Strain gauge measurements of friction on radial dam gate bearings

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ABSTRACT: At least five known radial gate failures are caused by trunnion bearing seizure. The radial gate arms are normally designed to withstand bending moments from nominal friction on the bearings. Experience has shown that lack of lubrication and years of deterioration leads to increased friction and even seizure of the bearings. The bending moments produced by bearing friction imposed on the gate arms are beyond the moment capacity, resulting in collapse. Norconsult has developed a method for measuring trunnion bearing friction while the gates are in service. By means of strain gauges attached to the gate arms, the strain caused by the bearing friction is measured during gate movement. The signals from the strain gauges and a gate position transmitter are logged digitally, allowing direct presentation of test results. The method gives objective and precise verification of measuring results, and the risk of subjective and wrong assessments is minimized.

1 BACKGROUND

1.1 *Introduction*

Increased friction and seizure of bearings on dam gates is a growing concern. At least five radial gate breakages in Norway and abroad are caused by bearing failure. Consequently, there is uncertainty among dam owners regarding the state of the bearings on radial gates after several years of service under severe conditions and sparse maintenance.

1.2 *Deterioration of bearings*

Early dam gates (before 1980) are most commonly designed with trunnion bearings using a carbon steel shaft and bronze radial and axial bearings. The shafts are often chromium plated, and the bearings are usually lubricated by a manual grease lubrication system.

Dam gate bearings are static bearings with small rotation and relatively few movements during operation. This operation mode is not suitable for a bearing requiring external lubrication as the lubricant is not distributed on the high pressure sector of the bearing.

When injected to the radial bearing, the lubricant often finds its way to the low-pressure side, leaving the high-pressure load transformation sector unlubricated. The axial bearings are often connected to the same lubricant pipe as the radial bearing. This gives an evenly distributed load, and the grease escapes through the low-pressure side of the radial bearing.

The bearing material and opposing surface often represent an unfavorable material combination becoming corroded and contaminated. This is probably the most important factor in deterioration of bearings. When water is present and an electrolyte can occur with the carbon steel shaft as the anode. This leads to corrosion on the bearing surface of the shaft and increased roughness from pitting and corrosion products. Tight bearing radial clearance worsens this effect.

1.3 *Damage mechanisms and consequences*

Radial gate arms are often slender steel structure dimensioned to withstand bending and buckling from the water pressure. Friction forces are often not taken into consideration, or nominal values of friction coefficient are used. Normally a lubricated bronze bearing and carbon steel shaft has a nominal friction coefficient of $\mu = 0.2 – 0.3$

Deterioration of the bearings leads to increased friction, for which the arms are not dimensioned. When the increased friction causes breakage, this is due to both fatigue and instantaneous breakage. In particular, cylindrical bearings with a manual lubrication system combined with an automatic or remotely operated gate are a vulnerable configuration.

All radial gate collapses lead to economic loss due to loss of power production. Excessive discharge results in downstream flooding and lowering of the reservoir, affecting boat traffic and recreational use of the water way.

1.4 *Arm design*

Exposure to failure due to increased bearing friction depends on the design of the arms. Areas of concern are the transition zones between the trussed beams constituting the arms and the hub accommodating the bearings. As an example we have analyzed the effect of a friction coefficient of $\mu = 0.5$ on the Lundevann dam radial gate arm. At full water head it imposes a bending moment resulting in a bending stress of 7MPa in the large cross-section hub. The bending moment is transferred to the more slender trussed beams, constituting the gate arms. In the transition zone between hub and arms, the stress concentration is especially high in this example. A friction coefficient of $\mu = 0.5$ results in a bending stress in the transition zone of 100MPa as shown in Figure 1. This stress change goes from plus to minus when the gate movement changes direction, exposing the transition zone to fatigue.

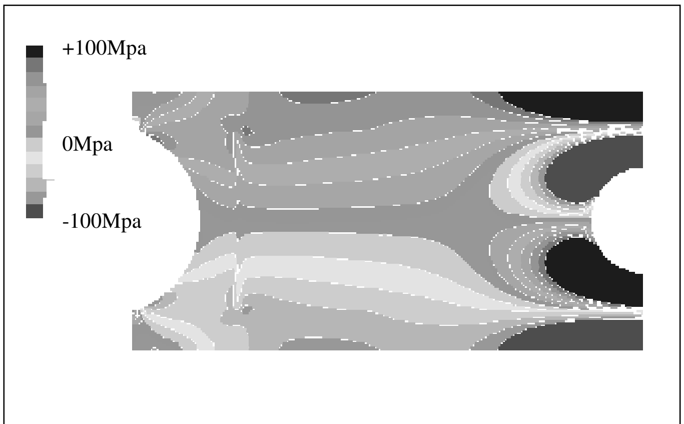

Figure 1. Lundevann dam radial gate arm, hub section. Stress resulting from friction coefficient, $\mu_{BRONZE\text{-}STEEL} = 0.5$

1.5 *Trunnion design*

Trunnion designs vary with regards to vulnerability for bearing seizure. For the common cantilevered trunnion shaft anchored to the abutment, symptoms of bearing seizure are difficult or impossible to detect by visual inspection. High friction moments can be transferred through the shaft without visible indications of increased bearing friction before the collapse occurs.

The trunnions may include a shaft lock allowing rotation of the shaft in the console, causing the shaft lock to be deformed after a bearing seizure.

2 EVALUATION OF METHODS

2.1 *Inspection and maintenance*

Inspection and maintenance of gate trunnion bearings often implies dewatering of the dam gate and dismantling of the bearing. Dewatering of the gate can be accomplished by lowering the reservoir. This is, however, both time-consuming and costly if production is lost. More common is dewatering by installation of stop logs in front of the gate. This is less expensive than lowering the reservoir, but still more expensive than other methods. Another disadvantage is that during the de-commissioning period the discharge capacity of the gate is not available. Dismantling of radial gate trunnion bearings is subsequently not routinely carried out to determine the condition of the bearing. Dewatering and dismantling of the bearing is carried out when and if the symptoms of bearing seizure are evident. On some radial gates total collapse has occurred without prior symptoms.

2.2 *Detection of change in maneuvering forces*

In theory an increase in lifting force could be detected when bearing friction increases. However, the bearing friction constitutes only a small fraction of the total lifting force. On a typical radial gate with upstream lifting chains, the total lifting force of 156kN is dominated by the gates own weight of 126kN (81%). The remaining 30kN (19%) is friction in rubber seals and trunnion bearings. To separate the two friction forces, the friction on the seals must be based on an assumption regarding the friction coefficient between rubber seals and the embedded stainless steel frame. Assuming $\mu_{RUBBER\text{-}STEEL} = 0.9$, the friction on the seals constitutes 20kN (13%) of the lifting force. The remaining, 10kN (6%) is the nominal bearing friction based on $\mu_{BRONZE\text{-}STEEL} = 0.2$. A variance of this relatively small force, compared to the total lifting force, is complicated to detect and is unreliable since the method is based on assumptions.

2.3 *Detecting bending moments in radial gate arms*

As a part of a safety revaluation program for dams, a diagnostic technique has been developed for radial gate bearings without dewatering the gate or dismantling the bearings. The method detects friction on the bearings during operation of the gate.

2.4 *Measurement technique*

The forces acting on the trunnion bearing can be divided into two classes:

- Perpendicular forces on the bearing surfaces is the result of water pressure, gate weight, operating forces and friction forces from the rubber seals. The resulting force from the water is the dominating the force on the trunnion.

Shear forces parallel to the bearing surface due to friction. Without friction (μ = 0), no shear forces will appear. These forces will give bending moments in the gate arms.

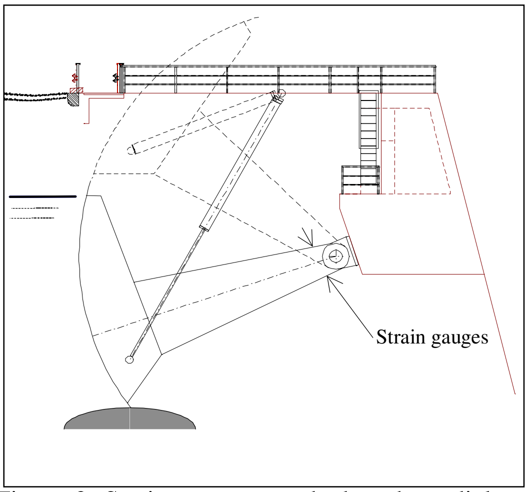

Figure 2. Strain gauges attached to the radial gate arms, close to the bearing.

The shear forces on the bearings cannot be measured directly without modifying the gate structure. Instead the mechanical stress variation is measured in the gate arm, near the trunnion bearing, using strain gauges. One strain gauge is attached at the upper side of the gate arm, and one is attached at the lower side of the gate arm as indicated in Figure 2. Each strain gauge measures the surface mechanical stress in parallel to the main stress direction in the gate arm.

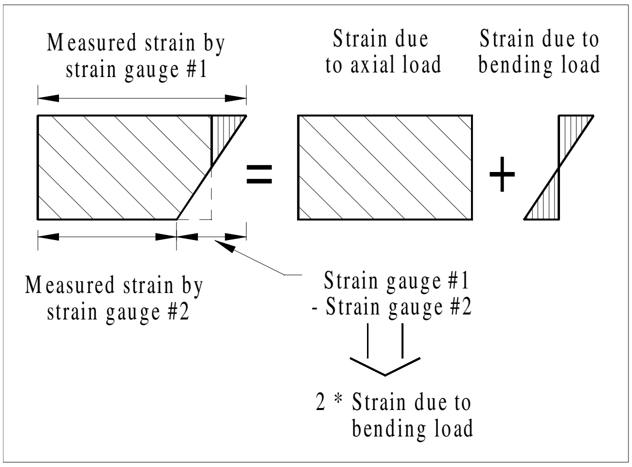

Figure 3. Stress measured by strain gauges.

Superimposed axial and bending forces cause the measured stress indicated in Figure 3. By connecting the strain gauges in a Wheatstone half bridge circuit the two measured stresses are subtracted and the output only indicates active bending moment in the gate arm (ref /1/). By using this circuit, superimposed axial (normal) strain is compensated, and the strain caused by thermal changes is compensated to a high degree.

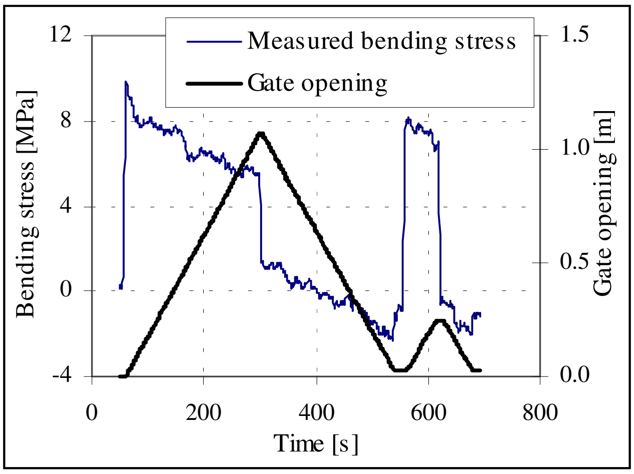

Figure 4. Lundevann dam, measured stress in right gate arm.

Figure 4 shows the measured stress in the right gate arm at the Lundevann dam with the original bearing thoroughly lubricated. The gate was opened, almost closed, opened and finally closed. The vertical gate opening was measured simultaneously as shown in the figure.

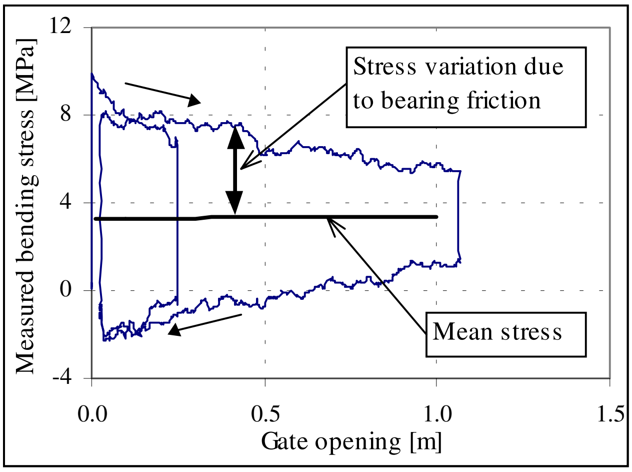

Figure 5. Mean stress variation.

The measured stress caused by bending is shown at the Y-axis and the vertical gate opening at the X-axis, see Figure 5. The figure shows that the measured stress creates a hysteresis curve superimposed on a mean stress variation. The variation in mean bending stress is mainly caused by variation in how the flow forces act on the open gate. These forces are dependent only on the gate opening, not the direction of the movement. The variation of these forces is not used in the analysis and may be ignored. The friction forces in the bearing always act against the direction of the gate motion. When the motion changes direction the measured bending stress, due to friction forces in the bearing, also changes direction. In addition the friction force varies with the gate opening, as the water load on the gate alters.

Dependent on the hoist design, the friction forces from the gate rubber seal have some influence on the total measured friction force. Upstream chain hoist has no influence. In this actual design the rubber seal friction gives less than 5% effect on the measured bending stress when we assume $\mu_{RUBBER\text{-}STEEL} = 0.9$ (worst case). This estimation is compensated in the calculations.

The friction torque at the bearing trunnion is calculated based on the measured bending stress due to friction. This calculation is done as a function of moment of inertia in the gate arm at strain gauge location and radial distance from the strain gauges to the bearing centre line.

The water load on the gate is calculated as load from the static water pressure at the wet surface of the gate. The accuracy of this calculated load is high when the gate is closed. At increased gate opening, larger areas are exposed to flow velocity, which decrease the static pressure. Our method will overestimate the load when the gate opening increase, but according to pressure distribution calculation on a gate (ref /2/) this error will be limited to approximately 15 % at 25% gate opening. This calculation gives the main input to the radial load at the bearings transmitted through the gate arms.

Dependent on the design, the gate arm axial force is split into two components, one acting on the axial bearings and the second on the radial bearings. This split is dependent on the gate design. When both radial load and friction torque on the trunnion bearings are known, we can calculate the average friction coefficient on the bearings. Figure 6 shows the friction coefficient dependent on the gate opening and direction of motion.

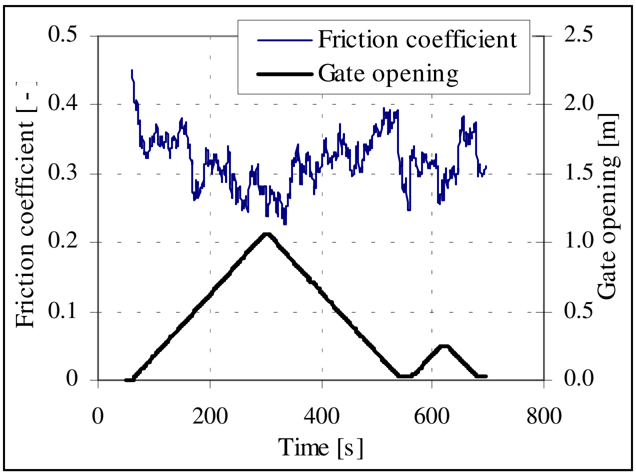

Figure 6. Calculated friction coefficient

3 MEASUREMENTS ACCOMPLISHED

3.1 *General*

Since the method was developed in 1998, a total of 30 bearings on 15 radial gates in six different dams have been measured. On one of the dams where increased bearing friction was detected, Lundevann Dam (owner: Sira-Kvina Kraftselskap), repeated measurements were carried out .

3.2 *Presentation of results*

Table 1. Key data of gates measured and results

W x H m	Bearing Shaft	Lubr. system	Friction coefficient Nominal	Friction coefficient Measured Left / Right	Prior lubrication
15 x 5.2	B/S	Grease	0.2	0.08 / 0.09	Yes
8.0 x 2.8	B/SS	Selflub.	0.1	0.35./0.25	N/A
20 x 8	B/PS	Selflub.	0.1	0.15 / 0.10	N/A
13 x 4	B/S	Grease	0.2	0.75 / 0.50	No
13 x 4	B/S	Grease	0.2	0.45 / 0.45	No
11.5 x 5	B/S	Grease	0.2	0.15 / 0.14	Yes
11.5 x 5	B/S	Grease	0.2	0.14 / 0.13	Yes
11.5 x 5	B/S	Grease	0.2	0.12 / 0.09	Yes
13 x 4	B/S	Grease	0.2	0.55 / 0.40	Yes
13 x 4	B/S	Grease	0.2	0.22 / 0.35	Yes
12 x 6.3	DU/PS	Selflub.	0.15	0.18 / 0.20	N/A
12 x 6.3	DU/PS	Selflub.	0.15	0.17 / 0.19	N/A
17 x 5	B*/PS	Selflub.	0.1	0.71 / 0.58	N/A
17 x 5	B/PS	Selflub.	0.1	0.43 / 0.42	N/A
13 x 4	C/SS	Selflub.	0.15	0.09 / 0.13	N/A

B = Bronze, S = Carbon steel, PS = Chrome plated carbon steel, SS = Stainless steel, DU = Glacier DU bushing, C = composite. * Oiles 500 w/SL4 lubricant plugs.

3.3 *Lundevann Dam*

The Lundevann Dam is the reservoir for the Åna-Sira hydropower plant. In the outlet of Lundevann a concrete dam was constructed with two spillways and surface radial gates.

Table 2. Key data for the radial gates on the Lundevann Dam

B x H	:	13.0m x 4.2m
Reservoir level	:	El. 48.5
Bottom sill	:	El. 44.5
Gate radius	:	7000mm
Old radial bearing diameter	:	250mm
Old axial bearing diameter	:	370mm
Old bearing material:	:	Cast steel shaft/bronze bush
New radial bearing diameter	:	216mm
New axial bearing diameter	:	350mm
New bearing material	:	Stainless steel/Orkot**

** Trade Mark from Busak + Shamban, non-metallic self-lubricating bearing material

The measurements were carried out on the bearings under three different conditions:

1 Original bearing without prior lubrication
2 Original bearing thoroughly lubricated
3 New bearing with self-lubricating bushing

3.3.1 *Measuring the original bearings*

The first measurements on the four bearings, two on each gate, were carried out in 1998. Prior to the measurements, the gates had been stationary for one year without maintenance or lubrication. The measurements revealed increased friction values in all bearings. The friction on the bearings of the most frequently used gate No. 1 was especially high. On the first opening movement, the friction coefficient was 0.75, dropping to left 0.60/ right 0.50 in the second opening. The coefficient of friction remained considerably higher than expected for the material properties of the bearings.

In 1999, we repeated the measurements after the bearings had been thoroughly lubricated and moved repeatedly to distribute the grease. The friction coefficient then fell by 25% to 0.45 and 0.35 on the same bearings. Our conclusion was that the bearings had suffered permanent damage and we recommended dewatering and replacement.

3.3.2 *Inspection and replacement of the bearings*

In 2000, the gates were dewatered and the bearings were dismantled. The inspection revealed traces of seizure on the bronze surfaces and seizure and corrosion on the surfaces of the cast carbon steel shaft. It was also evident that the manual lubrication system had not functioned as intended. Partly due to clogged grease channels and partly due to the fact that the grease escapes from the bearing on the low pressure side.

The bearings were completely replaced. New shafts were manufactured in stainless steel, SIS 2387. For radial and axial bearing, a non-metallic material was chosen. Orkot® is a brand name from Busak+Shamban. Orkot® TLM Marine grades are non-asbestos composite materials incorporating woven fabric reinforcement and solid lubricants within a thermosetting resin matrix. The manufacturer gives a friction coefficient between 0.10 and 0.15 against stainless steel.

3.3.3 *Measuring the replaced bearings*

After assembly and commissioning of the new bearings, the friction on bearings on gate no. 1 was measured. The result shows that the friction coefficients are within the values given by the manufacturer. The measured friction coefficient is 0.09 and 0.13 for the left and right bearings respectively. The results from the measurements of the new bearings with the known properties and characteristics of the bearing materials is also a verification of the diagnostic method.

3.3.4 *Comparison of the measurements*

Figure 7 shows the results from three of the measurements of the right bearing on gate No. 1 on Lundevann dam.

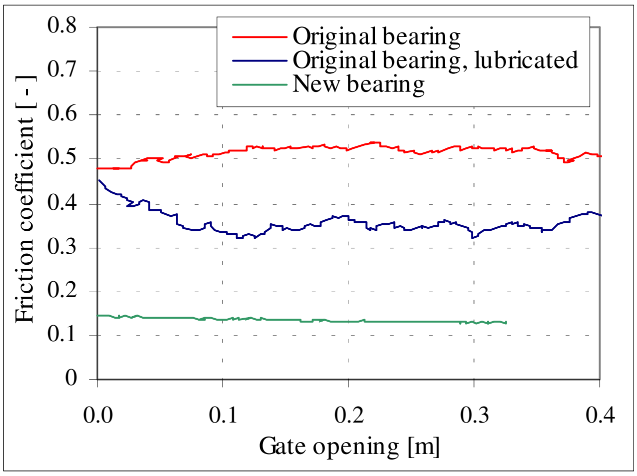

Figure 7. Comparison of measurements

The initial (static) and dynamic friction of the original unlubricated bearings is almost constant. When lubricated the original bearing has almost the same static friction as unlubricated, while the dynamic friction drops by 25%.

The uneven shape of the graph for the original bearing indicates increased roughness of the bearing surfaces, while the even shape of the graph for the new bearing indicates smooth bearing surfaces.

4 CONCLUSION

The method of measuring bearing friction by means of strain gauges provides dam owners with a better diagnostic technique. Experience has shown that the method will detect bearing failure at an early stage before the friction moment exceeds the gate arms bending moment capacity. The method is characterized by high reliability and accuracy. The influence from dynamic conditions and the friction on the seals is insignificant. Measurements are carried out without dewatering or decommissioning the gates. The method gives objective and precise verification of measuring results, minimizing the possibility of subjective and wrong assessments.

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Ref /1/ Hoffmann, Karl. *An Introduction to Measurements using Strain Gauges*. 1989, Darmstadt: Hottinger Baldwin Messtechnik GmBh.

Ref /2/ Wickert, G and Scmausser, G. 1971. *Stahlwasserbau*. Berlin: Springer Verlag.