Servo valve endurance test for Water-Hydraulic systems in ITER-relevant conditions

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ITER Divertor maintenance equipment operates in the vacuum vessel in elevated temperature and under considerable radiation load. The heavy Divertor assemblies are lifted and transported using servo valve systems, such as Cassette Multi-functional Mover (CMM). Systems are powered with water hydraulics, using demineralized water as a pressure medium. Operations have not been tested in ITER-relevant environmental conditions and over projected duty cycles. As the hydraulic medium is rather aggressive and there are no servo valves designed for demineralized water, over 2000-hour operational time was considered a potential issue. Hence, a project was undertaken to ascertain the component compatibility with the environment and pressure medium, and their robustness over the required operational period. Irradiation of components was not considered at this phase of technology validation. A heated test chamber was constructed to emulate the projected maximum ambient temperature of 50°C in the Divertor area. Test routines and measurements were specifically tailored to monitor the operational parameters of the servo valve. After the 2188-hour test the servo valve parameters remained within the limits promised by the manufacturer. Pressure gain decreased and hysteresis increased but remained within the allowable limits. These changes did not have significant effect on the joint angle tracking error.

Keywords: Remote Handling, Water-Hydraulics, Endurance Testing, Servo Valve

1. Introduction

In ITER Divertor maintenance, Cassette Multifunctional Mover (CMM) is a piece of water-hydraulic equipment working in the environment with gamma radiation and temperature of 50°C at maximum. Main task of the CMM is to transport heavy Divertor cassettes (Fig. 1). CMM operates in a maintenance tunnel between the vacuum vessel and a transfer cask.

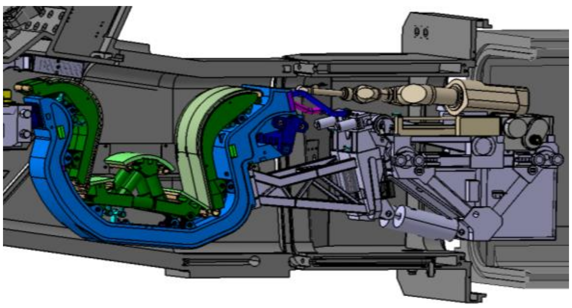

Fig. 1. CMM transporting a Divertor cassette

Endurance test was required in order to validate the feasibility of water hydraulics in elevated temperature and usage of demineralized water for over 2000-hour operation. Radiation hardening of the components was left for a later stage of the technology validation.

Out of the CMM hydraulic components, the most critical and the most susceptible to fluid contaminants is the servo valve as it has very small clearance between spool and housing. Contaminants or particles can cause wearing or even jamming of the valve. Currently there are no servo valves designed for water-hydraulics using demineralized water on the market. However, servo valves intended for oil hydraulics have been utilized in water-hydraulic applications in normal laboratory conditions [1]. The purpose of the study herein is to demonstrate the feasibility of servo valve systems over the duration of Divertor cassette exchange process in ITER-relevant temperature. The test includes testing of components required in single hydraulic joint actuation.

Main objectives of the research were; 1) Run a test replicating the duty cycles found during the full Divertor exchange campaign in ITER; 2) Run a single joint test system with demineralized water in 50°C ambient temperature; 3) Monitor the joint angle tracking accuracy within aforementioned conditions; 4) Execute and analyze both component and system level measurements at frequent interval.

2. Test System

As stated, out of the CMM hydraulic components, the most susceptible to contaminants is the servo valve and there are no servo valves designed for water-hydraulics on the market. Tampere University of Technology (TUT) has previously used in water-hydraulic applications Moog servo valves (series 30 and E050) which are intended for oil hydraulics. Moog servo valves are also utilized in the prototype CMM at Divertor Test Platform 2 (DTP2) [1]. For this test, E050 servo valve from Moog was selected. Other hydraulic components of the test system [2] are not discussed in this paper.

For testing the servo valve, a seesaw structure, the Single-Axis Mock-up (SAM) was utilized. The SAM (Fig. 2) can be loaded double-sided and it has variable fasteners for the cylinder actuator, enabling real-life

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emulation of loading and inertia conditions similar to those of the CMM/SCEE actuators [3]. Performing the tests with a cylinder (125/80-230 mm) and an asymmetric load, gravity loads of the CMM lifting or tilting joints can be emulated. In this test, the selected servo valve, Moog E050, was utilized to control the movement of the SAM cylinder.

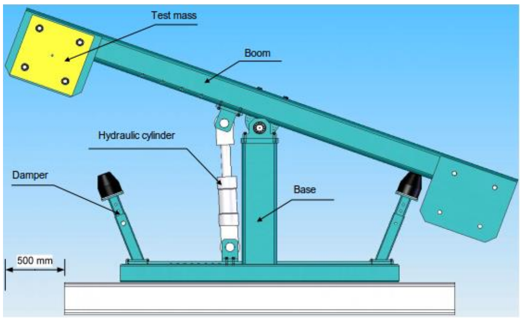

Fig. 2. Main components of SAM

There are some physical differences between the SAM and the CMM. Stroke of the cylinder is 230 mm in the SAM and 430 mm in the CMM. This means that cylinder movement in the endurance test is not exactly same as in the CMM. The cylinder positions are identical but due to the different geometries, the angle is not. Therefore, the joint angle accuracy achieved at the DTP2 [4] are not comparable to this system. Therefore, the tracking accuracy of the SAM was not compared to the prototype CMM. Instead, the objective was to observe any changes in the tracking accuracy over the testing period.

The lowest natural frequency of the CMM lift-tilt system is 5 Hz with a 9-tonne mass [5]. The SAM natural frequency can be changed with different loads to match this. During the endurance test the SAM was loaded with test mass of 1000kg resulting in approximately 5 to 6 Hz natural frequency for the SAM.

Fig. 3. Heated test chamber

As one of the main objectives was to test the components in elevated 50 °C ambient temperature, a heated test chamber was built around the SAM (Fig. 3). All the hydraulic components, Hydraulic Power Unit (HPU) and the heating system were inside the heated chamber. The external water cooling system was set to keep the hydraulic water at around 40°C, which is significantly higher than what is common in water-hydraulic applications. For example, water temperature in the prototype CMM and the DTP2 is kept at around 25°C. Moreover, the current cooling system concept for the CMM is designed to keep the water at 40°C.

The test system uses demineralized water as the pressure medium. TUT has previously used Type I demineralized water according to American Society for Testing and Measurement (ASTM) standard. According to International Organisation for Standardization (ISO), that is comparable to Grade 1 water. This water has minimum amount of ions and impurities hence it is not sensitive to radiation. Same water type is also utilized in the prototype CMM at Divertor Test Platform 2 (DTP2).

3. Test Routines

ITER Divertor maintenance use multiple CMMs, which will work in parallel. While one is operating in the maintenance tunnel between the vacuum vessel and the transfer cask, the other one is in transport in another Cask or at the Hot Cell. Therefore, most of the time the CMM is not actively used and is in idle state. We estimated idle to active time ratio in ITER Divertor maintenance being approximately 4.7. We also estimated that each CMM will perform a minimum of 210 cycles over 25 weeks of ITER shut down approximating a full Divertor cassette exchange campaign. Cycle in this context means the active time when CMM HPU is switched on. During the idle time, the HPU is switched off. Plan was to run the test system for 240 cycles over 12 weeks. The active time was 1885 minutes a week leaving 8195 minutes weekly idle time with minor variations. The final duration of the endurance test was 2188 h and idle to active ratio was 4.3.

Each test day four test cycles were executed, replicating a single joint actuation during 2nd Divertor Cassette exchange operations. During the cycles, a single hydraulic joint, in this case the SAM cylinder, was either held stationary or driven with four predefined trajectories (Fig. 4). These trajectory definitions were extracted from the trajectories of the prototype CMM's Lift joint during 2^{nd} Divertor Cassette exchange operations developed and tested at the DTP2.

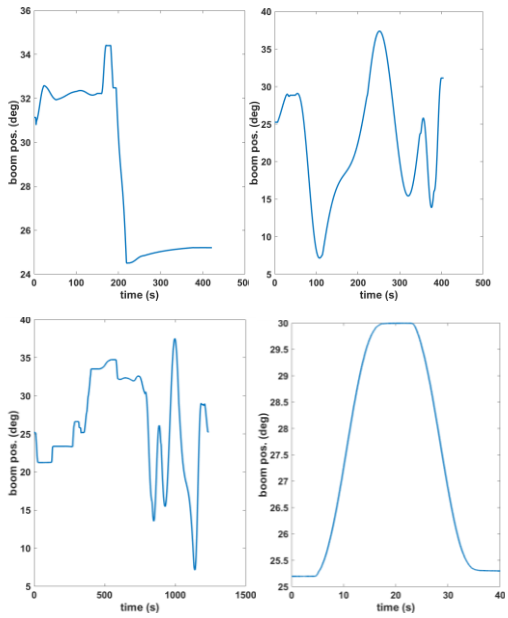

Fig. 4. Cylinder position references, trajectories 1-4

4. Measurements and Test Results

During the tests, component and system level measurements were performed. The system level measurements were executed during each test cycle and component level measurements once a week. In this paper, the changes in servo valve pressure gain, null shift, hysteresis, leakage flow and metering flow over the testing period are presented. The joint angle tracking error changes over the testing period is also discussed.

Leakage flow, metering test, pressure gain and null shift of the servo valve were defined according to ISO 10770-1:2009 standard. This standard applies to four-port directional flow-control valve.

Initial characteristics of components can vary significantly. In addition, change of seals or other modifications to the components can have an effect on the characteristics. Therefore, it is vital to measure the characteristics of each hydraulic component during the commissioning phase. Initial values of servo valve pressure gain, null shift, hysteresis, leakage flow and metering flow were measured at the beginning of the 12-week period and then after each test week, resulting 13 weekly measurements in total. In the following sections, the methods and results of the measurements are elaborated.

4.1 Pressure gain, null shift and hysteresis

The pressure gain was measured on weekly basis with closed actuator lines and 10 MPa supply pressure. In the Fig. 5, the measurements at weeks 1, 7 and 11 and final week (indicated 'Last' in the Fig. 5) are plotted. From the figure, the following observations can be made; 1) Pressure gain slope change has a clear trend; 2) Hysteresis increased significantly; 3) Valve offset seems to be shifted towards the end of the test period. Nevertheless, the pressure gain and hysteresis measured after the completion of the tests were within the acceptable limits recommended by the manufacturer Moog. In the Fig. 5, minimum required pressure gain stated by the Moog is marked in black line, with stars at both ends. According to Moog data sheet, a maximum hysteresis for normal operation condition is 3% and in our final week measurement, it was 2.2%.

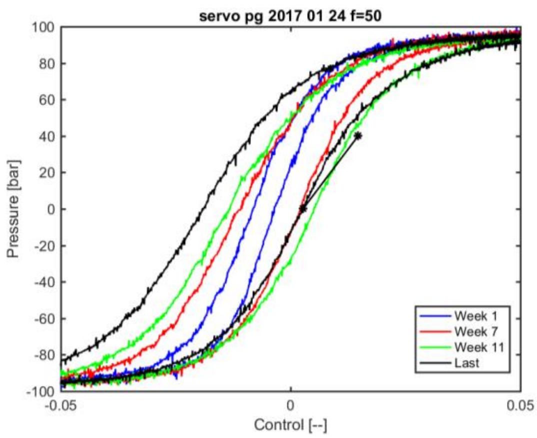

Fig. 5. Servo valve pressure gain on weeks 1, 7 and 11 and during the final test.

Servo valve null shift was evaluated from pressure gain curves but also measured manually by changing the control signal of the servo valve. Both methods gave similar results (Fig. 6). In the latter method, the control signal is set to -6%, after which it is increased by 0.1% steps until actuator line pressures are equal. Servo valve null point in positive direction is the value of control signal at that point. The same procedure was followed in the negative direction. As a result, null point seems to vary slightly around the initial value and having no clear trend or effect on the valve performance.

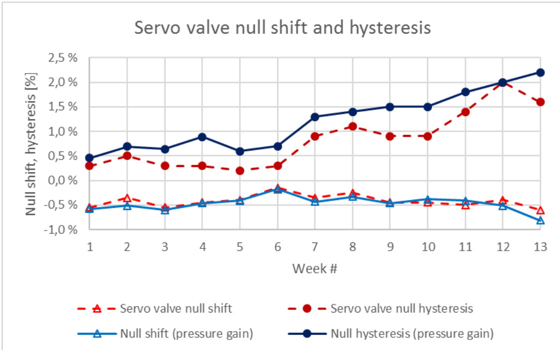

Fig. 6. Servo valve hysteresis and null shift during endurance test.

Hysteresis was evaluated from the pressure gain curves and by manually changing the control signal of the servo valve. Different measurement methods yielded different results although the trend is similar with both methods, excluding the last two points. Reason for difference is the different rate with which the control signal is changed. When pressure gain is measured, slow and steady ramp is used and when null point is evaluated manually, small (0.1%) steps are used. Furthermore, the measurement ramp is always the same in pressure gain measurements whereas when measuring manually the control signal change differs each time. Servo valve null point seems to be almost same with both measuring methods.

4.3. Leakage flow and metering flow

Leakage flow is the internal leakage of servo valve. It includes leakage in flapper nozzle, valve spool, and body clearance. The leakage flow was measured at constant 10 MPa supply pressure with actuator lines closed. Valve control signal was changed slowly from minimum to maximum and flow in tank line was measured. Supply pressure was measured with pressure sensor and leakage was measured with ultrasonic flowmeter.

As seen on the Fig. 7, both the maximum null point leakage and the width of the curve increased. Reason of increased maximum leakage is wearing of the valve spool control edges. At first measurement, maximum leakage was ~0.45 l/min, which increased to ~0.65 l/min in the final measurement. Absolute value of the leakage is quite low and within allowable limits. Relative increase, however, is significant (~45%), but it did not have any negative effect to the system performance during the test.

Tare leakage, i.e. leakage with high opening, did not change significantly. Tare leakage decreased with negative control and increased with positive control slightly. These changes are negligible, however.

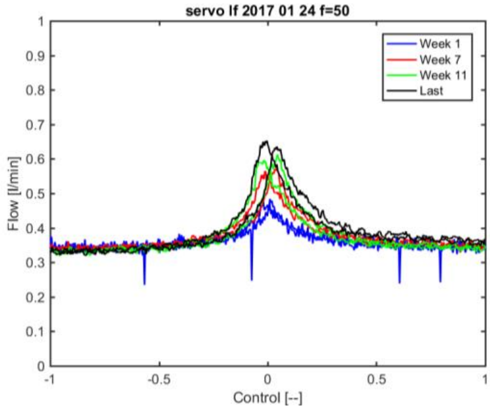

Fig. 7. Leakage flow over the testing period

Metering flow was also measured on a weekly basis but the measurements were almost identical and therefore not discussed here further.

4.3. Joint angle tracking error

Out of the largest absolute value of a joint angle tracking error (measured – reference angle) the maximum joint angle tracking error and root mean square error (RMSE) were calculated for each trajectory. Fig. 8 shows that maximum errors have no clear trend. Error fluctuations increase towards the end of the test. RMSE of the trajectories varies very little from day to day. In both cases, we can see a peak in the tracking error on day 39 but this was due to a measurement error. Hence, there was no significant changes on joint angle tracking error during the 2188h testing period.

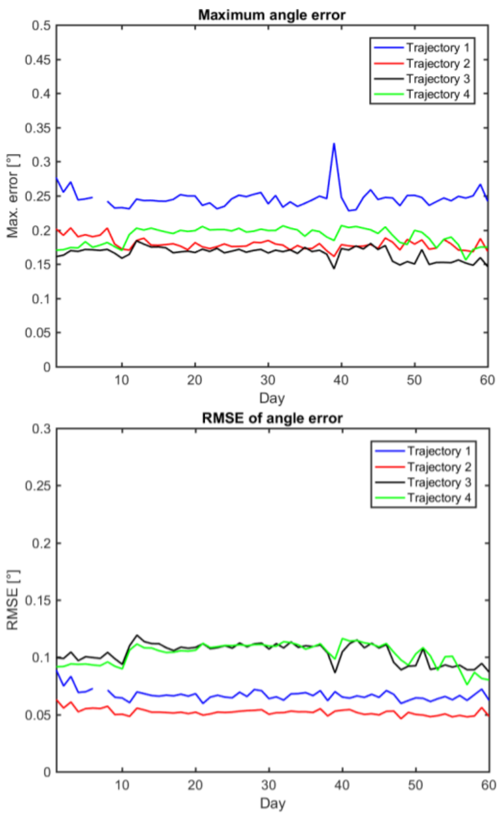

Fig. 8. Maximum joint angle tracking errors and RMSE

5. Conclusions

The test of a servo valve controlling a water-hydraulic joint and demineralized water as hydraulic medium was completed. The ambient temperature of the test system was 50°C and water temperature 40°C, which are estimated to be equivalent found during ITER Divertor operations. Test ran 240 cycles and 2188 hours over 12 weeks, which exceeded the minimum requirement of 2000 hours and 210 cycles. The test system SAM had similar duty cycles to what a single CMM joint will manage over a full Divertor Cassette exchange campaign. The active to idle time ratio of the ITER Divertor maintenance was also respected.

Some changes in the servo valve characteristics over the testing period could be observed. Null point leakage increased. Both maximum leakage and width of the curve increased. Absolute value of the null point leakage is quite low but relative increase is significant (~45%). Nevertheless, all the measured characteristics were within the allowable limits defined by the manufacturer.

Even though servo valve characteristics were changing towards the end of the testing period, it did not have significant effect on the joint angle tracking error. To conclude, the servo valve system has proven to be capable of functioning the required stretch of time in the environment it is projected to be subjected to, excluding the radiation. To further increase the technology maturity level of the servo system, it needs to be subjected to radiation loads present in the ITER environment.

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References

[1] H. Saarinen, *et al.* (2009), Optimized Hardware Design for the Divertor Remote Handling control system, Fusion Engineering and Design, 84, 1666-1670.

[2] J. Tammisto, *et al.* (2018), Water quality and cleanliness effects on water hydraulic components in ITER remote handling maintenance systems, 30th Symposium on Fusion Technology (SOFT 2018) [Submitted].

[3] H. Mäkinen (2006), Design of a test system for fusion reactor maintenance robot, Master of Science thesis, Tampere University of Technology

[4] H. Saarinen, *et al.* (2011), Results of CMM standalone tests at DTP2, Fusion Engineering and Design, 86:9–11, 1907-1910.

[5] Likui Zhai, *et al.* (2010), Analysis and Control of a Water Hydraulic Manipulator for Iter Divertor Remote Maintenance, International Journal of Fluid Power, 11:1, 47-59.