

## Universal Journal Bearing Test Rig Uncertainty and Validation Measurement to Enhance Marine Shafting Performance

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**1. ABSTRACT:** Enhancing the ship power transmission is surely a target sought by all those involved in the marine applications, mainly due to its beneficial results regarding making tangible reduction in fuel oil consumption, consequently considerable reduction in emissions to environment. The oil film lubrication within journal bearings is certainly a key factor in attaining that goal. Besides, journal bearings being essentially intrinsic structures by which numerous experimental tests could successfully be carried out. The first vital step in the uninterrupted series of the research efforts at hand has been to design and construct a journal bearing

test rig (JBTR) characterized by sufficient validity for embracing all aspired experiments. Additionally, following the construction of the test rig, there emerged the need to realize the second step which mainly focused on enhancing and promoting the range and capabilities of the journal bearing, which ultimately turned it into a universal journal bearing test rig (UJBTR). Such step has granted the structure the ability to embrace even more sophisticated and much wider range of experiments. Further, one of the main consequences resulting from conducting versatile experiments and tests are the inevitable errors, or rather more precisely the uncertainties. Conducting such essential tests would entail making measurements, which in turn would incur necessary uncertainties. Consequently, there arose the need to introduce the current paper presenting a thorough investigation relating to the uncertainty measurement with view to better identifying the nature of such errors, with view to keeping them to a minimum and trying to overcome their hazardous consequences in as far as the experimentation procedures and outcomes are related

**Keywords:** *Universal Journal Bearing Test Rig (UJBTR), hydrodynamic lubrication, pressure sensors, uncertainty measurement, validity.*

## 2. INTRODUCTION

To start with, the term (error analysis), also known as the experimental uncertainty, is a technical term that is often referred to when it comes to the issues related to the study and evaluation of uncertainty in measurements. No measurements can be completely free of uncertainties. Also, being mainly dependent on measurements, the whole structure and application of science can never do without a precise evaluation of these uncertainties with view to keeping them to a minimum. More important still, in science the word "error" doesn't essentially carry the usual connotations of mistake or blunder. The term "error" is always utilized to indicate the inevitable uncertainties necessarily existing in all measurements. It cannot be avoided via careful procedures, and the best thing to be done is to try to ensure that the experimental errors are as small as reasonably possible in all measurements. There are basically two types of errors, either of which can occur during scientific experimentation and accompanying measurements. The first is "Random Errors" which can be treated statistically and may be revealed through repeating the measurements. In such case, the measurement results are either overestimated or underestimated and the only possible solution for attaining reliable estimates of such random errors could be via the spread in results statistically. On the other hand, the other type of error is the systematic error, where the results of measurements always push in the same direction. Such systematic errors are hard to evaluate or detect. Further, they cannot be discovered by statistical analysis used in identifying random errors.

Again, real measurement devices always suffer from different kinds of imperfections which negatively affect and limit our knowledge of the true value of any measurement. Such deficiencies mean that the exact value of any measured quantity will always be uncertain. Consequently, uncertainty can be deemed to be an unavoidable part of the measurement process. It is just sought to reduce measurement uncertainty whenever possible. However, ultimately there will remain some basic uncertainty that cannot be removed. The main task is to estimate thoughtfully the size of the uncertainty and clearly communicate the result. Further, quantifying uncertainty could be accessible via defining a value's uncertainty in terms of the range focused on our measured value within which we are

95% sure that the true value would be found in case measurement is carried out perfectly. This means that we expect that there is but one chance in 20 that the true value doesn't lie within the specified range. This range is called the 95% confidence interval or 95% confidence interval. Also, this conventional method of determining this range is to state the measurement value plus or minus a specific number. Here, the uncertainty would have a magnitude that is equal to the variation between the measured value and either extreme edge of the uncertainty range. Hence, uncertainty is definitely an uncertain concept which represents rough estimates. Notwithstanding, knowing the uncertainty of a measured value is essential, if the meaning of a measured value is to be correctly interpreted.

A study by (Wale and Mba, 2005), was focused on highlighting sources of error for experimental journal bearing studies. Also, it presented a coherent source of information on best practice in the field of experimental bearing research, offering a clearly prescribed methodology to estimate uncertainty and reduce errors. Additionally, it was shown that hidden errors would well account for the widely reported scatter and variance of results in the experimental bearing studies. One suggested solution was the better dissemination of information on best practice, and more widespread adoption of quality systems.

The year of 2007 has witnessed an attempt by (Wale and Mba 2007), for the sake of presenting results from a design study for a new journal bearing test rig aiming at setting new standards of accuracy. Sources of errors such as those related to the measurement system and build errors were involved in the study. Also, the study introduced a numerical assessment of the sensitivity to errors in selected experimental configurations. It was found that significantly lower uncertainty in the dynamic coefficients could be obtained by excitation at (00, 900). Moreover, the simulation has given a guide to the required accuracy in the measurements and in the build accuracy.

Additionally, it is quite known that one of the most crucial parameters in the precise determination of the quality of results quantitatively is the stability of the pressure measuring instruments over the years. It helps the user to decide the optimum calibration interval of the particular

instrument. Based on the fact, a number of analogue / digital pressure transducers / transmitters / calibrators and pressure dial gauges have been investigated by (Yadav, Gupta, and Bandyopadhyay, 2010). Utilizing several pressure dial gauges and transducers in the pressure range up to 500 MPa, a new approach for the establishment of measurement uncertainty has been established. Further, using more than 50 pressure dial gauges and transducers, a nova approach was proposed for the estimation of measurement uncertainty of such devices. Also, the study has ascertained that curve fitting could be utilized regarding the establishment of different pressure instruments.

It was in the year of 2012 that I. Farrance and R. Frenkel (Farrance and Frenkel, 2012), launched a beneficial study, aiming at providing the general rules concerned with the evaluation and expression of uncertainty in measurement. Additionally, the research has outlined the method by which the general equation for combining uncertainty components could be used and also how it could be applied regarding versatile relationships for the sake of deriving a combined standard uncertainty for the output value related to the particular function.

A research carried out by (Taylor, 2012), has mainly been concerned with illustrating two methodologies for establishing measurement uncertainty for a family of digital pressure transducers by means of calibration data. Besides, a use has been made of the lumped method, assuming calibration data at each level to be statistically independent while lumping all errors together into a single propulsion disregarding pressure level. Also, defining propulsion parameters which were the basis for measurement uncertainty has been accessible via utilizing statistics. The study has ascertained the possibility of increasing the calibration interval via separating the facility pressure measurement into high-accuracy as well as low-accuracy requirements. Also, the study has recommended reviewing the measurement uncertainty requirements regarding each pressure that was being measured, utilizing this family of digital transducers.

Noteworthy that the factors affecting the measured signals would incur effects such as signal drift and response time changes, entailing techniques to distinguish between signal changes from plant or subsystem performance deviations and those from

sensor or instrumentation issues. One important study carried out by (P Ramuhalli, G Lin, SL Crawford, 2014), has comprised isolating the sensor from the system applying an artificial load and recording the result, as well as comparing the obtained result with the recorded one. Based on the conducted study, simulation models of a flow loop with a counter-flow heat exchanger were found to help generate data from the simulation model, representing conditions the experimental flow loop might not be able to achieve.

In addition to that, a research work was carried out by (Gralde, 2014), aiming at realizing and evaluating a start-stop journal bearing test rig. It also involved manufacturing, building and evaluating of a start-stop journal bearing test rig. Further, it comprised developing software for the test rig. Also, factorial design was utilized and compared to a simple theoretical model. The test rig has been realized and evaluation showed good correspondence to frictional values at starting of similar material combinations. The test-rigs concept has been proven to work.

It was in the year of 2017, that an attempt has been made by (Blomstedt, 2017), to create measure and control system for test parameters of tribological values, and also to validate those results from results of validation tests conclusions. It was shown that different measured values represented bearing operational conditions. Also, the study involved investigating previous measurements system and other similar systems in engine testing environments. The study has also comprised performing and presenting measurements, as well as calibration of the system. A new measurement and control system for bearing test rig was developed and built to get more accurate results.

(Schiering and Schnelle-Werner, 2019), have launched a beneficial study in 2019, which aimed at evaluating uncertainty in industrial pressure measurement. They presented the approach in which the measurement uncertainty could be calculated in industrial pressure measurements. The study has clearly shown the importance of introducing an example of a measurement uncertainty budget, as being an important tool in the measurement uncertainty calculation. In addition to that, the study assured the need to include factors like the calibration procedure, the ambient conditions, and the

calibration procedure in the process of measurement of uncertainty determination.

(Barsanti, Ciulli, and Forte, 2019), have carried out an analysis with view to determining the dynamic coefficients of Tilting Pad journal bearings via a new statistical method. The most significant result of the study was obtaining the random uncertainties associated to each stiffness or damping coefficient. Also, the dynamic coefficient was found to be dependent on the excitation frequency. Besides, the study has presented random error propagation as well as uncertainty analysis, which could help determine the dynamic coefficients of Tilting Pad journal bearings.

(Garoli and Castro, 2019), conducted an analysis of a rotor-bearing nonlinear system model, considering fluid-induced instability and uncertainties in bearings. Besides, the study could account for the uncertainties of radial clearance and fluid lubricant viscosity in the journal bearing. Also, the study could prove the possibility of modeling the stochastic dynamic response of a rotor-bearing system through applying stochastic collocation within generalized polynomial chaos expansion.

Aiming at modeling the kinetic friction coefficient and determining its uncertainty, (Vale and Silva, 2020), have presented a detailed assessment of a tribometer developed for dry journal bearing tests. More important still, the study involved modeling of kinetic friction coefficient, as well as uncertainty measurement evaluation for a journal bearing test apparatus. Based on the conducted study, it was found out that the load cell uncertainty varied over the tribometer's operating range. Furthermore, the last digit fluctuation error was also found to dominate the behavior pertaining to the load cell total standard uncertainty.

### **UJBTR DESIGN AND MANUFACTURE**

In fact, the design and manufacture procedures have comprised numerous research programs that aimed at ultimately introducing a structure that is quite capable of embracing a wide range of enhanced and sophisticated experiments and that is also characterized by the highest possible degree of validity. Such efforts have initially been oriented towards launching a study entitled "Journal Bearing Performance – State of The Art" (Marey et al. 2021), aiming at tracing and examining all

the critical and influential factors affecting the journal bearing. Furthermore, the research scope has been extended to achieve the second step focused on accomplishing the crucial calculation processes related to the design requirements of acquiring a UJBTR. Also, each step in the stages of planning, manufacture and assembly has been conducted with special care given to a number of considerations comprising the design material stresses, manufacturing standards and also the assembly risk assessment criteria. More important still, one of the foremost qualities marking the structure has been the inclusion of fully controlled and monitored systems, facilitating the process of obtaining versatile readings and graphs via SCADA system, and hence controlling of all the factors influencing the lubrication film. Noteworthy that the research program concerned with the previously mentioned UJBTR is currently under publishing, coming under the title "Development of A Universal Journal Bearing Test Rig (UJBTR) and Experimental Setup for Oil Film Lubrication Enhancement Regarding Marine Applications".

For better illustration of the comprehensive research efforts conducted, the following (Figures from 1 to 7) would best represent the whole UJBTR structure comprising firstly the shafting system, which in turn involves the drive shaft, the journal shaft, the main journal bearing, the supporting journal bearings and the thrust bearing. Also, the UJBTR comprises the lubricating oil system which consists of the lubricating oil pump unit, the filters, the lubricating oil cooler, the regulator valves, the pressure gauges and transmitters, the thermocouples and the oil hoses. Besides, the structure contains the hydraulic oil system comprising the hydraulic power pack unit, filters, two hydraulic pistons, hydraulic hoses, proximity sensors and pressure gauges and transmitters. Finally, for guaranteeing the perfect performance of all the previously outlined components, the UJBTR is marked by comprising a fully control system which ensures all procedures and experiments are accurately and efficiently manipulated and void of any sort of error. Such control system comprises a number of three control panels. The first one is concerned with the full control of the hydraulic oil system, the second ensures full control regarding the lubricating oil system, whereas the third and last one works on fully monitoring, controlling and manipulating the whole UJBTR structure via the advanced and highly

precise SCADA control system. Noteworthy that the following figures would best illustrate the detailed components involved in each individual system regarding the whole UJBTR structure.

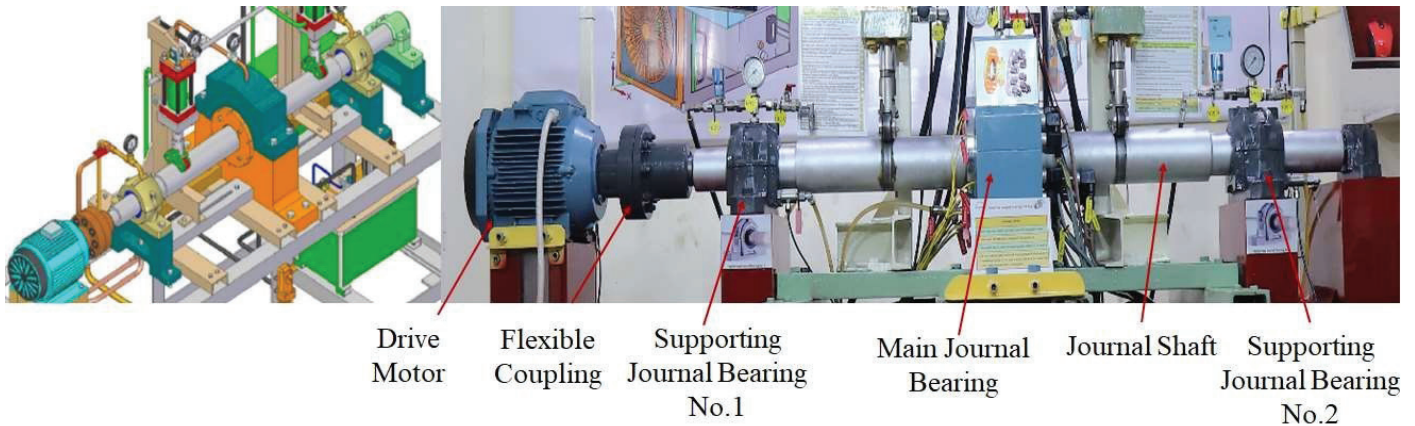


Figure 1. The shafting system of UJBTR

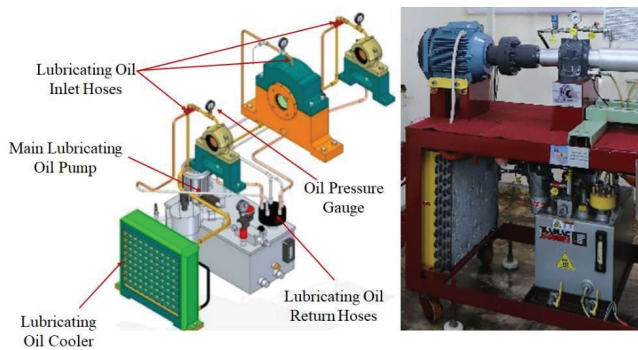


Figure 2. Main lubrication oil system

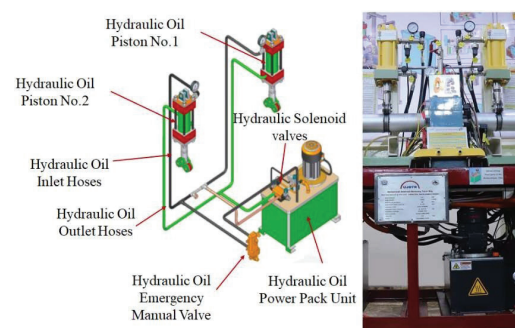


Figure 3. The hydraulic oil system



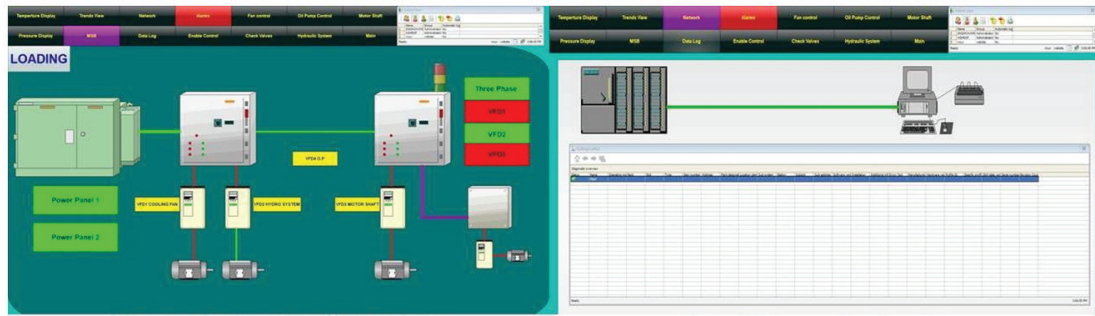
Figure 4. The first control panel contents



Figure 5. The second control panel contents

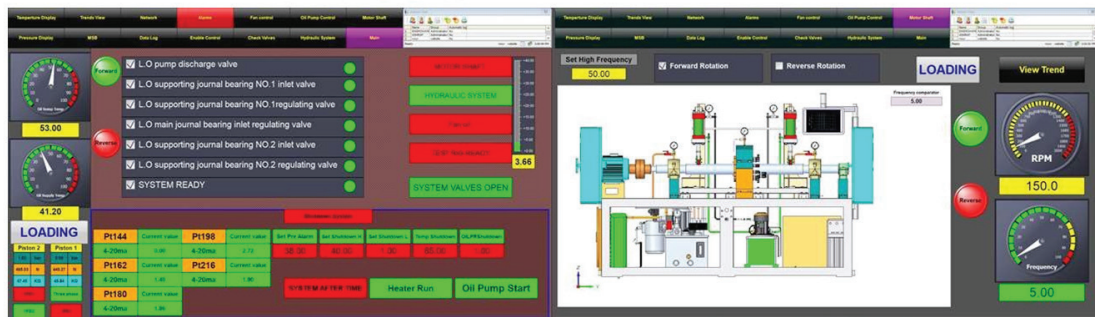


Figure 6. The third control panel contents



Main Switch Board (MSB) Display Page

Network Communication Status



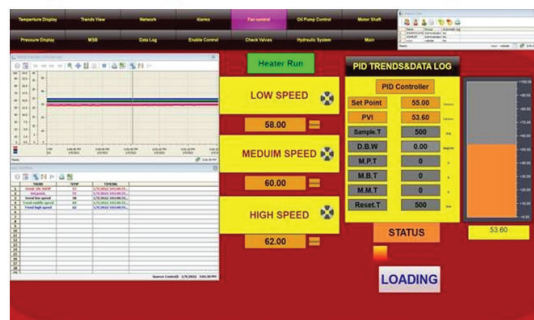
Main Page of SCADA System

Motor Shaft Display Page



Main Lubricating Oil Pump Control Page

Monitoring of UJBTR Valves Display Page



Lubricating Oil Cooling Fan Control Page



Oil Film Pressure Distribution Display Page

Oil Film Temperature Distribution Display Page

Figure 7. The SCADA system

## EXPERIMENTAL UJBTR UNCERTAINTY AND VALIDATION CALCULATIONS

It was for the sake of identifying and assessing the uncertainty and also for carrying out the validation processes that the UJBTR has been operated, based on and in accordance with the operation checklist related to the UJBTR. Closely observing such procedures would ensure the accurate operation of the UJBTR that is void of defects, that may otherwise result from human error. Figure 8 would outline the operation checklist.

| Universal Journal Bearing Test Rig                                                                                                                                                                                                                                                  |                                                                                     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Start of the UJBTR Checklist                                                                                                                                                                                                                                                        |                                                                                     |
| <b>Important: To ensure a safe and reliable operation of the UJBTR, all operation procedures of the UJBTR should be carried out only by skilled personnel.</b>                                                                                                                      |                                                                                     |
| Making sure that the power is properly connected via (3 phase 380 V, single phase 220 V and frequency 50Hz). Also, all of the referred to indications ought to be checked to appear on the multimeter, and it is necessary to make sure the lights of the L1, L2 and L3 are all on. |    |
| Ensuring the power switch regarding the first control panel is connected                                                                                                                                                                                                            |    |
| The source power switch related to the second control panel ought also to be selected.                                                                                                                                                                                              |    |
| Further, the connection of the power related to the second control panel should be checked where the lights of L1, L2 and L3 should all to be on.                                                                                                                                   |    |
| The next step would be switching on the computer and waiting for the SCADA program to be downloaded.                                                                                                                                                                                |   |
| Following the download of the SCADA program, it is necessary to turn the PLC operation switch from the stop mode to the run mode and then wait for the PLC run mode to occur.                                                                                                       |  |
| After that, the Manual /Auto mode ought to be selected.                                                                                                                                                                                                                             |  |
| The lubricating oil pump switch would be selected.                                                                                                                                                                                                                                  |  |
| Logging on the check valve page in the SCADA system, where all lubricating oil system valves that were opened would be selected.                                                                                                                                                    |  |
| The oil pump page would then be chosen, where the start pump icon would be selected and the value pertaining to the lubricating oil pump frequency would be appointed.                                                                                                              |  |
| All pressure transmitter and temperature sensor pages ought to be checked for the sake of ensuring that all sensors are properly working.                                                                                                                                           |  |
| A set point regarding the oil supply temperature in the fan control page ought to be appointed, where the cooling values of the cooling fan would be added as (Low speed, Medium speed and High speed).                                                                             |  |
| Regarding the operation of the drive shaft, a number of procedures ought to be observed and they would comprise (selecting the rotation direction of the shaft via the local control switch provided with an indication lamp and located on the second control panel).              |  |
| Heading for the motor shaft page, where both the username and the password would be determined for the sake of selecting the rotation direction i.e. forward or reverse.                                                                                                            |  |
| Utilizing the potentiometer located on the second control panel, the shaft rpm would be appointed.                                                                                                                                                                                  |  |
| The hydraulic oil pump would be operated via a control switch located on the first control panel, where the operation condition would be checked via an indication led.                                                                                                             |  |
| Ensuring the oil discharge pressure value concerning the oil hydraulic pump is within the required range, via the hydraulic system page within the SCADA system.                                                                                                                    |  |
| For manipulating the hydraulic pistons, two push buttons (Up / Down) would be utilized with the function of determining the loading and whether it is a loading or unloading mode.                                                                                                  |  |
| Utilizing the alarm page in the SCADA system, the condition of the UJBTR would be checked regarding whether it is normal or abnormal.                                                                                                                                               |  |

Figure 8. The operation procedure checklist

In addition to that, the UJBTR has been operated according to the operation parameters elaborately illustrated below.

### Experimental parameters

The bearing performance characteristics were obtained through the following parameters:

1. Constant load at 100 kgf.
2. Journal speed variation from 25 rpm to 200 rpm.
3. Lubricant used (shell helix HX8 ECT 5W-40).
4. Type of bearing (Circumferential groove journal bearing).
5. Material for bearing (White metal).

Further, in order that the uncertainty concerning the UJBTR could be measured, the UJBTR has been operated for each individual speed limit five times for the sake of obtaining the readings related to the pressure transmitters pertaining to the oil film pressure distribution within journal bearing. The following illustrations would best represent the detailed methods by which the uncertainty value would be precisely determined and calculated:

Firstly, the journal bearing test rig would be operated, utilizing a number of fourteen sensors circumferentially distributed around the groove journal bearing. The main objective would be to better identify the oil film pressure distribution within the groove journal bearing. Additionally, the measurement readings recorded regarding each individual sensor would be taken five times.

The next step would be to obtain the average value  $\bar{x}$  of the recorded five readings related to each of the fourteen pressure transmitters individually via the following equation:

$$\bar{X} = \frac{\text{Measured Values}}{\text{Number of Values}}$$

The following step would be focused on obtaining the deviation  $d_i$ , by means of obtaining the difference between the measured value  $X_i$  and the average value  $\bar{X}$  as shown below:

$$d_i = X_i - \bar{X}$$

The step to follow would involve acquiring the standard deviation estimate. The importance of such measurement would be to avoid the fluctuations that would otherwise be encountered regarding the average deviations  $d_i$ . In other words, it is a technique utilized to avoid being at loss regarding various positive and negative values. Standard deviation would be estimated based on the following equation:

$$\sigma_x = \sqrt{\frac{1}{n} \sum_{i=1}^n (d_i)^2}$$

It is in this way that the average uncertainty estimate would accurately be identified.

Finally, for the sake of appointing the standard error value or the uncertainty of the means, the following equation would be done:

$$SE = \frac{\sigma}{\sqrt{n}}$$

## UNCERTAINTY OF UJBTR

### Experimental procedures

The UJBTR has been operated according to the operation checklist instructions previously pointed out. Additionally, a routine check has been carried out regarding the UJBTR so as to carry out and ensure the following:

1. There is no abnormal noise.
2. There is no abnormal vibration.
3. There is no oil leakage of any sort.
4. There are no activated alarms which is assured via the alarm system page.
5. Adjusting the oil film supply temperature at 40 OC.
6. Setting the journal shaft speed at 25 rpm.
7. Recording the readings related to the oil film pressure distribution within journal bearing under a constant load of 100 kgf via the SCADA system.

Stoppage of that case in accordance with the stop checklist procedure, then operating once again under the same case outlined before for four additional times, this makes the number of trials reach five times in all. Noteworthy that all the experimental trials have been carried out under the different speeds of 50 rpm, 75 rpm, 100 rpm, 125 rpm, 150 rpm, 175 rpm and 200 rpm respectively.

The derived results were the basis for extracting the outcomes of uncertainty calculations. Those calculations were related to the average values, the measured values, the deviation values, the standard deviation values and finally the standard error values. Next to that, a relation has been created between the journal shaft speed and the average value of the fourteen pressure sensors, circumferentially distributed around the groove journal bearing.

Such relation is shown by (Figure 9), representing the variations recorded for the average value of pressure sensors (PS), resulting from changing the journal shaft revolution. Firstly, the average values of the pressure sensors taken at PS4, PS5 and PS6 are almost constant under all speeds of the journal shaft. On the other hand, the average values of pressure sensors recorded at PS9 and PS12 are noted to increase gradually as increments in shaft speed are made. Besides, the average value of the pressure sensor PS9 has reached a peak at 200 rpm shaft speed representing the highest value regarding all recoded pressure sensor measurements. Moreover, the tendency of all pressure sensor values to rise with the increases imposed in shaft speed is regarded as a doubtless indication of the validity of the UJBTR, the result which is in complete accordance with the hydrodynamic lubrication theory.

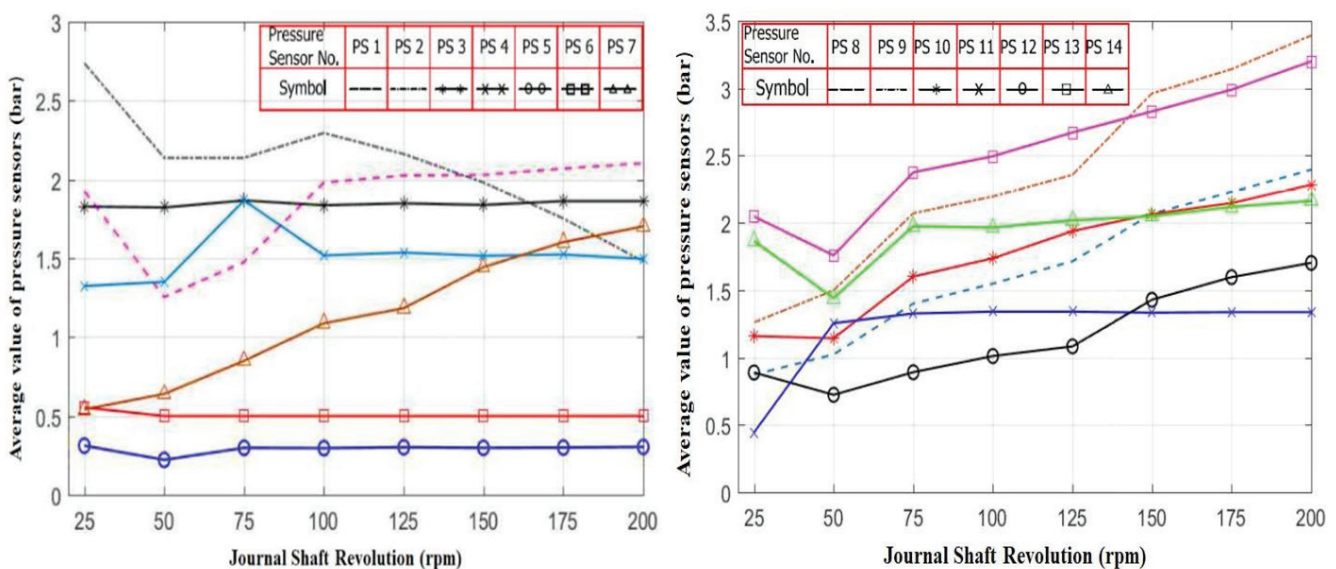


Figure 9. Sensitivity of the average value of pressure sensors to variations in shaft speed

Based on the derived outcomes related to the experimental trials conducted for identifying the uncertainty criteria Table 1, a number of facts concerning both the standard deviation ( $\sigma$ ) and the standard error (SE) may be derived. The minimum standard deviation value has been equal to zero, whereas the maximum has acquired the value of 0.05.

On the other hand, the minimum standard error has obtained the value of 0, while the maximum value has been recorded for PS13 and it was equal to 0.031 at 50

rpm. Also, the measured accuracy value related to the pressure sensors has recorded a value of  $\pm 1.0\%$  of span (WIKA, 2021). The derived results represent a certified and doubtless indication that the uncertainty regarding the conducted experimental trials has been kept to as much minimum degree as possible, the fact which also ascertains the efficiency and accuracy of experimental procedures related to the UJBTR. Additionally, Table 1 shows values of the standard deviation and the standard error attained from the data provided by the fourteen pressure sensors working under different speeds.

**Table 1. Values of standard deviation and standard error under different speeds**

| Press Sens No. | Speed (rpm) | $\sigma$ | SE    | Press Sens No. | Speed (rpm) | $\sigma$ | SE    |
|----------------|-------------|----------|-------|----------------|-------------|----------|-------|
| 1 at 0°        | 25          | 0.02     | 0.009 | 8 at 180°      | 25          | 0.05     | 0.02  |
|                | 50          | 0.01     | 0.004 |                | 50          | 0.05     | 0.02  |
|                | 75          | 0.01     | 0.004 |                | 75          | 0.01     | 0.004 |
|                | 100         | 0.05     | 0.022 |                | 100         | 0.03     | 0.014 |
|                | 125         | 0.02     | 0.008 |                | 125         | 0.05     | 0.02  |
|                | 150         | 0.03     | 0.012 |                | 150         | 0.05     | 0.028 |
|                | 175         | 0.02     | 0.011 |                | 175         | 0.03     | 0.014 |
| 2 at 36°       | 200         | 0.02     | 0.006 |                | 200         | 0.01     | 0.004 |
|                | 25          | 0.02     | 0.007 | 9 at 198°      | 25          | 0.02     | 0.008 |
|                | 50          | 0.05     | 0.023 |                | 50          | 0.05     | 0.009 |
|                | 75          | 0.05     | 0.023 |                | 75          | 0.01     | 0     |
|                | 100         | 0.03     | 0.014 |                | 100         | 0.02     | 0.01  |
|                | 125         | 0.04     | 0.019 |                | 125         | 0.03     | 0.012 |
|                | 150         | 0.03     | 0.012 |                | 150         | 0.02     | 0.01  |
|                | 175         | 0.03     | 0.013 |                | 175         | 0.03     | 0.011 |
| 3 at 72°       | 200         | 0.01     | 0.003 |                | 200         | 0.02     | 0.007 |
|                | 25          | 0.02     | 0.009 | 10 at 216°     | 25          | 0.01     | 0.004 |
|                | 50          | 0.01     | 0.003 |                | 50          | 0.05     | 0.02  |
|                | 75          | 0.02     | 0.008 |                | 75          | 0.02     | 0.01  |
|                | 100         | 0.04     | 0.019 |                | 100         | 0.02     | 0.009 |
|                | 125         | 0.03     | 0.015 |                | 125         | 0.05     | 0.02  |
|                | 150         | 0.02     | 0.011 |                | 150         | 0.01     | 0.006 |
|                | 175         | 0.02     | 0.011 |                | 175         | 0.03     | 0.011 |
| 4 at 108°      | 200         | 0.01     | 0.003 |                | 200         | 0.01     | 0.004 |
|                | 25          | 0.05     | 0.022 | 11 at 234°     | 25          | 0.002    | 0.008 |
|                | 50          | 0.01     | 0.004 |                | 50          | 0.001    | 0.004 |
|                | 75          | 0.01     | 0.003 |                | 75          | 0.014    | 0.014 |
|                | 100         | 0.01     | 0.003 |                | 100         | 0        | 0     |
|                | 125         | 0.03     | 0.012 |                | 125         | 0        | 0     |
|                | 150         | 0.02     | 0.008 |                | 150         | 0.01     | 0.005 |
|                | 175         | 0.01     | 0.002 |                | 175         | 0.01     | 0.004 |
| 5 at 126°      | 200         | 0.03     | 0.015 |                | 200         | 0.01     | 0.004 |
|                | 25          | 0        | 0.002 | 12 at 252°     | 25          | 0.01     | 0.003 |
|                | 50          | 0.01     | 0.005 |                | 50          | 0.03     | 0.014 |
|                | 75          | 0.01     | 0.003 |                | 75          | 0        | 0     |
|                | 100         | 0.01     | 0.002 |                | 100         | 0.02     | 0.007 |
|                | 125         | 0        | 0.002 |                | 125         | 0.01     | 0.004 |
|                | 150         | 0        | 0.002 |                | 150         | 0.02     | 0.007 |
|                | 175         | 0        | 0     |                | 175         | 0.02     | 0.008 |
| 6 at 144°      | 200         | 0.01     | 0.002 |                | 200         | 0.02     | 0.008 |
|                | 25          | 0.02     | 0.009 | 13 at 288°     | 25          | 0.02     | 0.009 |
|                | 50          | 0        | 0     |                | 50          | 0.05     | 0.031 |
|                | 75          | 0        | 0     |                | 75          | 0.02     | 0.006 |
|                | 100         | 0        | 0     |                | 100         | 0.05     | 0.022 |
|                | 125         | 0        | 0     |                | 125         | 0.04     | 0.016 |
|                | 150         | 0        | 0     |                | 150         | 0.02     | 0.011 |
|                | 175         | 0        | 0     |                | 175         | 0.03     | 0.008 |
| 7 at 162°      | 200         | 0        | 0     |                | 200         | 0.03     | 0.014 |
|                | 25          | 0.1      | 0.04  | 14 at 324°     | 25          | 0.01     | 0.006 |
|                | 50          | 0.05     | 0.02  |                | 50          | 0.01     | 0.003 |
|                | 75          | 0.05     | 0.02  |                | 75          | 0.01     | 0.002 |
|                | 100         | 0.03     | 0.015 |                | 100         | 0.05     | 0.024 |
|                | 125         | 0.05     | 0.02  |                | 125         | 0.03     | 0.014 |
|                | 150         | 0.04     | 0.016 |                | 150         | 0.02     | 0.011 |
|                | 175         | 0.02     | 0.009 |                | 175         | 0.01     | 0.003 |
|                | 200         | 0.02     | 0.008 |                | 200         | 0.02     | 0.009 |

## VERIFICATION OF UJBTR RESULTS

### Experimental Procedures

On carrying out an experimental study on the groove journal bearing using the UJBTR under consideration, it is important to check the consistency and validation of its derived results for its potential targets. The material of groove bearing was white metal and the utilized lubricating grade oil was of the type shell helix HX8 ECT 5W-40. It should be observed that the value required in relation to the density was 850 kg/m<sup>3</sup> at 15 OC, whereas the kinematic viscosity was 84.7 cSt at 40 OC. Further, the lubricant was supplied to the groove bearing at an inlet port on the vertical center line of the bearing. Also, it should be noted that the oil film pressure distribution working on the groove journal bearing has been accurately measured and registered at different speeds ranging from 25 rpm up to 200 rpm at a constant

load of 100 kgf. The fourteen pressure transmitters were installed all around the circumference of the main journal bearing, with the aim of indicating the pressure variations occurring in the groove bearing.

The positions at which the pressure transmitters were fitted were carefully chosen according to the theoretical calculation considerations, so as to experimentally reflect the values relating to the pressure distribution within the groove journal bearing. Based on the previously mentioned factors, the oil film pressure distribution working on the UJBTR would be derived as shown in Figure 10, whereas Table (2) represents the technical data obtained experimentally in relation to the maximum- film pressure ratio ( $\frac{P_0}{P_{max}}$ ) at different speeds.

**$P_{max}$**

Noteworthy that while  $P_0$  refers to the terminating oil film pressure,  $P_{max}$  indicates the maximum oil film pressure.

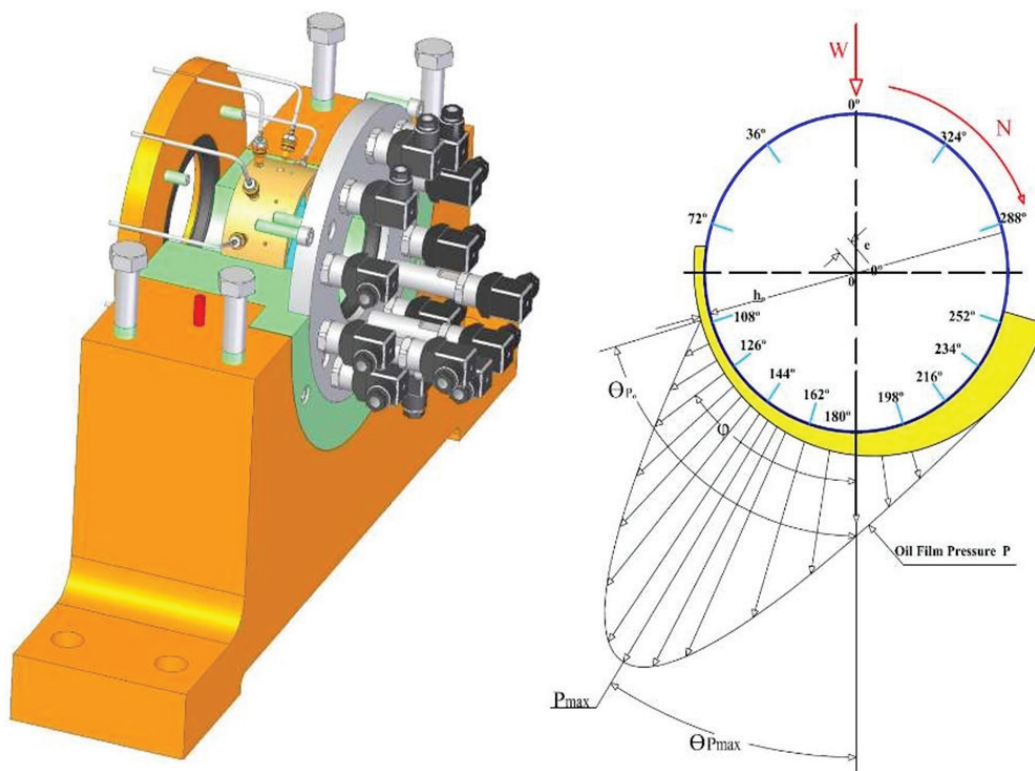


Figure 10. Polar diagram of oil film pressure distribution

**Table 2. Maximum- film pressure ratio (  $P_0$  ) obtained experimentally at different speeds  $P_{max}$**

| Journal shaft Speed (rpm) | Experimental  |
|---------------------------|---------------|
|                           | $P_0/P_{max}$ |
| 25                        | 0.367         |
| 50                        | 0.422         |
| 75                        | 0.429         |
| 100                       | 0.452         |
| 125                       | 0.456         |
| 150                       | 0.470         |
| 175                       | 0.504         |
| 200                       | 0.510         |

**Table 4. Theoretical values of (  $P_0$  ) obtained under various speeds (Shigley et al, 2002)**

| Journal shaft Speed (rpm) | S    | Theoretical $P_0/P_{max}$ |
|---------------------------|------|---------------------------|
| 25                        | 0.24 | 0.327                     |
| 50                        | 0.47 | 0.402                     |
| 75                        | 0.71 | 0.439                     |
| 100                       | 0.95 | 0.46                      |
| 125                       | 1.19 | 0.475                     |
| 150                       | 1.43 | 0.48                      |
| 175                       | 1.67 | 0.498                     |

### Theoretical calculations

|                                                   |             |
|---------------------------------------------------|-------------|
| Bearing length (L)                                | 58.0 mm     |
| Inner diameter for plain bearing ( $\Phi_h = D$ ) | 105.05 mm   |
| Shaft diameter (d)                                | 104.85 mm   |
| The radius for journal shaft (r)                  | 52.425 mm   |
| Total clearance ( $C_0$ )                         | 0.1 mm      |
| Radial clearance (C)                              | 0.05 mm     |
| Applied load                                      | 100 kgf     |
| Oil viscosity ( $\mu$ )                           | 0.0847 Pa.s |

To check the validity of UJBTR results, the following procedures were followed. Calculation of the nominal bearing pressure:

$$P = W/2rL$$

Calculation of the bearing characteristic number (Summerfield number, S) at different speeds ranging from 50 up to 200 rpm is as follows:

$$S = \frac{r^2 \mu N}{c' P}$$

Where  $\mu$ ,  $c$  and  $N$  are the oil viscosity, the radial clearance and the angular velocity respectively. The values of  $N$  are taken from 25 to 200 rpm. The  $L/d$  is equal to approximately 0.55.

Using the charts of "Raimondi and Boyd" (Shigley et al, 2002), the value of the maximum film pressure ratio

(  $p_0$  ) are reproced here for different speeds  $P_{max}$  (see Table 4).

### THE VALIDITY OF UJBTR

UJBTR validity is ascertained through experimental and theoretical values, which are proportionally on the rise, in relation to both the experimental ratio (  $P_0$  ), and that derived theoretically (see Figure 11).  $P_{max}$   
On carrying out a quick scanning of Table 5, it is noted that at 25 rpm, the deviation extent of the (  $P_0$  ) relating  $P_{max}$

to both of the theoretical and the experimental results has assumed the value of - 0.04, representing the highest recorded value related to the deviation. Moreover, the deviation outcomes taken at both 50 and 125 rpm have been observed to be very close to each in value with just marginal variation. Additionally, the deviation extents registered at 75 rpm, 150 rpm and 200 rpm have levelled off, assuming exactly the same values of 0.01, 0.01 and - 0.01 respectively.

Furthermore, the error percentage shown in Table 5 would outline the resulting theoretical and experimental error percentage which was 1.2 at lowest and 12.2 at highest. The error likelihood is thus noted to be very limited, insignificant and obviously very marginal. That would safely account for the validity of the introduced UJBTR. The difference between technical data obtained theoretically and those obtained from experimental study is shown in Table 5.

Table 5. Experimental results Vs Theoretical results

| RPM | Experimental<br>$P_0 / P_{max}$ | Theoretical<br>$P_0 / P_{max}$ | Deviation<br>$P_0 / P_{max}$ | Error<br>% |
|-----|---------------------------------|--------------------------------|------------------------------|------------|
| 25  | 0.367                           | 0.327                          | -0.04                        | 12.2%      |
| 50  | 0.422                           | 0.402                          | -0.02                        | 4.90%      |
| 75  | 0.429                           | 0.439                          | 0.01                         | 2.27%      |
| 100 | 0.452                           | 0.46                           | 0.008                        | 1.74%      |
| 125 | 0.456                           | 0.475                          | 0.019                        | 4.00%      |
| 150 | 0.470                           | 0.48                           | 0.01                         | 2.08%      |
| 175 | 0.504                           | 0.498                          | -0.006                       | 1.20%      |
| 200 | 0.510                           | 0.50                           | -0.01                        | 2.00%      |

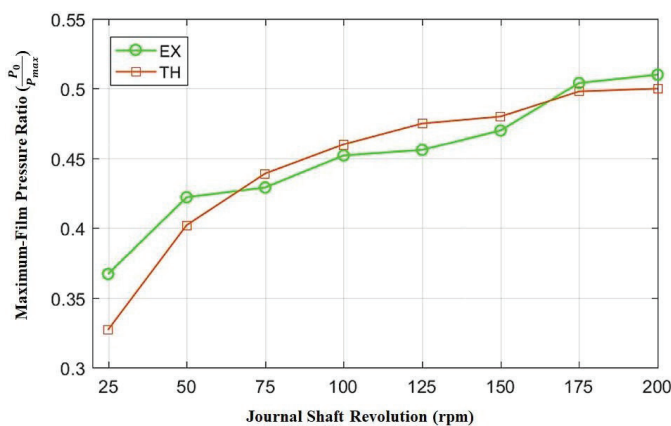


Figure 11. Experimental results Vs Theoretical results

## CONCLUSION

In conclusion, the UJBTR has been designed, developed and modified for the sake of simulating the practical conditions of standard journal bearing for a ship power transmission. The UJBTR has mainly been constructed and has also been fully monitored and manipulated, utilizing the most accurate SCADA control system, for enhancing the oil film lubrication within journal bearing and providing the most optimal operating conditions. In this way, considerable promotions could be attained in relation to the ship power efficiency, the most crucial target on which the whole study has essentially been focused. Further, the paper at hand has comprised extensive experimental trials related to the uncertainty measurements under various speeds but under a constant load. Also, the UJBTR has been tested repeatedly under the above mentioned experimental conditions, and UJBTR validity has been ascertained through experimental and theoretical values, which were proportionally on the rise, in relation to both the experimental ratio ( $\frac{P_0}{P_{max}}$ ), and that derived theoretically.

## NOMENCLATURE

- A Cross-Section area of cylinder,  $\square 2$   
A Current, A  
D Inside diameter of cylinder, mm  
F Force, N  
N Rotational speed of journal, rpm  
n Number of trials  
P Pressure, bar  
 $P_0/P_{max}$  Maximum film pressure ratio  
 $P_0$  Terminating oil film pressure  
 $P_{max}$  Maximum oil film pressure.  
SCADA Supervisory Control and Data Acquisition  
SE Standard error  
 $\sigma$  Standard deviation

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