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Published in:
12th EDF - Pprime Workshop: “Solutions for performance improvement and friction reduction of journal and thrust bearings”

Publication date:
2013

Citation (APA):
Klit, P., Persson, S., & Vølund, A. (2013). Testing of Bearing Materials for Large Two-stroke Marine Diesel Engines. In 12th EDF - Pprime Workshop: “Solutions for performance improvement and friction reduction of journal and thrust bearings”

Testing of Bearing Materials for Large Two-stroke Marine Diesel Engines
Tests des matériaux de paliers pour de gros moteurs diesel deux temps de bateau.

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Keywords: Fatigue, White Metal, Crack Propagation, Journal Bearing.
Mots-clés : Fatigue, Régule, Propagation de fissure, Palier.

In large two-stroke marine diesel engines bearings are designed with the intention that these need not be replaced during the life of the engine. The design has shown very good service experiences. The design parameters of the main bearings are, among others, based on the average maximum specific load which the bearing should operate under. In general, the frictional loss is less than 1% of the nominal power of the engine but is still a target for optimization. Fatigue mechanisms of bearing lining material are not fully understood and the design limits with regards to minimum oil film thickness, max oil film pressure and oil film pressure gradient is not established. Large two-stroke journal bearings are not suitable for fatigue test due to the size, the low rotational speed and the complexity of such test-rig. The Disc Fatigue Test Rig (DFTR) was designed with the purpose to test white metal coatings under realistic bearing conditions, in a confined time-frame. The test-rig simulates a scale model of a thrust bearing, in contrary to standard design the bearing lining material is applied to the rotating collar. On each side of the disc three stationary tilting-pads applies a load to the test disc, with a rotational speed of 2000 rpm. Parameters, such as bearing load, rotational speed, oil temperature, oil contamination is controlled/monitored in order to achieve repeatability and a systematic approach to the experiments. Test performed on the test-rig shows good correlation on the fatigue cracks with those experienced on large two-stroke journal bearings.

Dans les moteurs deux-temps diesel de bateaux, les paliers sont souvent conçus afin de ne pas avoir à être remplacés pendant la durée de vie du moteur. La conception a montré sa robustesse. Les paramètres de conception des paliers principaux sont, entre autres, basés sur la charge spécifique moyenne à laquelle le palier est censé fonctionner. En général, la perte par frottement est inférieure à 1% de la puissance nominale du moteur mais reste tout de même un bon critère d'optimisation. Les mécanismes de fatigue de la couche de revêtement des paliers ne sont toujours pas bien compris et les limites de conception en ce qui concerne l'épaisseur minimale du film d'huile, la pression maximale ainsi que le gradient de pression ne sont pas encore établies. Les paliers équipant de tels moteurs que ceux présentés dans le papier ne sont pas utilisables à des fins expérimentales. En raison de leur taille, de la faible vitesse de rotation ainsi que de la complexité d'un banc de test de cette dimension. Le banc d'essai de fatigue sur disque (DFTR) a été conçu pour permettre de tester les revêtements en régule soumis à des conditions de fonctionnement réelles, en un temps relativement restreint. Le banc simule une butée à l'échelle où, contrairement au cas usuel, le régule est appliqué sur le grain mobile. Sur chacune des faces du grain mobile, trois patins oscillants fixes permettent d'appliquer une charge au disque tournant à 2000 tr/min. Plusieurs paramètres comme la charge, la vitesse de rotation, la température d'huile ou son éventuelle contamination sont régis par un contrôle/commande afin d'obtenir une grande répétabilité ainsi qu'une approche systématique des expérimentations. Les tests réalisés ont montré une bonne corrélation entre les fissures de fatigue observées sur le banc d'essais et celles des paliers de moteurs deux temps de grandes dimensions.

1. Introduction

Bearings for large two-stroke marine diesel engines are typically in service for the entire lifetime of the engine – up to 20-30 years is not unusual service life [Figure 1]. The bearing shell is installed in the engine and firmly positioned by the design of the structure surrounding the bearing [Figure 2]. The design of these bearings is to a large extend based on empirical knowledge in combination with simulations. These simulation results are compared to basic design rules and thus assisting in the validation of the new design. The typical white metal bearing shell [Figure 3], consist of a base material (steel) on which the white metal has been applied.

Traditionally bearings installed in MAN Diesel & Turbo SE (MDT) engines were equipped with white metal as bearing lining. This mindset changed years back when certain bearing in certain engines started to show less good performance due to fatigue cracks at bearing edges. This required a modification in order to address this issue. The solution was the introduction of the AlSn40 bearing – a steel lining with an AlSn40 roll bonded on top as bearing lining. The fatigue properties of this bearing shell in somewhat superior to a conventional white metal bearing, which has also been demonstrated by the service experiences with this bearing type. But the drawback of this bearing type is the reduced capability to operate under extreme conditions. From time to time failures occur. These failures may originate from foreign particles, water in oil, poor quality in the production process, erroneous installation or poor design. The reduced capability to operate under extreme conditions can lead to engine failures, where major components (Engine structure or crankshaft) needs to be replaced or re-machined. This is typically not the case for with white metal main bearings.

The introduction of more sophisticated simulation tools has helped MDT to increase acceptable nominal load on the main bearings. At the same time more understanding of which parameters that affect the performance such as minimum oil film thickness and maximum oil film pressure has led to new designs. The 'Blended Edge' [Figure 4] design compared to the conventional design increased the minimum oil film thickness significantly thus enabling the possibility to re-introduce the white metal bearing, with its superior tribological properties. Having this in mind there is still a need for understanding the mechanisms in relation to fatigue of white metal bearings.

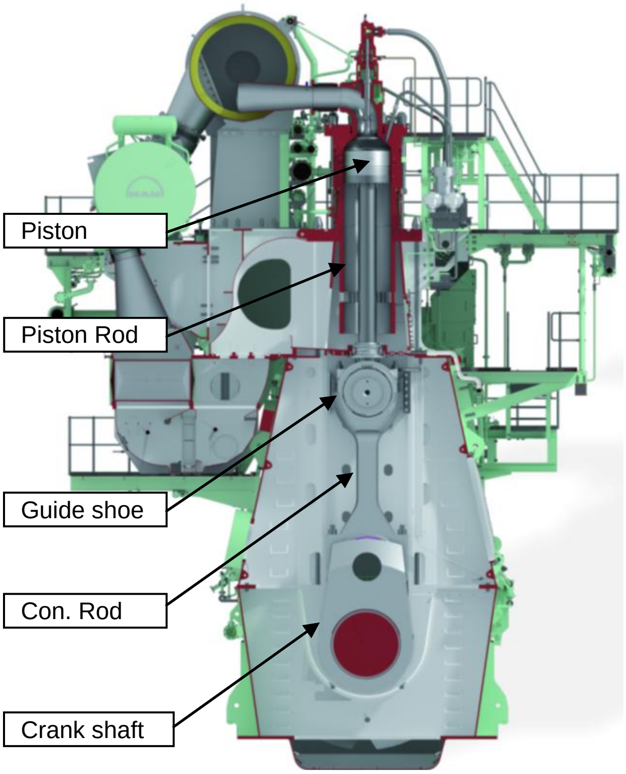


Figure 1: Engine Section

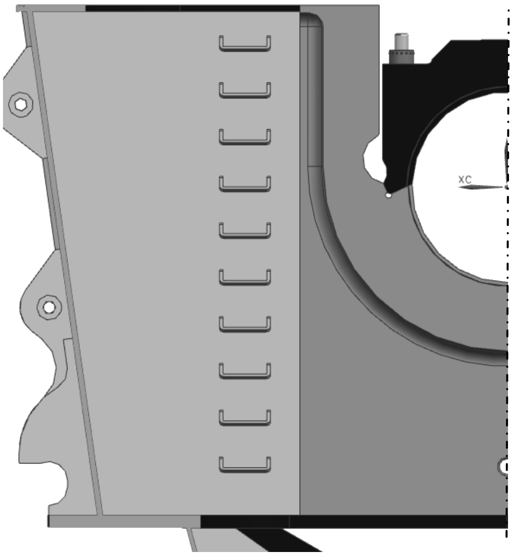


Figure 2: Section view of bottom part of engine section, showing the main bearing structure with bearing shell

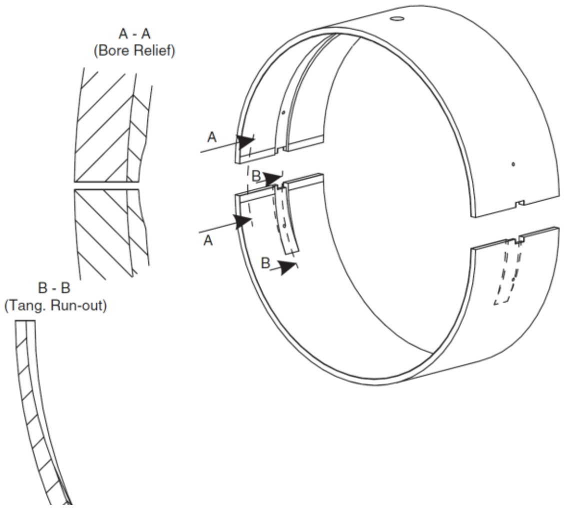


Figure 3: Main Bearing Shell Design (Thin Shell design)

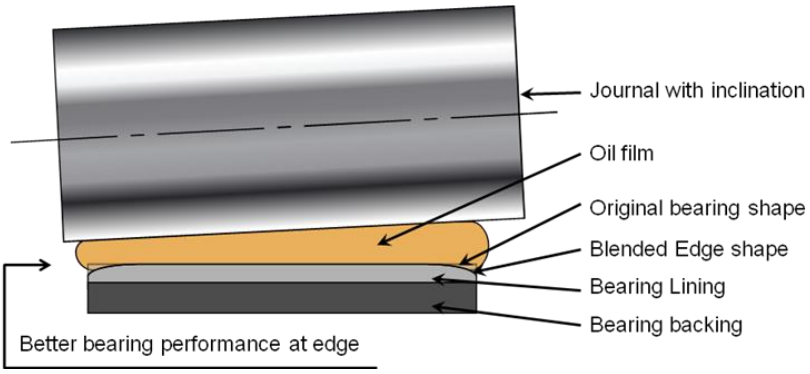


Figure 4: Cross section of concept of blended edge bearing design

2. Testing of White Metal Bearing Alloys

White metal fatigue tests are described in DIN 50100, 50113 and 50142 where compound material is tested with alternating tensile/compressive stress and rotating bending. This test is commonly used by bearing manufacturers to test the lining fatigue properties. But since the test is performed on specimens that have little in common with a thin bearing lining the test results cannot be transferred to plain bearings. In the last century plain bearing has been tested countless times on many designs of test rigs to simulate realistic bearing conditions. These kinds of test rigs tend to be complicated and repeatability is hard to achieve –e.g. ISO 7905.

In an EC-collaboration project denoted 'Hercules-β'- Rolf Koring from ECKA granulates developed a new fatigue test bench in collaboration with the Technical University Dusseldorf and MDT (Koring, 2013). The purpose of the test bench was to evaluate the fatigue properties of laser lined bearing linings under realistic conditions. The concept developed by Rolf Koring is based on the principle of a thrust bearing system. In a standard thrust bearing the tilting pad is lined and the rotating collar is made of steel. In the ECKA test rig the tilting pad is made of steel and the rotating disc was lined with white metal. With three tilting pads the disc is loaded three times during one revolution, in comparison with a plain bearing the tests can be performed on a short time. The idea behind this rig was utilized in the process of designing the Disc Fatigue Test Rig presented in this paper.

3. Disc Fatigue Test Rig

The Disc Fatigue Test Rig (DFTR) was designed as a collaboration between The Technical University of Denmark (DTU) and MDT with the purpose to test white metal coatings under realistic bearing conditions, in a confined time-frame. The test-rig simulates a scale model of a thrust bearing. The purpose with this test-rig is, through experimental analysis, to clarify some of the reasons and mechanisms for crack formation and growth in white metal coatings due to fatigue. One of the big challenges, when designing new bearings is the design limits for minimum oil film thickness and maximum oil film pressure and the combination of those two. With a better knowledge of bearing fatigue the bearings can be designed with lower friction losses since the area of contact can be optimized/ adapted to the bearing in focus.

4. Concept and principle

The disc fatigue test rig developed in the EC-project 'Hercules-C' is based on the same principle as the test rig used in the Hercules-β project. And with the knowledge from the ECKA test rig an improved fatigue test rig has been constructed.

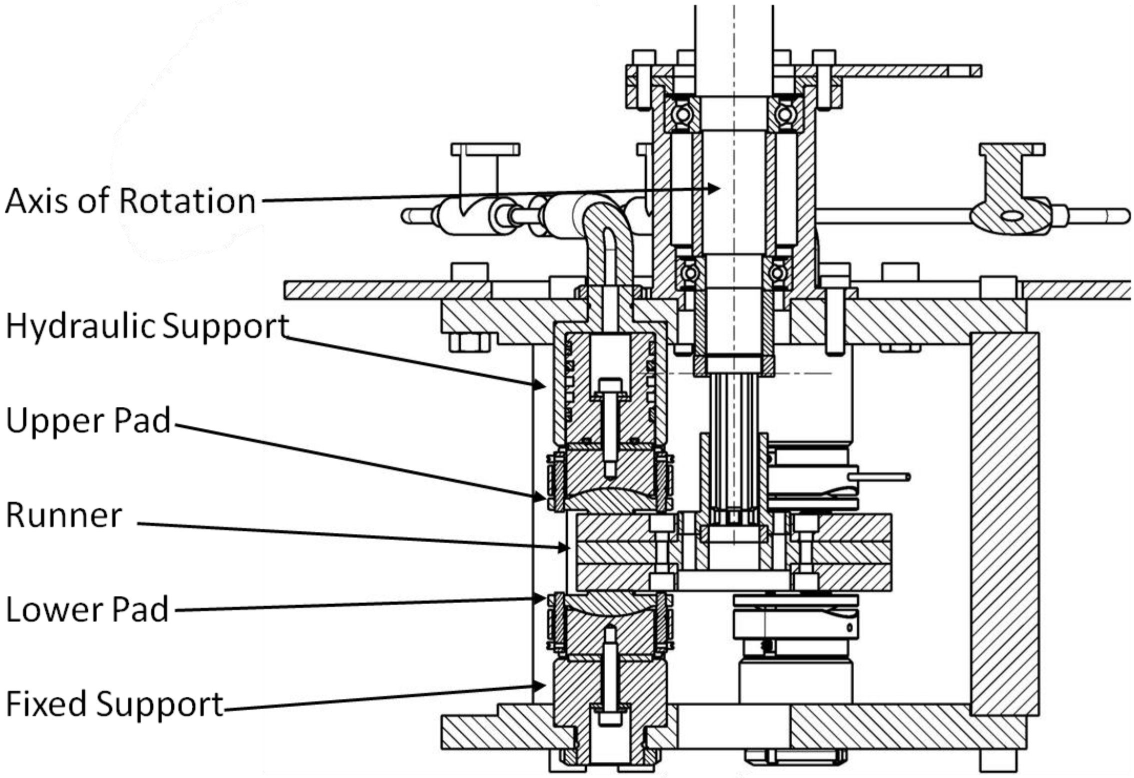
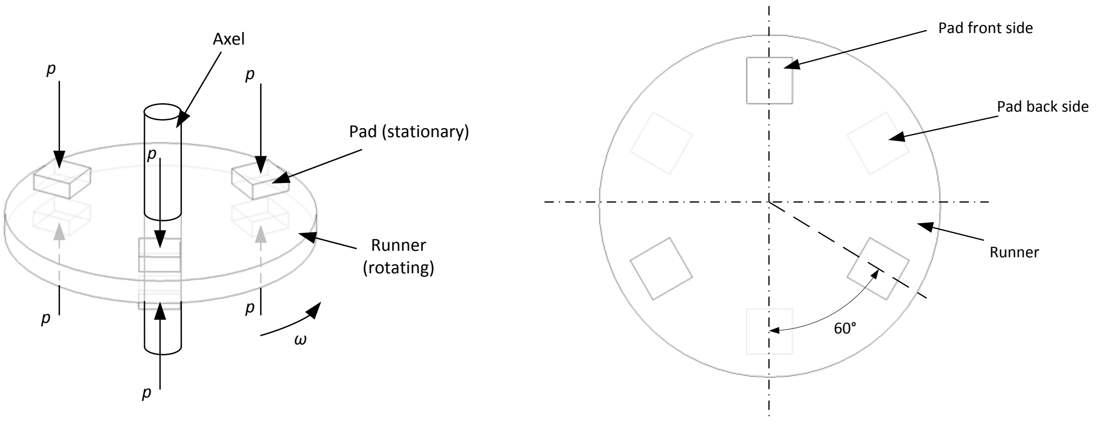


Figure 5 CAD sketch of DFTR

The test disc consists of three parts, an upper and lower disc with lined white metal on the outer and a middle disc which is used to assemble the set of discs, see CAD sketch of DFTR - Figure 5. The design allows for two tests with almost the same environment to be tested at the same time. The pressure pads can be shifted 60° in comparison to each other to induce bending stresses in the test disc to replicate the effect of bending stress in backing and coating materials of journal bearings. The amount of bending stress is controlled by changing the thickness of the centre disc. The principle of applying bending stresses to the runner is shown in Figure 6.



a) b)

Figure 6. Principal sketch. a) Pads placed on top of each other, b) Pads (viewed from the top) shifted 60° in relation to each other to induce bending moment.

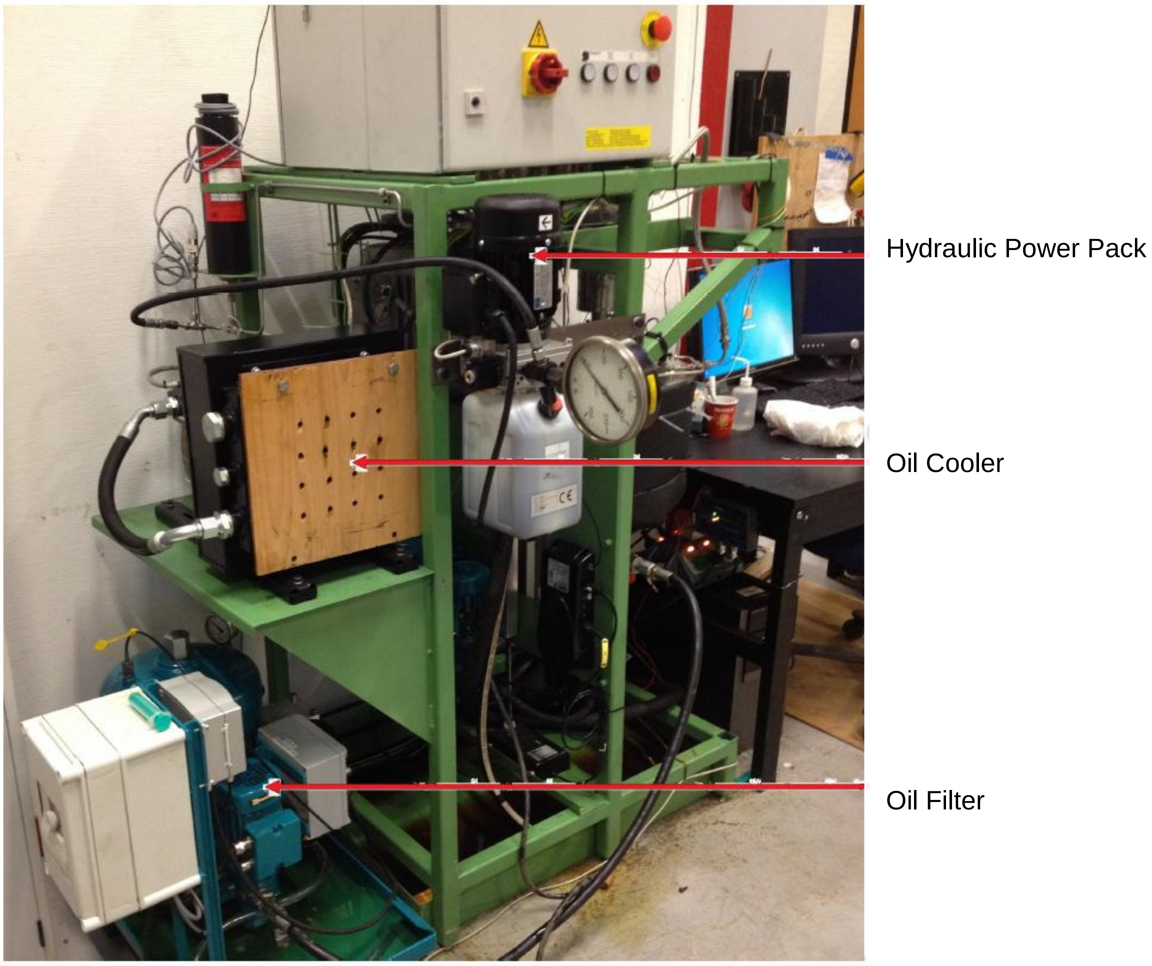


Figure 7 Image of DFTR – Status 2013

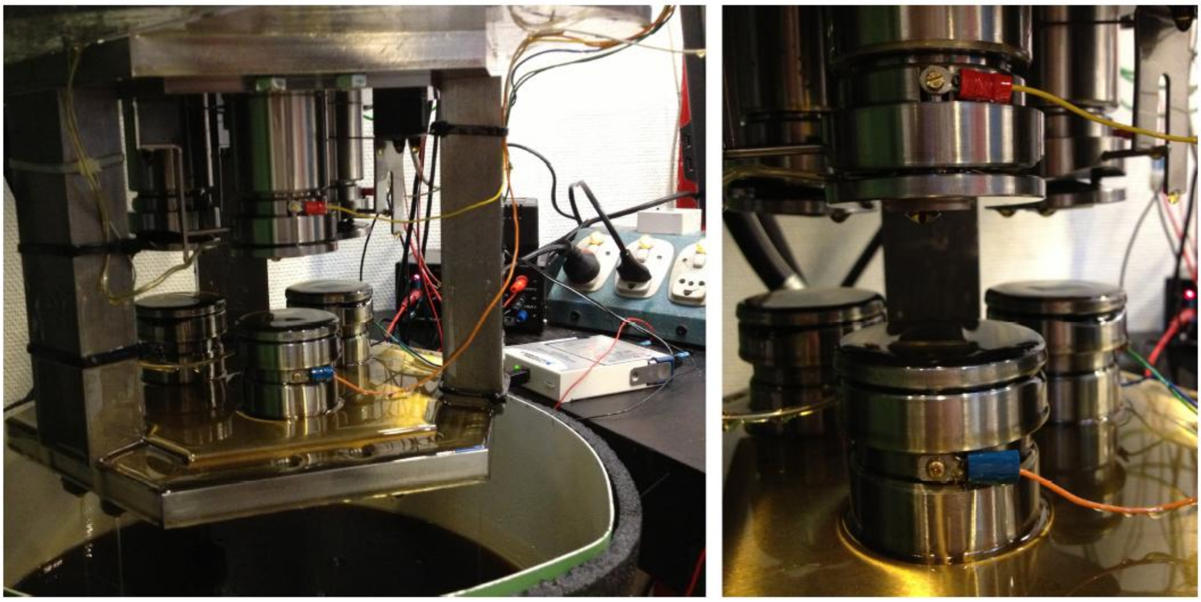


Figure 8: Hexagon. The pads with wires for the ERM-system can be seen

The ideas were converted to a physical setup and the result after a few iterations is shown in Figure 7 -Figure 8.The pictures show the frame in which the test piece is installed - Figure 7 and a close-up of the test piece itself in Figure 8

1.1 Loading System

The pads are pressed against the test specimen (the white metal disc) using a hydraulic piston. The hydraulic pressure acting on the upper tilting-pad is delivered by a computer controlled power pack. The hydraulic pressure (force) acting via the upper pads on the runner is absorbed in the lower pads and thereby ensuring that the forces in the test hexagon are kept internally. The same principle may be seen in the brake system of a car. The advantage in this respect is that the friction forces generated are easy to quantify. An accumulator is attached to the hydraulic system to ensure a stable pressure.

1.2 Disc driving unit

The disc rotation is driven by a 4 kW electric motor, which is controlled by a frequency converter. A timing belt connects the electric motor with the test disc setting the maximum rotation speed of the disc to 2000 rpm. Experience shows that higher speed may cause problem with oil whipping/splash. With 2000 rpm a 10 million cycle fatigue test can be done within 28 hours.

1.3 Cooling system

A frequency controlled cooling system is utilized together with PID controller to keep a constant oil temperature during the test. During the initial tests the cooling system has proven to be slightly over dimensioned, the problem is fixed with an air restrictor.

1.4 Oil filter

To be able to keep the oil clean a fine off-line particle filter with a capacity of 120l/h is connected. This ensures that the initial amount of particles in the oil can be kept at a the same level for all experiments.

1.5 Temperature

The temperature is one of the most influential factors in the test rig, both the oil viscosity and the fatigue properties of the bearing material are influenced by the temperature. The temperature is measured in the oil bath and in one of the bearing pads. The lining temperature can be estimated from the temperature in the bearing pad surface and the oil bath temperature – see Figure 9 -

Figure 10.

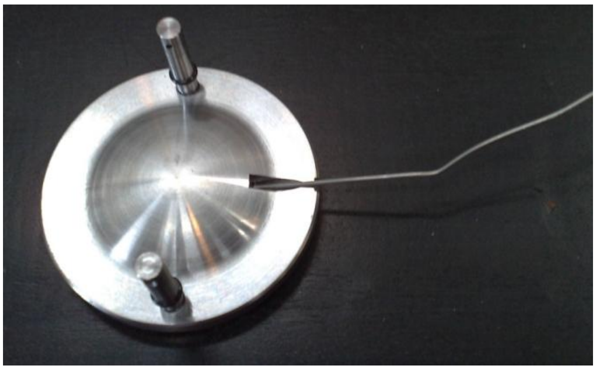


Figure 9. Temperature hole in pad with thermocouple inserted

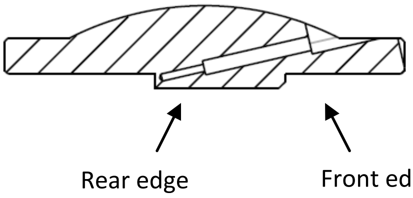


Figure 10. Graphic illustration of thermocouple holes placement

1.6 Friction force

The accumulated friction force of all six tilting-pads is measured with a force transducer. The force transducer measures the necessary retaining force to keep the test hexagon from rotating. The friction force may together with a distance measure and a speed measure give an idea of the power loss in the bearing arrangement. See Figure 11.

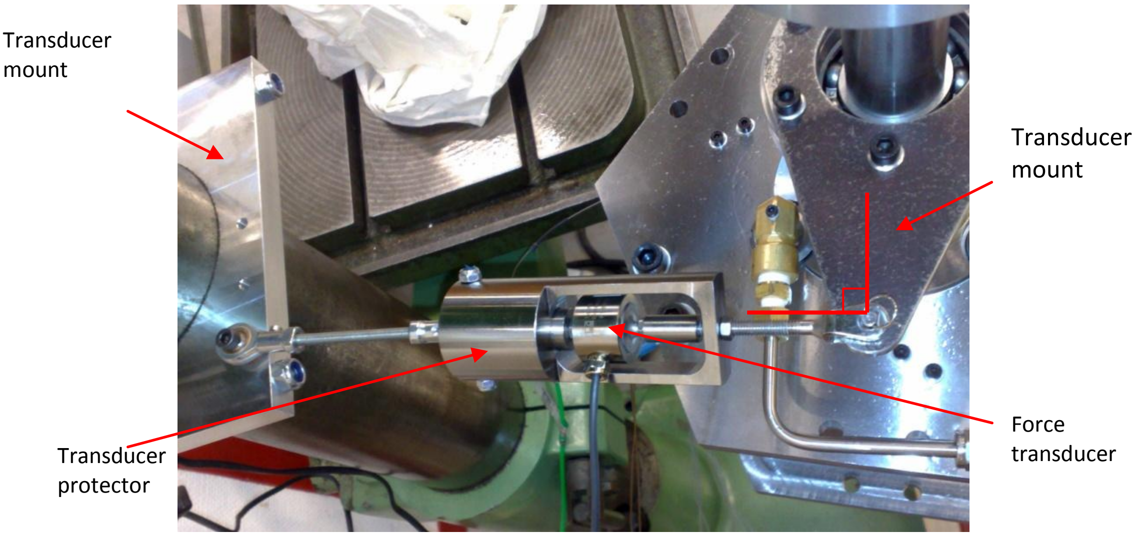


Figure 11. Force transducer installed on the test-rig

1.7 Electrical resistance contact measurement

The individual tilting pad is electrically isolated from the test-rig to allow for contact measurement between disc and each of the tilting pads. The tilting pads are isolated with ceramic washers thus enabling monitoring of the running condition. The electrical contact between disc and pad may be established by particles entering the gap and/or by direct contact between runner and pad.

1.8 Oil contamination monitor

An offline oil contamination monitor is measuring the number of particles entering the oil filter according to ISO – 4406:1999 with a sampling interval of 20 seconds. The level of particles in the oil is an indicator for the wear situation of the white metal discs.

5. Results

The initial tests performed on DFTR intend to validate the hydrodynamic full film lubrication and repeatability. The fluid film lubrication regime has been validated in several different experiments listed below.

1.9 Stribeck

To achieve realistic conditions for fatigue evaluation the hydrodynamic condition must be validated. Before each test a Stribeck curve is created by either changing the speed of rotation or the bearing load. The measured data can then be used to validate that the test parameters lies on the increasing part of the Stribeck curve – see Figure 12. The area of interest is situated in the right part curve – (to the right of D).

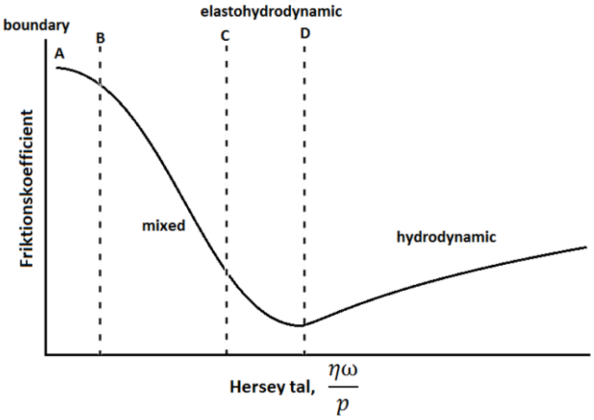


Figure 12: Stribeck Curve

1.10 Repeatability

A step test where either the bearing force or the rotation speed has been changed in steps up and down has been performed to validate that same results is obtained with the same test conditions. The test has shown good repeatability – see Figure 13.

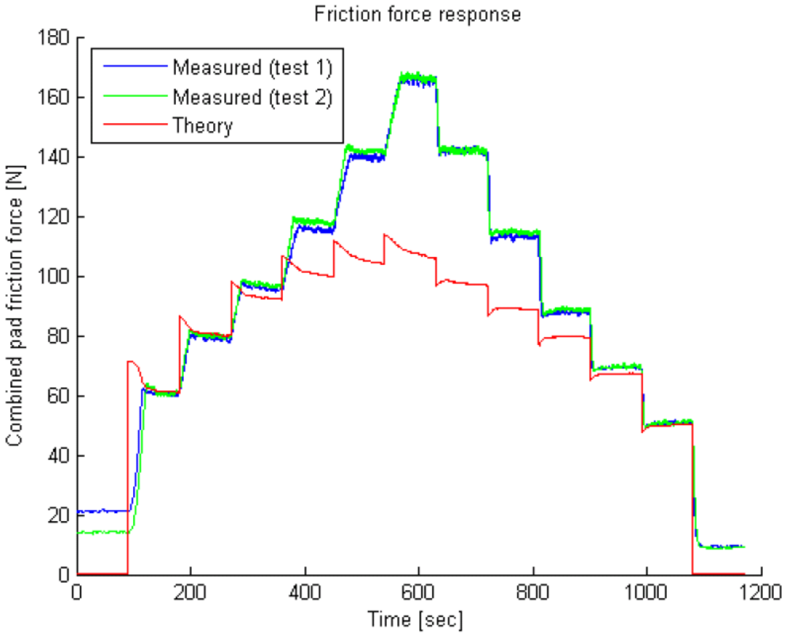


Figure 13: Friction Force versus Time. The friction force shows the same behaviour between different experiments and also between different load cycles. The load was ramped up every 90-100s until the max load was applied after 600 sec. Following that the load was reduced in steps until the load was fully removed.

1.11 Oil contamination

The oil was filtered during the experiment and the level of particles was monitored during the experiment – see Figure 14. The oil contamination monitoring system has in some cases proved to be a good indicator of crack detection – see Figure 15. But in some of the experiments no apparent increase of particles could be seen although initiation and build-up of fatigue cracks was ongoing.

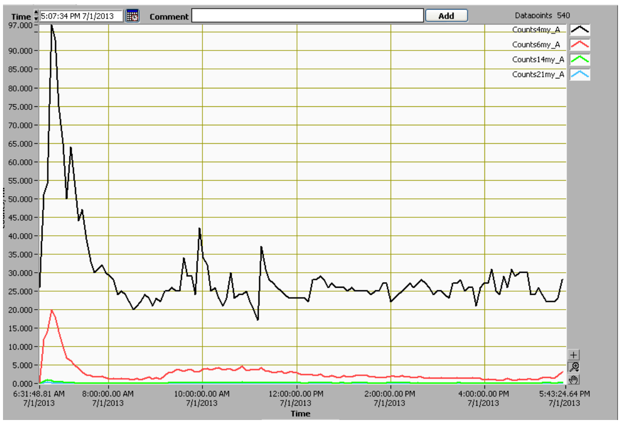

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Figure 14 Oil contamination during startup. The figure shows that at the initiation of each experiment a lot of particles are present in the system which need removal, hence a certain start-up sequence is initiated before each experiment.

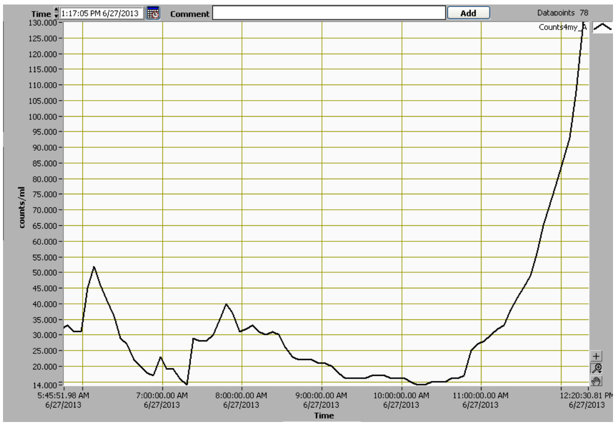
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Figure 15 Oil contamination of 4 µm particles suddenly increased. When the experiment was stopped a crack was detected by visual inspection.

1.12 Electric Resistance Measurement (ERM)

The ERM method was evaluated by adding scratches on a test disc to simulate fatigue cracks. The scratches results in puncturing of the oil film pressure build up and hence contact between tilting-pad and disc as a result. Due to the low oil film thickness with the specific load of 300 bar the particles in oil also results in contact. In Figure 16 a damaged disc, two momentarily polar plots of the contact voltage and the accumulated contact intensity is shown. For detection of cracks it is intended to use some sort of moving average for the accumulated intensity plot where contact due to particles are filtered.

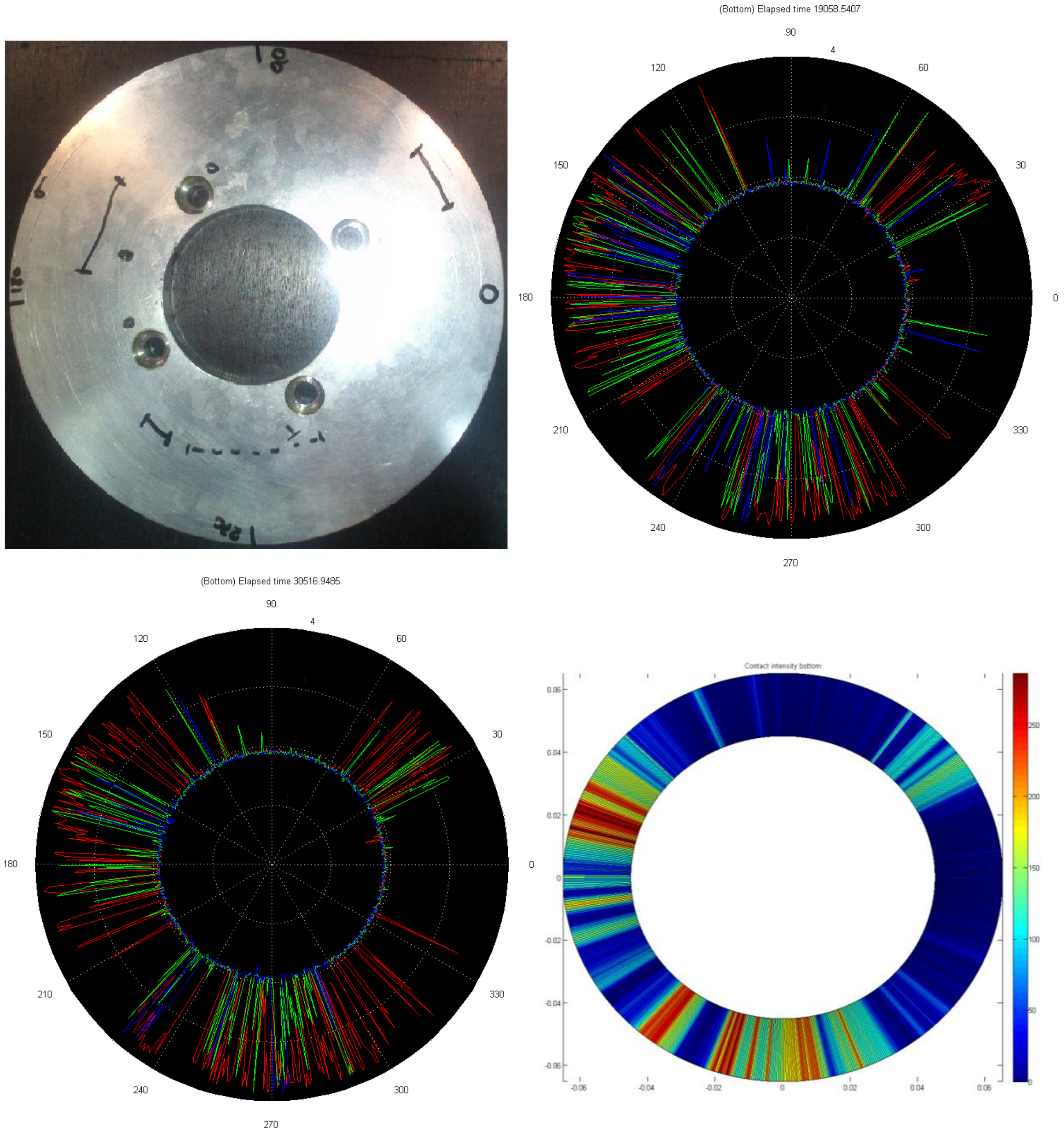

Figure 16 ERM experiment with damaged disc. Upper left: The Markings shows where damages are observed applied. Upper right: Contact during one revolution after 5.3 hours. Lower left: Contact during one revolution after 8.5 hours. Lower right: Accumulated contacts during test.

1.13 Fatigue Damages

The initial test after the verification was completed showed that the specification of the DFTR was adequate for establishing fatigue damages in the produced white metal discs – Figure 17. The picture shows markings of individual areas where cracks have been observed.

Figure 17 : Disc With Fatigue Damages

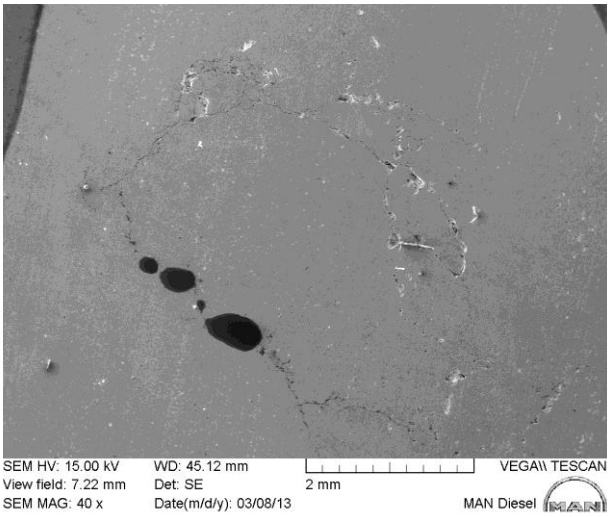

Figure 18: SEM-image of Fatigue Crack

These cracks were further examined using a scanning electron microscope (SEM). An example of this may be seen in Figure 18. The cracks are similar in appearance to the cracks typically found in conventional bearings for large two-stroke marine diesel engines. Figure 18 shows an area where multiple cracks are present and thus very interesting. In many of the cracks observed in real engines the cracks spread out and eventually meet each other. This may lead to areas of islands where the white metal island is fully separated from the main body by cracks and eventually disengages from the rest of the structure thus leaving a void – see Figure 19 . The pictures show this tendency of crack evolvement, the pictures originate from an earlier experiment with the DFTR.

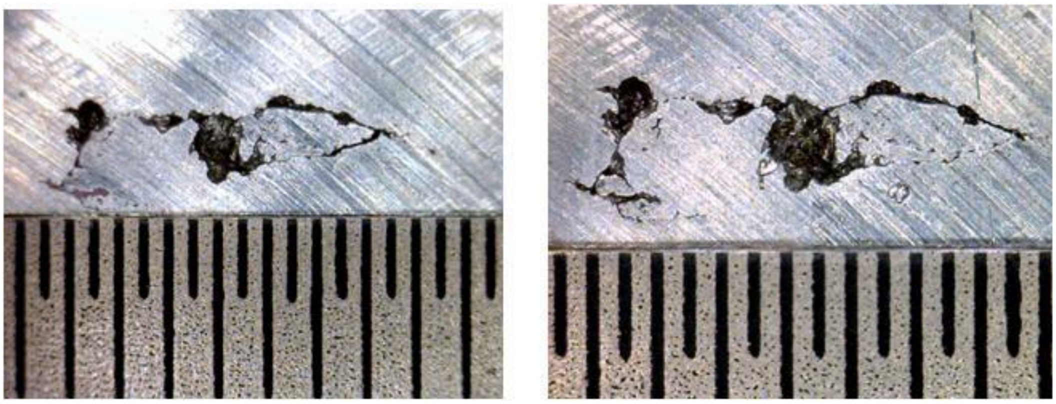

Figure 19: Fatigue Crack after a) 6.1 Mio. Cycles and b) 7.7 Mio. Cycles

Having examined the cracks in Figure 18, a selected part of the disc was cut. The position of the cross section cut can be seen in Figure 20.

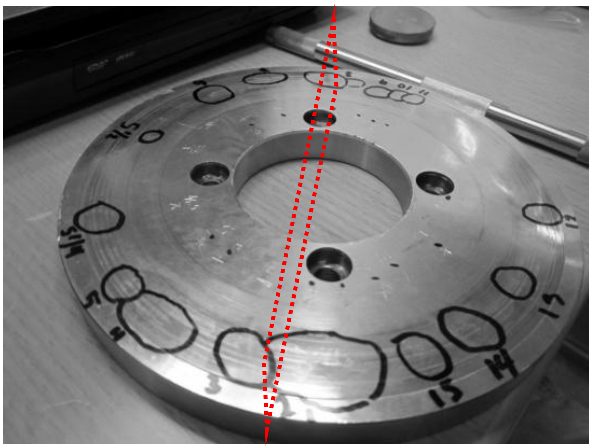

Figure 20: Cutting of Cross-section

Figure 21: Cross-section of Crack

The cut out was grinded and further inspected in the microscope – see Figure 21. The picture shows the running surface as a line in the upper part of the picture, the white metal layer and the base material (steel). As shown in the picture it is obvious that some cracks (originating on the surface) are crossing each other below the surface thus making it possible for white metal particles of significant size to leave the disc. Furthermore it is observed that the cracks tend to change direction once the crack is getting closer to the steel interface. The examination clearly demonstrates the nature of the crack generation and propagation in white metal bearings. Furthermore it is concluded that the DFTR is capable of producing fatigue behaviour of white metal bearing alloys.

6. Future work

Several tests with the DFTR are planned. The tests are grouped in two different groupings very briefly described below.

Find fatigue limit with current design
The fatigue limit of the white metal is to be found and the variance of the result to be established. This requires that several experiments are conducted using the standard white metal bearing design.

Influence of edge fatigue
It is known that fatigue damages on main bearing are most frequent on the bearing edge. This experiment aims to find out if it can be explained by the lack of support on the edge

Monitoring of Crack Initiation and growth
Currently cracks in bearing lining are detected by visual inspection. Previous test has showed that friction force and contact measurement can be used as indicators for cracks. But an online crack detection system would be a great improvement of the test rig.

Oil heating
The rig consists of a number of subsystems that all influences the thermal equilibrium of the rig. Due to this and the relatively large amount of oil in the system it can take several hours to achieve equilibrium in oil temperature. An oil heater will eliminate this problem.

Disc temperature
Precise information about the temperature of the lining is important to be able to evaluate the fatigue properties of a material. Tests will be performed to validate that the tilting-pad temperature can be used to get an accurate estimate of the lining temperature. If this cannot be achieved a wire-less temperature monitoring system on the disc will be installed.

Offline oil filtering and particle counting
The rig is equipped with an offline filtering system with a laser based particle counter. The oil filtering system can operate independently of the ongoing experiment. Before a new experiment is started the oil is filtered to a defined cleanliness according to ISO – 4406:1999. Since oil cleanliness is monitored

continuously a sudden increase in the number of particles in the oil can indicate that a crack is under development. Particles are classified into three groups: 4µm, 8µm and 14µm particles. A typical failure indication is that the number of 4µm particles starts to increase and shortly after also the number of larger particles increases.

7. Discussion

The test rig is still under development and there are still issues that must be addressed. The overall conclusion is however that the rig is capable of producing fatigue damages in white metal bearings. The damages are similar to damages observed in main bearings for large two stroke marine diesel engines. The results have shown to be sensitive to the thickness variation of the discs, and hence the assembled discs must be re-machined after assembly in order to assure even thickness. The ERM results have showed that one of the lower pads tend to be more in contact than the two others which is an issue that needs to be addressed.

8. Acknowledgement

The authors wish to acknowledge the HERCULES-C project for the financial contribution to the current project. HERCULES-C is a part of the 7th framework programme entitled 'Towards zero emission marine engines'.

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