A Simulink Library of cryogenic components to automatically generate control schemes for large Cryorefrigerators

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Abstract. In this article, we present a new Simulink library of cryogenics components (such as valve, phase separator, mixer, heat exchanger…) to assemble to generate model-based control schemes. Every component is described by its algebraic or differential equation and can be assembled with others to build the dynamical model of a complete refrigerator or the model of a subpart of it. The obtained model can be used to automatically design advanced model based control scheme. It also can be used to design a model based PI controller. Advanced control schemes aim to replace classical user experience designed approaches usually based on many independent PI controllers. This is particularly useful in the case where cryoplants are submitted to large pulsed thermal loads, expected to take place in future fusion reactors such as those expected in the cryogenic cooling systems of the International Thermonuclear Experimental Reactor (ITER) or the Japan Torus-60 Super Advanced Fusion Experiment (JT-60SA). The paper gives the example of the generation of the dynamical model of the 400W@1.8K refrigerator and shows how to build a Constrained Model Predictive Control for it. Based on the scheme, experimental results will be given. This work is being supported by the French national research agency (ANR) through the ANR-13-SEED-0005 CRYOGREEN program.

1. Introduction

Large superconducting tokamak devices produce significant pulsed heat loads on magnets, due to huge eddy currents encountered in the magnetic system, AC losses and 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 [1], 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

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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 [2, 3, 4, 5, 6] 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 [7]. In [8], the problem of control of the bath pressure is addressed, while in [9, 10], the high pressure level is monitored in order to control the bath level. In [11], the optimal multivariable control of a refrigerator is proposed, considering pulsed heat loads.

In this paper, a new Matlab/Simulink library of cryogenic components is proposed to help the designer to simulate the behaviour of a refrigerator and to tune the PI control loops of it. This paper is organized in six parts. The second part recalls the results obtained with advances control on the 400W@1.8K refrigerator (in the 450W @ 4.4K configuration) and on a CERN warm compression station for LHC. The third part shows how to obtain a model a refrigerator from our new Matlab/Simulink library. The Joule-Thomson cycle of our refrigerator will be given. The fourth part deals with obtaining the constrained operating point and the model linear approximation of the refrigerator. Based on the linearized model, the fifth part presents the methodology to design a model-based PID controller or an advanced model predictive controller (MPC) which deals with process constraints. The sixth parts summarize the paper and gives ideas for future work.

2. Experimental results obtained with model-based advanced control

In this section, the experimental results obtained with the different methodologies described in the next sections will be recalled. The specifics are not given, but can be found in the quoted literature.

2.1. CERN Warm Compression Station for LHC

In [11], a model for the CERN warm compression station for LHC is described and a model-based controller is synthesized. An experimental test has been done to compare the advance multivariable control strategy with the classical PID based controller that actually works on the machine. All the specifics about the experience and the controller design can be found in [11]. Figure 1 presents trends that have been obtained. The presented three events consist of plant disturbances. The conclusion of this test was that advanced multivariable controller for warm compression station is more efficient than classical PID control scheme if it is concerned with pressure stability.

![Figure 1](image.png)

Figure 1. Trends for the medium pressure and the low pressure during three events. The solid curves represent pressure values with the advanced control scheme, while dashed curves show results under the PID control scheme. The first event consists of a low stage compressor start while the second consists of a high stage compressor start. The third event is a low stage compressor start immediately followed by a low stage compressor going to full power mode.
2.2. SBT 400W@1.8K Cryogenic Fest Facility Cold Box
This section is concerned with the experimental results obtained on the SBT 400W@1.8K (on the 450W@4.4K configuration) with model predictive controller. All the details on the model-based predictive controller are given in [12]. The controller has to adapt the refrigerator’s actuators to deal with the very variable thermal load. The controller have to respect operational constraints on both actuators and process values (here the bath level that have to stay between two bounds). All the specifics about modelling and designing the controller can be found in [12]. Figure 2 presents the trends obtained with such a controller. One can see that operational constraints are respected, particularly on the helium level, despite the highly variable thermal load.

Figure 2. Trends for the SBT 400W@1.8K refrigerator submitted to variable heat loads. One can see that thanks to the advanced controller, the operational constraint set on the helium bath level is satisfied.

Be seeing the experimental results of this section, it has been decided to build software to facilitate the construction of model based controllers. The next section is concerned with the model library.

3. Obtaining the control oriented model with our new MatLab/Simulink library

3.1. The MatLab/Simulink library
Within the MatLab/Simulink software, we build a library of cryogenic components that can be assembled into a Simulink schematic. Available components consist of the following list:

Components:
- Screw compressor
- Valve
- Cross current heat exchanger
- Pipe
- Turbine
- Phase separator
- Distributor / Mixer
- Cold compressor (to come)

Sensors:
- Pressure
- Temperature
- Flowrate
- Quality
- Etc.

Sources:
- Pressure/Temperature
- Pressure/Flowrate

Utilities:
- Heat load
- Helium properties
- Connection pipe
- Pressure drop

All the modelling details are available in [13], including algebro-differential equations.
3.2. Model construction
For illustration purposes, we propose to show the schematic of the SBT’s cryogenic test facility Joule-Thomson cycle’s with the MatLab/Simulink software. Our JT cycle is composed of a heat exchanger, pipes, valves, a phase separators and some sensors. One can see that the physical connections between components are made exactly like a Process Instrumentation Diagram (P&ID) would have shown. The parameters are given to the software via a dialog box that appears while clicking of the component. For the list of required parameters for each component, see [13]. The obtained model for simulation or control design is of the form:

\[
\frac{dx}{dt} = \dot{x} = f(x, u, w)
\]

\[
y = g(x, u, w)
\]

where \(x\) represents the state of the system (temperature, helium level, etc.) while \(w\) stands for boundary conditions imposed to the model. \(u\) represents the manipulated variables (heating power, valve opening, etc.). \(y\) is used to recall the output variables (measured or not).

**Figure 3.** SBT 400W@1.8K Joule-Thomson cycle MatLab/Simulink schematic. The physical port on top are connected to a Brayton cycle, the physical port on the left bottom are connected to the final consumer.

3.3. Model simulation
To show our model sufficient accuracy for control purposes, open loop simulations have been done and compared to experimental data. The results are given in [12,13].

4. Constrained operating point and Model Linear approximation
Now that the model of our JT cycle has been design with a Simulink schematic and that its open-loop prediction capabilities have been assessed [12,13], we will extract the linear approximation to design the control loop. To extract the linear approximation of our non-linear model, an operating point is first needed. This is the purpose of the next section.
4.1. Constrained operating point

In this section, we propose to find the operating point of our JT cycle. The operating point is defined by the following equalities:

\[ f(x_0, u_0, w_0) = 0 \]
\[ g(x_0, u_0, w_0) = y_0 \]

The first equality means that the system is in a stationary state (more precisely: nothing’s move). The drift cancelation is no easy task since every variable is depending on each other. That is why we propose software to do so. The software user is asked to set the boundary conditions, and respecting the boundary conditions, the software finds the associated operating point. Let us continue with our JT example. The boundary conditions are set as presented by Table 1 while the opening of the CV155 and CV158 valves are set as free variables. A ten bar pressure constraint is set for the pipe connected to the final helium consumer.

After a few iterations, the software finds the boundary conditions for both valves for the system to be in equilibrium and the constraints to be respected. Precisely:

- \( CV155 = 20.63 \% \)
- \( CV158 = 45.59 \% \)

If the system of interest is bigger that our JT cycle, it is possible to set more constraints (turbine inlet or outlet temperature, maximum in/outflow, JT valve inlet temperature, etc.) as soon as there is enough free variable to be optimized (valve opening, heat exchange coefficient, high pressure, etc.). The user interface of the software is presented by Figure 4. Now that the operating point of the refrigerator is available, the linear approximation of the state space model will be expressed.

Table 1. Boundary conditions used to determine the operating point of the refrigerator.

| Variable     | Value | Unit | Variable     | Value | Unit |
|--------------|-------|------|--------------|-------|------|
| T_H_cons     | 4.7   | K    | P_H_bt       | 16    | bar  |
| M_H_cons     | 0.025 | kg/s | P_C_bt       | 1.1   | bar  |
| M_C_cons     | 0.025 | kg/s | CV157        | 95    | %    |
| T_H_bt       | 8.5   | K    | NCR22_cmd    | 0     | W    |

Figure 4. Operational point finder. User interface.
4.2. Linear approximation

The purpose of this section is to present how to obtain the linear approximation of the state equation, to design model-based controllers. The linear expression is described by the following equation:

\[
\dot{x} = A\tilde{x} + B\tilde{u} + F\tilde{w} \\
\dot{y} = C\tilde{x} + D\tilde{u} + G\tilde{w}
\]

in which the variation of \(\tilde{x}\) is linear in \(\tilde{x}, \tilde{u}, \tilde{w}\). The tilde accent describes the variation of the original variable regarding the operating point. It is called a linear state space model and it can be used to made many studies such as stability, bode diagram plotting and especially control design. According to the Taylor-Lagrange principle:

\[
A = \left. \frac{\partial f(x, u, w)}{\partial x} \right|_{x=x_0, u=u_0, w=w_0}, \quad B = \left. \frac{\partial f(x, u, w)}{\partial u} \right|_{x=x_0, u=u_0, w=w_0}, \quad C = \left. \frac{\partial g(x, u, w)}{\partial x} \right|_{x=x_0, u=u_0, w=w_0}
\]

and equivalently for the \(F, D\) and \(G\) matrices. One can see in [13] that the linear approximation of the plant is capturing well the main dynamic of it and that the linear simulation results are not very different than the nonlinear simulation.

5. Model-based controller design

The model depicted in the previous section is now ready to be used to design a linear control scheme. This section will present how to design a PI (or PID or more generally any monovariable controller) controller using the Matlab/Simulink software suite and associated simulation results. It also will be explain how an advanced constrained predictive control for a refrigerator is working and how can it be generated.

5.1. PID controller

Based on a linear model, the Matlab/Simulink software suite offers a tool to tune a PI or PID controller, based on some criteria (robustness, time response, etc.). To use the tool, we use the following Simulink schematic:

![Simulink Schematic](image)

**Figure 5.** Simulink Schematic used to automatically tune the PID parameters. The helium level is controlled by the JT valve. The plant is here disturbed by a variable thermal load simulated by NCR22.

By cliquing on the PID controller, an interface is proposed to the user to set the robustness and the time response of the process. It leads in a few minutes to the simulation results shown by Figure 6. The PI setting is allowing a fast disturbance (thermal load variation) rejection with the JT valve.
5.2. Constrained model predictive control

The background to understand how a model predictive controller (MPC) works is not entering in what we want to present in this paper. Nevertheless, the basics will be recalled. Model predictive controller is a model-based optimal controller that can deal with operational constraints. It means that the controller will try to minimise the deviation of the controlled variables regarding their set-points, while checking if operational constraints are and will be respected. Operational constraints consist of actuators limitations (both amplitude and derivatives) and excursion limitation of constrained measured variables. To summarize, the model predictive controller will focus on its primal objective, the set points respect for controlled variable while it will forget about it when a deviation is needed to satisfy operational constraint.

It leads to an objective function that has to be minimized in real time, respecting the constraints. A convex optimization problem that has to be solved in real-time is then addressed. At the cryogenic engineering department of the CEA Grenoble, we developed a solver [14] for model predictive control that fit the computing capabilities of a PLC that is well used in industry. Then we developed software to accelerate the development of a model predictive controller for a refrigerator. It allows to set controlled variables as well as every operational constraints that hold on the process (turbine outlet temperature, turbine outlet pressure, bath level, JT valve inlet temperature, etc.). This software will be available soon for downloading.

6. Conclusion and future work

In this paper, we present the complete path to design a PID or an advanced controller based on the model of the refrigerator, or a subpart of it. Model-based designed PID is very easy to derive using the proposed model and framework. If more control performance or more safety are needed, it is possible to use model predictive control, which is also simple to derive which is also simple to derive thanks to the software. The constrained model predictive control of our refrigerator appears to be very efficient in the case of variable heat loads. It allows operational constraints respect, leading to a possible growth of availability and safety. It may also help to avoid plant oversizing in the case of variable heat loads thanks to appropriate reaction at any time. To get more information about (or a demonstration of) the software we developed, it is possible to contact the main author of this publication.

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