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Increasing concern about oil leakage into rivers in recent years has encouraged turbine manufacturers to develop new solutions. The self-lubricating bearings for Kaplan runners, described here, can be applied to oil-filled, water-filled or dry runner hubs.

The traditional solution for the bearings of Kaplan runner hubs is the use of cast bronze bearings, since the runner is normally filled with oil. Oil lubricates the bearings, which represents a high risk to the environment, as seals are not always reliable, and oil leakage has to be considered as a major concern.

A survey among Kaplan turbine owners [Stevenson and Street, 2008] carried out by the Columbia Power Corporation with the assistance of the CEATI (Canadian Electricity Association Technologies Incorporated) indicates that blade trunnion seals are the source of more than 60 per cent of Kaplan runner leakage.

The high risk of oil leakage to rivers has motivated most Kaplan turbine manufacturers to develop solutions to eliminate the use of oil inside the runner hub. The most promising solutions consist of replacing oil by water or by air.

1. Introduction
The environment-friendly Deva self-lubricating bearing system offers hydro plant owners a reliable alternative to oil-lubricated systems. Oil-filled Kaplan runners can contain thousands of litres of oil, and blade shaft seals are the only barrier between the oil and the river. It can be expected that these seals will wear or be damaged after some time in operation and so there is a risk of leakage to the river.

Manufacturers and powerplant owners can avoid this environmental liability by using oil-free Kaplan runner systems, and Deva self-lubricating bearings.

Federal Mogul Deva has successfully applied deva.bm self-lubricating bearings in Kaplan runners for more than 30 years. Along with this long-term field experience, the company has also carried out tests in its own laboratory, to develop the most technically feasible solution for each of the three possible runner hub operating conditions.

1.1 The self-lubricating system
The deva.bm self-lubricating material consists of a bimetal structure, that means, a stainless steel support with a sintered bronze sliding layer, containing small particles of solid lubricant, which can be graphite or PTFE, homogeneously distributed in the bronze structure, as shown in Fig. 2.

The self-lubricating concept is based on surface activation of the self-lubricating material when in contact with a shaft in movement and under load. During this process, the solid lubricant is transferred to the shaft surface, forming a film of solid lubricant, the so-called transfer-film, around the shaft.

Several reasons justify the use of these bearings as an optimum solution for Kaplan runner hubs:

- Reduction in friction between the shaft and bearings, reducing the necessary force to move the blades. Therefore less load is required to actuate the hydraulic cylinders.
- The bearings have a longer lifetime because of the lower wear rate.
- Neither the lubricant graphite nor the PTFE are affected by the catalytic characteristic of the bearing and its metallic counter-material, while hydro-carbons (oil and grease) are.
- Kaplan runner blades have a very low frequency of movement, remaining static most of the time.
- The blades are normally quite heavy and, depending on the turbine size, their weight can be several tons. In addition, there is considerable radial pressure by centrifugal acceleration during running.
- Because of its stainless steel backing, the deva.bm material has a high Young’s modulus (stiffness), so in the case of the blade trunnion bearings, this minimizes any misalignment of the trunnion during operation.
- In the case of oil-filled runners, as a result of the conditions mentioned above, it is possible to conclude that a sufficient stable oil-film between the shaft and bearing is not ensured when the blade is moved. Because of the high load applied on the blade trunnion/bearing assembly, boundary friction occurs, leading to seizure and excessive wear. Finally, an increased friction is observed.

Fig. 1. A typical Kaplan runner hub.

Fig. 2. The deva.bm material structure.

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Since oil does not promote adequate lubrication when movement starts, the solid lubricant (graphite or PTFE) embedded in the structure of the deva.bm material ensures an adequate lubrication, especially under high load operating conditions.

• In the case of oil-free runners, (water filled and dry runners), the use of self-lubricating materials is essential, as the bearing/shaft assembly requires lubrication which can only be obtained by the use of self-lubricating materials.

• A Kaplan runner is characterized by more reliable operation, as it is not exposed to unexpected failures.

According to one turbine manufacturer, other non-metallic types of self-lubricated soft materials are normally not recommended for the application in runner trunnion bearings, because their deformation, resulting from their low Young’s Modulus can cause critical misalignments of the blade trunnion [Labreque, Roy and Delisle, 2009] resulting in leakage.

2. Research and development

Federal Mogul Deva’s R&D department is continuously developing new materials, as well as supporting the company’s Application Engineers in the development of new applications. The R&D facility is equipped with several test rigs capable of testing different materials and simulating a variety of conditions. These test rigs can control and monitor speed, load, movement, friction, wear and monitor temperature online.

This paper presents some results from the test programme carried out on the Federal Mogul Deva test rigs to evaluate the tribological performance of deva.bm 342 (containing graphite lubricant) and deva.bm 362/9P (containing PTFE lubricant) bearings in Kaplan runner hub operating conditions.

The test programme had the objective of comparing the available alloys of deva.bm material to identify the best solution for each of the three runner hub operating conditions, by simulating a typical Kaplan turbine runner hub operation and investigating the mechanisms of friction and wear. These friction and wear mechanisms depend on:

• the type of lubricant used in the self-lubricating bearing material;
• the type of fluid used to fill the runner : oil, water, water + corrosion inhibitor and air; and,
• design parameters: such as load, blade shaft material, blade shaft material roughness, assembly tolerances, and so on.

2.1 Definition of the test protocol

The operating conditions of Kaplan turbines vary depending on the power station requirements and design. To conduct a realistic and representative investigation, it was necessary to design a test protocol considering a motion pattern which could reproduce typical Kaplan runner blade operating conditions. This protocol was developed together with Voith Hydro GmbH.

The blade trunnion motion pattern adopted comprised a sequence of three angular movements: 3°, 5° and 45°. A loop was defined as a series of movements having:

• 100 cycles of ± 45° movement;
• a pause of 10 minutes;
• 1000 cycles of ± 5°;
• a pause of 10 minutes; and finally,
• 2500 cycles of ± 3° movement.

The loops were repeated until the amount of cycles reached approximately 60 000 cycles.

2.2 The test rig

The tests were carried out on the Federal Mogul Deva test rig VRP2, see photograph below.

The cross section of the test rig (Fig. 4) shows that the shaft (dia. 70 mm) is mounted on roller bearings,
to minimize the error on the friction torque. The bearing was press-fitted into an H7 housing. The hydraulic load unit applied load on the housing/bearing with a maximum capacity of 10 000 kN. The housing was completely filled with the required test fluid (water or oil) from the beginning of the test.

2.3 Test conditions

The parameters used for the Kaplan test protocol are given in Table 1. The shaft was made of stainless steel according to DIN 1.4057, ground to surface finish in the range of 0.4μm < Ra < 0.6μm and had a hardness between 240 HB and 260 HB. The shaft diameter tolerance was h7 and the inner tolerance was D8.

2.4 Test results

Before starting each test, the shaft was ground and cleaned with acetone, and the surface roughness was measured in the sliding direction and in the direction perpendicular to the sliding direction. During the test, friction was monitored at certain intervals and therefore friction curves as a function of the quantity of sliding cycles were recorded.

The test started and held constant throughout the test.

3. Water-filled Kaplan runner hubs

It is acknowledged among design engineers that water-filled runners must have self-lubricating bearings, as this is the only way to ensure efficient lubrication of the bearing/shaft-system. Deva.bm bearings have been used in water-filled Kaplan runner hubs at many new power stations, as well as in upgrading projects.

One of the challenges for a designer of a water-filled runner is to deal with the protection of the inner com-

Table 1: Tribological system parameters

<table>
<thead>
<tr>
<th>Test Identification</th>
<th>Load (MPa)</th>
<th>Sliding speed (m/s)</th>
<th>Environmental considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wear / COF 40</td>
<td>0.01</td>
<td>Bearing immersed in oil</td>
</tr>
<tr>
<td>2</td>
<td>Wear / COF 40</td>
<td>0.01</td>
<td>Bearing immersed in pure water</td>
</tr>
<tr>
<td>3</td>
<td>Wear / COF 40</td>
<td>0.01</td>
<td>Bearing immersed in water + inhibitor</td>
</tr>
<tr>
<td>4</td>
<td>Wear / COF 40</td>
<td>0.01</td>
<td>Dry running</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test</th>
<th>Material</th>
<th>Shaft hardness</th>
<th>Shaft surface roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>deva.bm 1.4057</td>
<td>240-260 HB</td>
<td>R_a = 0.4 - 0.6 μm</td>
</tr>
<tr>
<td>2</td>
<td>deva.bm 1.4057</td>
<td>240-260 HB</td>
<td>R_a = 0.4 - 0.6 μm</td>
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</tr>
</tbody>
</table>

Fig. 6. Results of friction values for each test.
ponents against corrosion. Therefore, an appropriate corrosion inhibitor is normally added to water.

The inhibitor has to be selected carefully, and consideration must be given to its interaction with the self-lubricating bearings. The type of inhibitor to be used is a decision for the turbine designer, and this should be done together with the inhibitor and bearing manufacturers.

Federal Mogul Deva has conducted several investigations with water and additives mixtures for various customers, including some related to non-hydro applications such as adjustable ship propellers. As part of a recent application development with one of the leading turbine manufacturers, deva.bm 342 bearings were tested with water and an inhibitor. To have a reference for comparison, and to understand the impact of the inhibitor in the bearing system, it was necessary to include in the test matrix a test with pure water.

3.1 Impact of inhibitor in deva.bm self-lubricating bearing performance

The comparison of the total bearing wear observed in both tests with water and water + inhibitor shows that the wear difference is so small that it can be considered negligible. The bearings in both tests had similar coefficient of friction values.

Therefore, the result of these tests demonstrates that water + inhibitor is a technically feasible solution for Kaplan runner hub when used with deva.bm bearings.

3.1.1 Test conditions

The test conditions were as follows. The specific bearing load was 40 MPa, and the sliding speed was 10 mm/s. The dimensions of the bearing were $\phi 70 \times 0.676 \times 40$ mm, and the diametric clearance was 0.1 - 0.15 mm. The shaft material was 1.4057 with surface roughness in the range of 0.4 $\mu\text{m} < \text{Ra} < 0.6 \mu\text{m}$. Angular movement was $\pm 45^\circ, \pm 5^\circ, \pm 3^\circ$.

3.1.2 Total wear

The Tables and Fig. 7 above show: (a) total wear for the bearing immersed in pure water, and (b) total wear for the bearing immersed in water plus the inhibitor.

3.2 Comparison of friction values

Fig. 8 below shows the results of friction values for test with pure water (green) and test where the bearing was immersed in water + inhibitor (blue).

4. Dry-running Kaplan runner hubs

Of the three possibilities for runner hub design, the deva.bm self-lubricating bearings had the best tribological performance in the dry-running runners. The reason is that oil and water normally interfere in the process of reaction plating of bearing solid lubricants on the tribological system.

It is also simpler for the bearing application engineer, as the self-lubricated materials were originally designed to work in dry conditions and the Kaplan runner application can be associated to several other similar well known applications. CKD Blansko has been using deva.bm bearings successfully in their dry running Kaplan runners for more than 10 years.

5. Oil-filled Kaplan runner hubs

Although some designers do not consider that self-lubricating bearings are necessary in oil-filled runners, Federal Mogul Deva’s experience in the modernization/refurbishment of Kaplan turbines shows that the oil used inside the runner hub does not promote efficient lubrication, since mixed friction conditions and even boundary friction occurs.
In some cases of refurbishment projects in which Federal Mogul Deva participated, when the runner was dismantled, the old bronze bearings were found to have excessive wear. In a few cases, there were even indications that the bronze bearing had moved inside its housing as a result of high friction between the shaft and bearing.

A well known problem in the case of plain bearings is the so-called ‘stick-slip effect’, which can be identified by a ‘squeaking’ or ‘scattering’ noise that is generated. This normally occurs whenever the static coefficient of friction is considerably higher than the dynamic one, a typical situation for oil or grease lubricated systems.

Deva.bm material was developed to have similar values of both static and dynamic coefficients of friction. The material has this characteristic because the lubrication by transfer-film of solid lubricants is not related to variable parameters such as viscosity, or pressure distribution depending on the gradient of shear-tension, which are common in case of oil or grease lubrication.

When a self-lubricated material is used, a stable solid lubricant film will be formed on the shaft surface. This lowers the static coefficient of friction to such a low level that stick-slip does not occur, even in the presence of water or oil.

The refurbishment work carried out on six turbines at CESP’s Jupiá powerplant in Brazil is one of the successful applications of deva.bm bearings in oil-filled Kaplan runners.

6. Conclusions
The significant increase in environmental awareness in recent years has not only stimulated changes in people’s behaviour as regards their respect for nature, but has also influenced the expectations and demands from governments and industry.

The ecological movement put a lot of pressure on some industrial companies. As a reaction to this pressure, hydro generation companies and equipment manufacturers have developed more environmental friendly solutions.

Self-lubricating bearings have become a standard solution for the bearings of dam gates and turbine distributor mechanisms for more than 40 years, and now oil-free Kaplan runners are also becoming a standard solution.

Federal Mogul Deva’s investigations and field experience with the application of deva.bm self-lubricating bearings in Kaplan runner hubs has proved to be a feasible and reliable solution.

References

Paulo Pereira graduated in Mechanical Engineering in 1984 from the Universidade Católica de Petropolis, Brazil. His career has included working as a design engineer in the Santa Matilde passenger train engineering department, an application engineer at Garrett Turbochargers, and a sales engineer at KHS. He joined Deva do Brasil in 1996 as sales manager for the automotive business, and later became responsible for the industrial and hydro business. In October 2004, he moved to Germany to work for Federal Mogul Deva GmbH as Hydro Application Manager.

Kamran Laal Riahi graduated in Physical Engineering (Material Sciences) from the University of Aachen, Germany. During his studies, he worked for Cerobear (ceramic bearing technology). He also worked for three years in the Laboratory of Material Science at the University of Jülich, Germany. He joined Deva in 2005 as R&D Engineer, and later became the R&D manager. In June 2009, he joined the Federal Mogul Deva sales team.

Peter Schmitt has more than 25 years of experience in bearing technology. After his graduation in Mechanical Engineering, he became an application engineer at Federal Mogul Deva, specializing in the application of self-lubricating bearings for hydropower equipment, and for many years has been responsible for the coordination of the Application Engineering Department.

Martin Müller-Brodmann has more than 25 years of experience in bearing technology. After his graduation in Mechanical Engineering as well as precision engineering, he mainly focused on tribology. Starting in the field of carbon based bearings, he took R&D responsibility for powder metallurgy bearings at Schunk Sintermetalltechnik GmbH. He represented SST in public-financed development projects as well as in standardization associations, and published some related papers. He joined Federal Mogul Deva GmbH in 2006 and became Senior Head of Engineering in January 2007.

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