showed that the surfaces of some pads had become wavy, which would reduce or destroy the oil film. It was a 40-year-old turbine, with no drawing of the pad details. Only when an attempt was made to remove some babbitt for analysis did the owner discover there was no chemical bond and that only the dovetails retained the babbitt.

This same condition occurred in a turbine where the babbitt was chemically bonded and, although the ultrasonic test results were within specifications, there was babbitt separation that caused overheating, with a potential for failure. It was found that the bond was weak due to improper babbitting procedures and that deformations owing to normal temperature changes caused the separation. The pads affected were spares, and the damage could have occurred due to atmospheric changes during storage. The lesson learned: spare pads should be retested for bond before use. A good bond can withstand severe deformations, in or out of the turbine.

Hydrostatic Lift

Hydrostatic lift, in which the bearing surfaces are separated using an external source of lubricant pressure and flow, commonly is used in thrust and journal bearings during starting (until the shaft gets up to speed) and during stopping. Each pad has a check valve in its piping system to prevent lubricant backflow from the pad film when the lift system is shut down during normal turbine operation. Where bearings have operated marginally with a thin lubricant film, I have seen cases where the tubing between the pad and check valve had broken and allowed the pad film pressure to be sufficiently reduced to cause the bearing to fail. Therefore, when possible, the check valve should be built into the pad.

Effect of Turbine Vibration

The effect of turbine vibrations on bearing life can be physically evaluated. With babbitt-surfaced pads, it's standard procedure during normal maintenance shutdown to inspect for surface fatigue cracks and distress that would indicate the severity of the effect of vibrations. With tilting pads, another area of concern and source of information is the pivot surfaces, where one would look for signs of fretting corrosion. This is a deterioration of the contacting surfaces, in the form of pitting, due to high-frequency, low-amplitude, relative motion at the pivot material interface.

As an example, a large vertical hydroturbine had vibration values above the power plant standards. There was a concern for the effect of the vibration on the life of the tilting-pad guide bearings. A physical inspection of the areas noted above disclosed no sign of babbitt fatigue or pivot fretting corrosion, so the relatively excessive vibration had no observable effect, and a normal bearing life could be expected.

Summary

Understanding how the tilting-pad type of journal bearing works and the practical aspects of its design and use in hydroelectric facilities can be helpful to both designers and operators with regard to equipment design, plant operations, and generator rehabilitation. ■

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Notes:

[1]Abramovitz, Stanley, "Trouble-Shooting Bearing Problems in Large Hydroturbine Generators," *Hydro Review,* Volume X, No. 6, October 1991, pages 72-83.

[2]Fuller, D.D., *Theory and Practice of Lubrication for Engineers,* Second Edition, John Wiley & Sons, New York, New York, 1984.

[3]Abramovitz, Stanley, "Fluid Film Bearings: Fundamentals and Design Criteria and Pitfalls," *Proceedings of the 6th Turbomachinery Symposium,* Houston, Texas, 1977.

[4]Boyd, J. and A.A. Raimondi, "Clearance Considerations in Pivoted Pad Journal Bearings," *ASLE Transactions 5,* 1962.