# Digital Valve System for ITER Remote Handling – Design and Prototype Testing

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ITER-RH system is used to exchange the divertor's 54 cassette assemblies in the vessel. Water hydraulics and servo valves are currently used in the task but concerns exist with robustness and availability of suitable components. An alternative option is to use digital technology where on/off valves and intelligent control is used to produce proportional output. So far, no proper high-pressure on/off valves existed in the market and therefore a new concept was developed and tested with promising results. A mock-up of the remote handling system was used as test bench. The system was simulated in order to dimension the valve system and to tune the valve controller. A complete valve package with 16 prototype on/off valves and a manifold was manufactured and long-term tests of 60 working days was conducted. A new level of performance was demonstrated throughout the tests as tracking accuracies were approximately ten times better than with servo valve. Although some design faults where detected and system had faulty components, tracking accuracy was very good. Tracking and positioning capability of digital valve system exceeds all requirements and seems applicable for ITER RH application.

Keywords: Remote handling, tracking control, digital hydraulics

## 1. Introduction

The aim of the study is to assess the suitability of digital water hydraulic system for ITER RH use. The system must be able to install and maintain the divertor's 54 cassette assemblies in the vessel. Water hydraulics has been used for the task and control has been made with commercial servo valves [1]. However, some issues are known to exist, as servo valves have been prone for wear and even jamming. In addition, they may require water cleanliness level of up to NAS 3 [2].

Digital hydraulic valve system is proposed as control system for the water hydraulic actuator. The system consists of several on/off valves connected in parallel. The valves are controlled with a controller that calculates control signals based on references, measured values of pressures and actuator position or joint angle. Digital hydraulics has been studied e.g. by research team of Matti Linjama at Tampere University and one approach been also studied for ITER RH use [3]. Now, digital hydraulics is commercially used e.g. for controlling train tilt system [4] and some paper machine applications [5].

The topic of this study is to design and implement a water hydraulic digital valve system where each individual valve is similar type. The valve system is attached to a base manifold. The valve system is controlled from distance with an amplifier and a control system.

## 2. Requirements for the ITER RH application

### 2.1 Tracking and positioning accuracy

Requirements for tracking control and positioning accuracies are based on previous studies with full-scale prototype, DTP2, which is used to trial the exchange of cassettes. In addition, the performance of the earlier unpublished study made with Moog E050 servo valve was known.

The comparison system with a servo valve and an adaptive robust controller was known to perform approximately 0.3° tracking accuracy during faster 8 mm/s movements that reflects to approx. 1.6 mm piston position error. Accuracy at below 5 mm/s velocity was approx. 0.16° or 0.85 mm. Other notable study with the same test bench was made with velocities below 1.9 mm/s and approximately 0.025° or 133 μm tracking accuracy was demonstrated. Positioning accuracy was 0.01° or 53 μm [6]. These values were used as tracking and positioning requirements for the digital valve system.

### 2.2 Flow rate and pressure level

Maximum flow rate was estimated based on information from the Divertor Test Platform 2 (DTP2) given for the use of the project. Four trajectories were studied and at least 6 l/min is required from all flow edges. The supply pressure of the long-term test bench used in this study is 12 MPa, while the DTP2 test bench is known to have supply pressure of approx. 17 MPa. A typical industrial pressure level of 21 MPa was selected as the basic requirement for the design.

### 2.3 Physical size limitation

Based on the current preliminary design of the RH system, it was estimated that a cubicle of 53 mm x 90 mm x 132 mm (LWH) fits within available space reserved for the remote handling equipment. In addition, a wider 140 mm design fits with minor re-design.

### 2.4 Miscellaneous requirements

The estimated total integrated dose of radiation that the hydraulic system may be exposed during ITER

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operational lifetime is one MGy according to internal technical report. The in-vessel environment may also have one mT level residual magnetic field during ITER maintenance campaigns. Therefore, valve must not react on such level. The fluid medium that will be used in the test is grade 1 de-mineralized water and the temperature of the fluid will be approx. 40°C while ambient temperature will be around 50°C.

## 3. Model based design

### 3.1 Long-term test system simulation model

The long-term test system used in this study is a configurable pivoting boom able to replicate similar mass and natural frequencies found by the hydraulic joints of the RH equipment. The boom is roughly 4 meters long center pivoted "see-saw" and is actuated with a 125/80 hydraulic cylinder. The location of the load mass was estimated to be 1900 mm and cylinder connection point 300 mm from joint. The mass of the boom itself is neglected in this study as well as the weight of hydraulic cylinder. Effective mass is calculated with equation 1 by using one-ton load mass:

$$m_{eff} = m_{real}\left(\frac{1900}{300}\right)^2 \qquad (1)$$

The cylinder has two chambers both modeled with standard pressure build up equation. Linear fit of the load force was calculated from pressure measurements and position information (angle sensor) of an earlier study. Cylinder friction is modelled with a dynamic friction model, which takes into account static friction with elastic seal, stick-slip phenomena, and hysteresis. Model is originally based on [7].

The basic equation for a flow edge is shown in equation 2. The $K_v$ describes the flow rate with certain pressure difference and $b$ value defines the cavitation choking range. Valve dynamics model has transport delay and first order transfer function that represent the delay and response of the valve respectively.

$$Q(u,p_1,p_2) = \begin{cases} uK_v(p_1 - p_2)^{0.5}, & bp_1 < p_2 \leq p_1 \\ uK_v[(1-b)p_1]^{0.5}, & p_2 \leq bp_1 \end{cases} \qquad (2)$$

### 3.2 Control method

Digital valve system controller consists of upper level motion controller, controllers for each flow edge and some auxiliary elements. The motion controller of the valve system has a feed-forward term based on velocity reference and a PT1-controller for feedback. The PT1 is used as the test system has tendency to oscillate with the natural frequency 6 Hz if error signal is used as direct input for P-controller. The auxiliary parts include pressure filtering and driving mode selection (extending, retracting or stopped).

Input for each flow edge controller is a proportional float number between zero and four. The A-side input comes directly from steady-state model whereas B-side float numbers are calculated from A-side value and cylinder area ratio. Only the A-side is pressure compensated thus B-side pressure sensor is not used for control. The output is a vector for controlling four valves of one flow edge. The controller has two internal modes: Pulse Frequency Modulation (PFM) and Pulse Width Modulation (PWM). PFM controller is always used as the first option until PFM frequency reaches PWM frequency. Basic principle for calculating optimal control sequence from float is described in [8].

### 3.4 Simulation results

Simulations were performed in order to make preliminary tuning of the controller and to find valve characteristics requirements (delay and response time, flow capacity). The model was also used to study fault situations and different loading conditions. The performance of the simulated system fulfilled the requirements with tracking accuracy of below 60 µm and positioning accuracy 12.4 µm. The diameter of 0.9 mm was selected for prototypes.

## 4. Single valve development and testing

### 4.1 Development of an on/off valve

The basic mechanical structure of an on/off valve is shown in figure 1. A ceramic ball is used in order to improve lifetime as needle valves may have issues with wear [9]. The sleeve, hull, top, shell and seat parts are stainless steel, holder is PEEK and coil is made from standard coil wire. MP 35 N super compound was selected for the spring material. The PEEK is the most problematic from radiation perspective but it was deemed sufficient based on [10]. An industrial M8 electric connector was selected for use in this phase of the development.

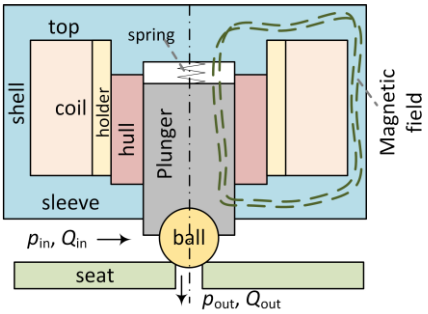

Fig. 1. Water on/off valve basic structure

### 4.2 Single valve test results

The pressure hull of the valve was tested up to 100 MPa with no signs of leakage. A running-in period of 100 000 repeats was conducted with 21 MPa supply pressure. Leakage was measured before and after the pQ-measurements and the result was approx. one drop per five minutes (21 MPa).

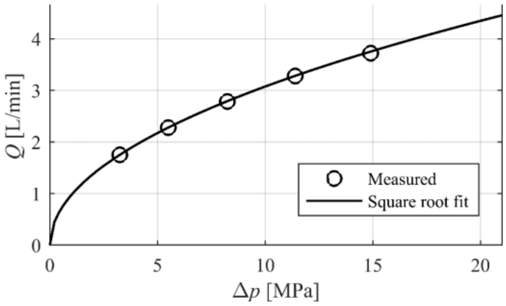

Fig. 2. Water on/off valve pQ-curve

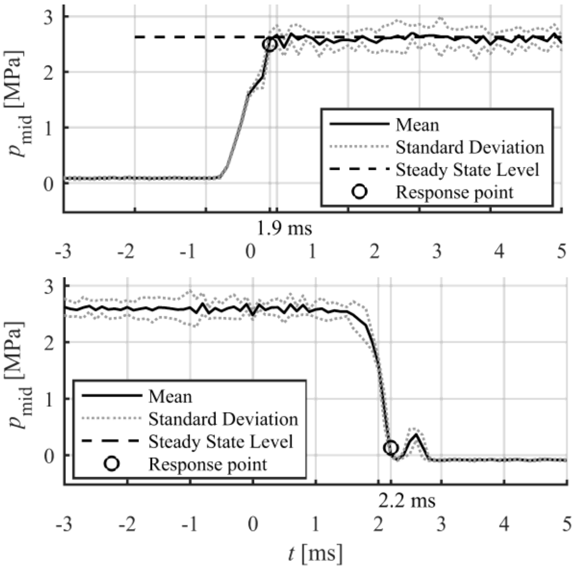

Fig. 3. Valve delay and response test for opening with 12.1 MPa (top) and closing with 9.5 MPa (bottom) pressure difference.

The pQ-curve was measured with five measurement points and result is seen in figure 2. For the combined delay and response time measurements, a separate orifice was used in series with the valve as has been done in other studies concerning fast on/off valves [11]. The pressure difference is measured between the valve inlet and outlet and valve is actuated on and off multiple times. Three pressure differences for both opening and closing were used. Valve was operated with 3 ms boost time by using 24 VDC for opening the valve and 1.5 VDC for holding the valve open. See table 1 for combined delay and response time results. An example is shown in figure 3.

Table 1. Combined delay and response time against 95% pressure change

| Open | | Close | |
|---|---|---|---|
| Δp [MPa] | [ms] | Δp [MPa] | [ms] |
| 20.9 | 2.5 | 16.2 | 1.9 |
| 12.1 | 1.9 | 9.5 | 2.2 |
| 3.7 | 1.5 | 2.9 | 2.5 |

After the valve performance was tests, a 200 000 repeat small-scale endurance test was conducted. The valve was disassembled, and no issues were found.

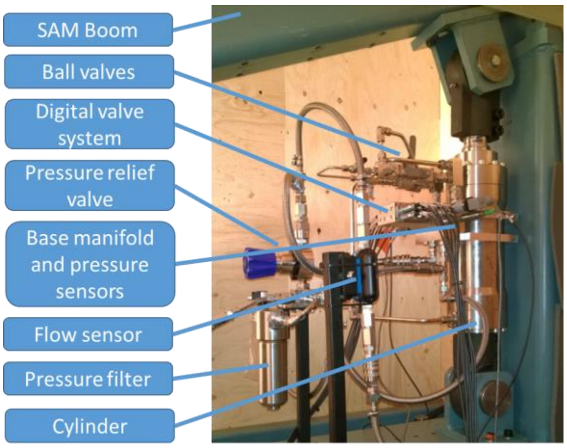

Fig. 4. Long-term tests system

## 5. Long-term tests

The long-term tests include 60 working days of running approx. eight hours a day. Each day consisted of four trajectories and waiting times. Measurement system was autonomous and human operator was only monitoring the events. During tests, the hydraulic system was in controlled ambient and water temperature.

The test system has CAT 781 pump, frequency converter, heat exchanger, filters, non-return valves, pressure relief valve, temperature gauges, and particle sensor. System also included multiple pressure sensors and a pulse sensor for measuring the joint angle. Piston position is calculated from the angle. Digital valve installed near the cylinder can be seen in figure 4. It consists of 16 on/off valves, four for each flow edge.

### 5.1 Results of maximum angle and RMS errors

The main result from long-term tests is shown in figure 5. Each day included four trajectories of different types. The maximum angle error value was tracked during the trajectories. All of the trajectories have velocities above 1.9 mm/s and all measurements show error values below 0.16° that was the requirement for the control system. Typical maximum tracking error is below 0.03°.

The root main square (RMS) error is shown in figure 6. The values are calculated from measured data after the tests. Typical values were below 0.005°. Figure 7 shows an example run from day two with cycle one.

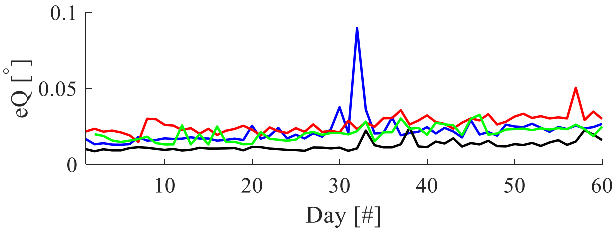

Fig. 5. Maximum angle errors during long-term test. Trajectories 1 (blue), 2 (red), 3 (black) and 4 (green)

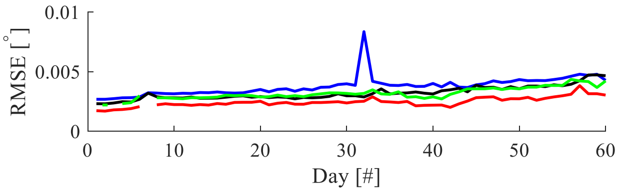

Fig. 6. RMS errors from long-term tests. Trajectories 1 (blue), 2 (red), 3 (black) and 4 (green)

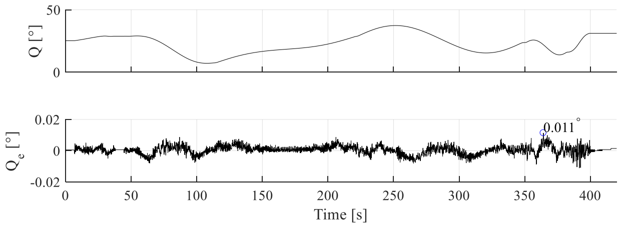

Fig. 7. Example trajectory of trajectory 1 (day 2/60). The 0.011° reflects to roughly 60 µm. $Q$ is measured angle and $Q_e$ is angle error.

### 5.2 Deviations

After first week, some of the plunger guidance pins cracked and started causing increased internal leakage. The system was not stopped due to this, as performance was still good. The first real problems started mid-way the tests when some of the valves started jamming to open-position. Operation was continued normally for two days (32-33) and then a prepared maintenance was made where three valves were replaced. In total, five valves were failing simultaneously at this point. No other maintenance actions were done during the tests. Other valves started to show similar symptoms later and their state was only observed.

In addition to actual valve faults, there were issues with cooling system, joint angle calculation, state-machine and pump leakages that show as missing data in the figures 5 and 6. Only trajectory four from day one was not driven but the rest had only unreliable data.

### 5.6 Water cleanliness

Water cleanliness was constantly monitored and it was NAS 10 when tests started. During next weeks, values settled to around NAS 6 but after a longer rest time, the level increased back to NAS 9. The cleanliness level did return to NAS 6 after the system had been run for several days. The valve used in the study (see figure 8) does not have strict requirements concerning water condition and NAS 10 is already good enough.

Fig. 8. Prototype on/off valve used in the study

## 6. Conclusions

A digital valve system was designed, simulated and tested for ITER RH application. Model based design was used in order to dimension the system and to test and tune the controller. Single valve tests were done in order to verify that valve design is valid. After design process and component testing, a complete digital valve system was manufactured, assembled and commissioned.

The system was able to demonstrate good tracking performance during the long-term tests. The requirements for positioning, slow velocity tracking and higher velocity tracking were easily fulfilled, as even typical tracking result was more accurate than the positioning accuracy requirement of 133 µm.

The tested prototype valves showed two problems; short term intermittent sticking to open position that was caused by wear in metal-to-metal contact and five valves had a cracked guidance pin that caused internal leakages. These problems are separate and both can be corrected with small engineering work. Despite these problems, performance was still good which shows good fault tolerance. In addition, system does not set high requirements for water cleanliness.

The designed valve is compliant with environmental requirements of ITER RH although radiation tolerance was not tested. The next step is to make some design modifications, validate them and switch to DTP2.

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