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Modelling and Model-Based-Designed PID Control of the JT-60SA Cryogenic System Using the Simcryogenics Library

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Abstract. This paper deals with the Japan Torus-60 Super Advanced fusion experiment JT-60SA cryogenic system. A presentation of the JT-60SA cryogenic system model, from 300K to 4.4K -using the Matlab/Simulink/Simscape Simcryogenics library- will be given. As a first validation of our modelling strategy, the obtained operating point will be compared with the one obtained from HYSYS simulations. In the JT60-SA tokamak, pulsed heat loads are expected to be coming from the plasma and must be handled properly, using both appropriate refrigerator architecture and appropriate control model, to smooth the heat load. This paper presents model-based designed PID control schemes to control the helium mass inside the phase separator. The helium mass inside the phase separator has been chosen to be the variable of interest in the phase separator since it is independent of the pressure which can vary from 1 bar to 1.8 bar during load smoothing. Dynamics simulations will be shown to assess the legitimacy of the proposed strategy. This work is partially supported through the French National Research Agency (ANR), task agreement ANR-13-SEED-0005.

1. Introduction

Large superconducting tokamak devices produce significant pulsed heat loads on magnets, due to huge eddy currents encountered in the magnetic system, to AC losses and to neutron flux radiations coming from the plasma. Such high pulsed loads disturb the cryogenic plant that are cooling magnets, and make it necessary to use appropriate control strategies. The aim is to maintain the stability of the overall process subject to the variable thermal load and to satisfy operational and safety constraints (turbine operational temperature range, maximum capacity of the helium tank, compressor suction and discharge pressures, etc.).

Currently, technological solutions (such as thermal buffers, as described in [7], by-pass valves, etc.) are studied to smooth the effect of the thermal disturbance on the cryoplant and to avoid the over-dimensioning of the process. These solutions have to be combined with specific control algorithms, resulting in optimally designed closed-loop systems that can operate near their maximum capacity without the need for too conservative security margins.

The recent interest in advanced control methodologies has motivated many studies on modelling and control of cryogenic plants. In particular, several dynamic simulators have been
proposed by [1, 10, 3, 5, 12] for operator training, dimensioning and/or control design. Based on a better dynamic modelling of the underlying process, advanced control schemes have been proposed which were often dedicated to a particular key variable. For instance, scalar model predictive control (MPC) of the helium bath temperature at 1.8 K using a Joule-Thomson expansion valve has been proposed in [13]. In [9], the problem of control of the bath pressure is addressed, while in [2, 6], the high pressure level is monitored in order to control the bath level. In [4], the optimal multivariable control of a refrigerator is proposed, considering pulsed heat loads.

In this paper, the JT-60SA cryogenic system model made with the Simcryogenics library for MATLAB/Simulink/Simscape is presented. The relevance of the model is done as a first shot by comparison with an Aspen HYSYS static simulation. Based on that model, MATLAB tools will be used to extract the linear equivalent model of the plant, to design PI control loops with. This paper is organize as follows: section 2 presents the JT60 Cryogenic system model and compares the steady state operation obtained with the Aspen HYSYS software. Section 3 is concern by the extraction of the linear equivalent model and the model-based designed PI controllers for the system and the associated simulation results. Section 4 summarize the paper results and gives ideas for future work.

2. JT-60SA modelling using Simcryogenics
This section presents the JT-60SA cryogenic system model and compares the steady state that has been obtained with both the model made with the Simcryogenics library and the one made with Aspen HYSYS.

2.1. The model
The model of the JT-60SA cryogenic system has been build with the Simcryogenics library for MATLAB/Simulink/Simscape. It is composed of several elements such as valves, pressure drops, 0D pipes, three and four fluids heat exchangers (one or two high pressure(s) (HP), low pressure (LP) and very low pressure (VLP)), turbines, thermal loads, compressors and phases separators (one at 4.4K and one at 3.7K), sources and sinks. Components are connected through nodes (in blue) like presented by Figure 1 Figure and 2. Components are roughly initialized around the operating point of interest, in this case study, at full power capability (9kW equivalent at 4.5K [11]) of the cryoplant. Component parameters has been given with courtesy of ALaT.

2.2. Steady-state operation
Aspen HYSYS model steady state simulation results where provided to the authors and it has been chosen to presents the steady state results obtained for both software. To obtain the steady state operation with Simcryogenics, the dynamic simulation is to be run until the system is stabilized. Temperatures, pressures and flowrates at the end of the simulation are listed. Table 1 and Table 2 resume the obtained temperature, flowrates and pressures for sensors presented by Figure 1 and Figure 2. One can notice that both software are giving the same steady state within a few tenth of percent. Now that the operating point has been found, a linear dynamical model around this operation point of interest will be extracted.
Figure 1. First part of the JT-60SA cryogenic system. It starts at 306K to end up at 30K. It is composed of several 3 and 4 fluids heat exchangers, heat loads, and pressure drop (to model the thermal shields for instance) and turbines. It is connected to the second part presented by Figure 2. Rounds with blue font represent sources and sinks while rounds with yellow font represent sensors. Nominal pressures, flowrates and temperature are given by Table 1 and 2. On the right hand side of the picture, the white box represents the heat load of 44kW and the pressure drop of 1.5bar introduced by the thermal shield @80K.
Figure 2. Second part of the JT-60SA cryogenic system. This part starts at 30K to end up at 3.7K. The model is composed of several heat exchangers, pressures drops, pipes, valves, turbines, heat loads and the two phase separators (4.4K and 3.7K). Rounds with blue font represent sources and sinks while rounds with yellow font represent sensors. Nominal Pressures, flowrates and temperature are given by Table 1 and 2. Complete scheme with supercritical loops, all controls loops, valves and instrumentation is to complex and it is thus not displayed here. It can be requested upon the authors.
### Table 1
Comparison of results obtained with Aspen HYSYS and Simcryogenics and associated deviation. All presented flowrates are given in g/s and temperature are given in K while deviations are in %

| Flow  | HYSYS | Simcryogenics | dev. |
|-------|-------|---------------|------|
| FT210 | 637.4 | 639.2         | 0.281|
| FT211A| 592.2 | 594.1         | 0.319|
| FT211C| 637.4 | 639.2         | 0.281|
| FT215 | 212.4 | 214.5         | 0.972|
| FT215B| 191.4 | 193.4         | 1.046|
| FT221 | 425.0 | 424.7         | 0.068|
| FT222 | 425.0 | 424.7         | 0.068|
| FT223 | 439.3 | 439.2         | 0.037|
| FT223A| 418.4 | 418.1         | 0.069|
| FT226 | 419.6 | 419.5         | 0.031|
| FT231 | 589.0 | 591.0         | 0.342|
| FT234 | 589.0 | 591.0         | 0.342|
| FT241 | 23.34 | 23.30         | 0.000|
| FT250 | 45.16 | 45.10         | 0.131|
| FT312 | 191.5 | 193.4         | 0.995|
| FT319 | 191.5 | 193.4         | 0.995|
| FT329 | 191.2 | 193.4         | 1.150|
| FT329A| 189.9 | 193.1         | 1.669|
| FT330 | 399.6 | 399.5         | 0.032|
| FT338 | 398.9 | 398.7         | 0.040|
| FT702 | 20.00 | 20.00         | 0.000|
| FT732 | 283.5 | 283.5         | 0.000|
| FT799 | 397.9 | 395.6         | 0.583|

| Pres.  | HYSYS  | Simcryogenics | dev. |
|--------|--------|---------------|------|
| PT332  | 13.07  | 13.07         | 0.001|
| PT338  | 4.87   | 4.87          | 0.000|
| PT339  | 4.88   | 4.88          | 0.001|
| PT702  | 8.145  | 8.15          | 0.002|
| PT799  | 1.34   | 1.34          | 0.051|
| PT249  | 0.5    | 0.50          | 0.000|
| PT338  | 4.87   | 4.87          | 0.000|
| PT702  | 8.145  | 8.15          | 0.016|
| PT732  | 4.7    | 4.77          | 1.467|
| PT737  | 4.2    | 4.20          | 0.000|
| PT790  | 1.089  | 1.07          | 1.873|
| PT799  | 1.34   | 1.34          | 0.000|

### Table 2
Comparison of results obtained with Aspen HYSYS and Simcryogenics and associated deviation. All presented pressures are given in bars while deviations are in %

| Pres.  | HYSYS  | Simcryogenics | dev. |
|--------|--------|---------------|------|
| PT210  | 15.43  | 15.43         | 0.000|
| PT211  | 15.28  | 15.28         | 0.003|
| PT215  | 14.97  | 14.97         | 0.010|
| PT225  | 13.43  | 13.43         | 0.001|
| PT230  | 1.13   | 1.13          | 0.000|
| PT240  | 0.405  | 0.41          | 0.000|
| PT249  | 0.5    | 0.50          | 0.000|
| PT295  | 13.19  | 13.19         | 0.001|
| PT312  | 14.77  | 14.77         | 0.025|
| PT319  | 6.357  | 6.40          | 0.621|
| PT322  | 6.307  | 6.35          | 0.616|
| PT329  | 1.35   | 1.33          | 1.451|
3. Linearisation and PI Control Design

As a first help to design the system’s controllers, model-based PI control will be designed for the auxiliary cold box. To generate a model-based design controller, the plant has to be linearised around the operating point of interest. Assuming that the plant non-linear model can be written \( \dot{x} = f(x, u, w) \) (where \( x \), \( u \) and \( w \) respectively denote the state of the model, the control action and the boundary conditions), the linearised model will be of the following form:

\[
\dot{x} = A\tilde{x} + B\tilde{u} + F\tilde{w}
\]  

(1)

where \( \tilde{x} \), \( \tilde{u} \), \( \tilde{w} \) respectively denotes the deviation of the state, control effort and boundary conditions w.r.t. the operating point, while matrices \( A \), \( B \) and \( F \) are given by the following expressions:

\[
A = \left. \frac{\partial \dot{x}}{\partial x} \right|_{x_0,u_0,w_0} \quad B = \left. \frac{\partial \dot{x}}{\partial u} \right|_{x_0,u_0,w_0} \quad F = \left. \frac{\partial \dot{x}}{\partial w} \right|_{x_0,u_0,w_0}
\]  

(2)

where variables with the 0 suffix denote the value of the original variable at the operating point of linearisation. The linear model (1) is now available and is ready to be used in model-based PI control scheme.

3.1. Level control using a heating device

A first PI controller will be generated to control the helium Level LT700 using the electric heater EH703, as Figure 3 illustrates it.

![Figure 3. PI control loop for the LT700 level using the electric heater EH703](image)

Figure 3. PI control loop for the LT700 level using the electric heater EH703

![Figure 4. Time-responses for the level LT700 controlled by the electric heater EH703. Solid line represents the time response setted to 600s while dashed line stands for the 1200s time response](image)

Figure 4. Time-responses for the level LT700 controlled by the electric heater EH703. Solid line represents the time response setted to 600s while dashed line stands for the 1200s time response
By cliquing on the PID controller block, one is able to set PI parameters by itself or to ask MATLAB to do it by analysing the model. The latter solution as been chosen, and by setting the criteria "time response" to 600 and 1200, PID parameters are model-based computed by MATLAB and the response to a $-1000W$ disturbance at time 200min is shown by Figure 4. One can notice the the plant is well stabilized by the derived PID controllers.

3.2. Density in the bath control using the inlet valve

Following the same procedure, a PI controller as been generated to control the global density (i.e. the helium mass) in the phase separator, through the inlet valve CV700. Controlling the global density in the phase separator instead of the level presents the advantage of equalize the inflow and the outflow, regardless of pressure variations. The control strategy must be choose to be pressure independent because the pressure may vary during heat pulses, to offer a thermal buffer effect \[8\]. To directly control the level in such conditions is inappropriate due to its variations inducted by pressure variations. Figure 5 presents the obtained time-result on the non linear model presented by figures 1 and 2. It has to be noted that the helium density is not directly measured. In this case study, it has been obtained using the helium level and the bath pressure associated to helium properties.

![Figure 5. Time-responses for the density in the phase separator controlled by the CV700 valve. Solid line represent the time response setted to 600s while dashed line stands for the 1200s time response](image)

4. Conclusion

In this paper, we shown the schematic of the JT60-SA cryogenic system model using the Simcryogenics library. We shown that the obtained operating point is the same than the one obtained with the Aspen HYSYS model if same input parameters are given. With the dynamical linearised model, a controller has been generated to control the helium level and the bath mixture density, that has been simulated on the non-linear process. In the future, the model will be validated for others operating points and also dynamically against experimental data that do not exists for now. In next researches, we will be focused on the synthesis of multiple PI control loops for the whole process, and on the experimental validation of the derived controllers on the JT-60SA cryogenic system.
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