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PROCESS IDENTIFICATION THROUGH TEST ON CRYOGENIC SYSTEM

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UNICOS (UNified Industrial Control System) is the CERN object-based control standard for the cryogenics of the LHC and its experiments. It includes a variety of embedded functions, dedicated to the specific cryogenic processes. To enlarge the capabilities of the standard it is proposed to integrate the parametrical identification step in the control system of large scale cryogenic plants. Different methods of parametrical identification have been tested and the results were combined to obtain a better model. The main objective of the work is to find a compromise between an easy-to-use solution and a good level of process identification model. The study focuses on identification protocol for large delayed system, the measurement consistency and correlation between different inputs and outputs. Furthermore the paper describes in details, the results and the tests carried out on parametrical identification investigations with large scale systems.

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Abstract

UNICOS (UNified Industrial Control System) is the CERN object-based control standard for the cryogenics of the LHC and its experiments. It includes a variety of embedded functions, dedicated to the specific cryogenic processes. To enlarge the capabilities of the standard it is proposed to integrate the parametrical identification step in the control system of large scale cryogenic plants. Different methods of parametrical identification have been tested and the results were combined to obtain a better model. The main objective of the work is to find a compromise between an easy-to-use solution and a good level of process identification model. The study focuses on identification protocol for large delayed system, the measurement consistency and correlation between different inputs and outputs. Furthermore the paper describes in details, the results and the tests carried out on parametrical identification investigations with large scale systems.

Keywords: Parametrical Identification, Cryogenics, Large scale solution, Controller Tuning.

Presenting Author's Biography

Marco Pezzetti. Graduated in Mechanical Engineering at Politecnico di Milano (Italy), Automation specialization, in the academic year 1995/96. He is working at CERN in the control section of the cryogenics for experiments since 1998, specialized in large scale cryogenic system. He is currently doing a PhD at the Picardie Jules Verne University and ESIEE-LMBE, Amiens.

1 Introduction

To exploit the capabilities of the CERN Large Hadron Collider (LHC) with colliding protons and heavy ions, four particle detectors are installed in underground caverns. ATLAS [1] is the largest of these detectors, comprising a complex cryogenic system for superconductive magnets and liquid argon ionization sampling calorimetry [2]. The calorimeters are housed in three cryostats with a total volume of $83m^3$ of sub-cooled liquid argon at a temperature of approximately 87 K.

UNICOS (UNified Industrial Control System) is the CERN object-based control standard [3] for the cryogenics of the LHC and its experiments, which includes a variety of embedded functions, dedicated to the specific cryogenics processes. In this standard the current object used for control loops is a PI controller (no derivative term). This is a not mere coincidence , in the cryogenic "industry", operators are apprehensive about derivative action and its response to noise, especially when the actuators involved are valves. This UNICOS controller is suitable most of the time for cryogenic processes and it is optimized by the operation team with "try & error" methodology. This procedure is common for industrial control engineers who do not use any identification guideline, although an urgent need for efficient and effective identification methods is required. A possible reason for this is the failure of the transfer of identification technology as a whole, researchers focus most of their efforts on parameter estimation and convergence analysis, while a few study test design and model validation the part closer to the application. Another reason is due to the identification toolboxes, most of the time very flexible, complex and not adapted to control engineers who do not have academic training in system identification.

This paper describes the different steps on the control of large scale cryogenic systems for recursive identification and optimisation method including data acquisition, filtering, modelling, uncertainty estimation and tuning methods for a PI controller, to enlarge the capabilities of the standard. Different approaches of parametrical identification (single and multivariable) have been experimented. A synergy between an industrial and a scientific solution has been implemented. The main objective is to find a compromise between an easy-to-use solution and a good level of fidelity in model's outputs. The study focuses on generalized identification protocol for large delayed system, on the measurement consistency and on correlation between different inputs and outputs.

2 Cryogenic system

In the central part of the ATLAS detector (see Fig. 1) is located the liquid argon calorimeter: a barrel calorimeter and two end-cap detectors with respectively 120 tons and $2 * 219$ tons cold masses. They are housed in three independent cryostats filled with $40m^3$ and $2 * 19m^3$ of liquid argon at 87 K. The cryogenic system chosen for the tests is the central barrel calorimeter.

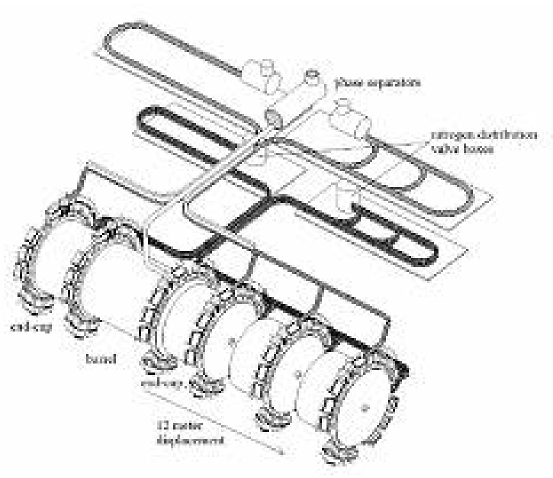

Fig. 1 Overall view of the cryogenic system

The cooling system of the cryostat (see Fig. 2) is based on 7 liquid nitrogen heat exchangers; 6 heat exchangers are positioned in circular geometry around the calorimeter immersed in the liquid Ar and 1 is positioned in the gaseous volume of the expansion vessel to control the Ar saturated pressure. The expansion vessel is located 2.8 m [2] above the calorimeter, the hydrostatic pressure provide the subcooling of the liquid in the bath to avoid bubble formation [4]. Furthermore the heat exchangers control the temperature of the subcooled liquid to obtain the best operating point.

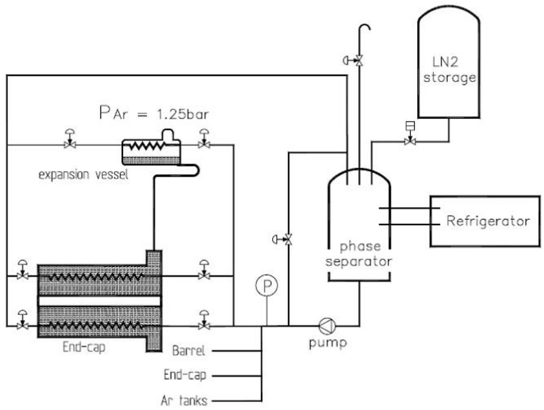

Fig. 2 Nitrogen cooling circuit principle

The liquid nitrogen (LN_2) flow and pressure within each cooling loop are regulated by respectively the inlet and outlet control valves. The LN_2 flow must always be sufficient to maintain wet the area along the entire surface of the heat exchangers, in their final configuration the inlet valves are maintained in a fixed position. Thus LN_2 saturated pressures (e.g. temperatures) provide the variables for controlling the liquid Ar subcooled temperature in the cryostat. The saturated pressures within each heat exchanger needs to be optimisely controlled in order to improve the overall liquid argon temperature stability and uniformity. The set up for these tests has been carried out using the UNICOS based cryogenic control system in its final configuration see Fig. 3.

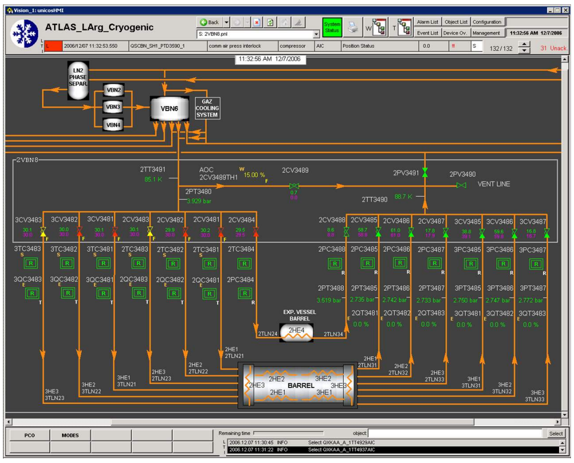

Fig. 3 UNICOS synoptic of cryogenic barrel circuits

3 Combination of industrial and scientific solutions

In order to perform reliable data recording and model identification, we have used a common industrial solution developed by Schneider for SISO system, Optireg [5]. Measurements filtering, model simulation and controller tuning has been developed using MATLAB-SIMULINK environment, a scientific tool.

3.1 SISO model identification for the pressure of the heat exchangers of the barrel calorimeter

There are 2 times 3 different types of heat exchanger, vertical, bottom horizontal and top horizontal. The tests has been performed for each type of heat exchanger using a series of command on the open loop. The scope was to analyse pressure response according to the valves positions as single-variable step in different time periods, under different disturbance conditions. The tests have been done manually, the heat exchanger in the expansion vessel was not included in the test procedure. Manual steps on valves have been done within their operational safety limit, and optimal signal spectrum variation. Thus, reducing disturbance effects and representing an advantage for understanding the step responses of the cryogenic process. The duration of each identification test per heat exchanger took 8-10 hours. The data record has been processed with a digital low-pass filter to match the desired closed-loop bandwidth. The choice of the digital low-pass filter was a compromise between the attenuation of the noise and the maintaining the signal dynamics in order to use reliable data for identification [6]. Fig. 4 presents the different steps of the identification procedure.

We consider one transfer function per heat exchangers, which has its own response to its connected outlet valve depending on several variable such as dimensions, installed measurement variables and location in the Ar bath. We define $[H_1, H_2, H_3, ..., H_6]$ and $[PI_1, PI_2, ..., PI_6]$ corresponding respectively to the transfer functions and to the designed controllers for the 6 immersed heat exchangers (see Fig. 5).

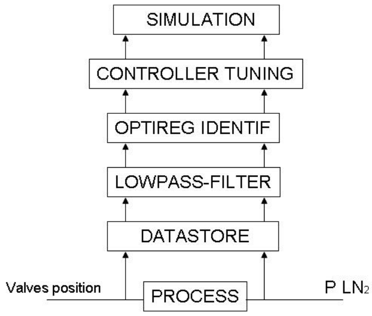

Fig. 4 Data taking, filtering and analysis procedure

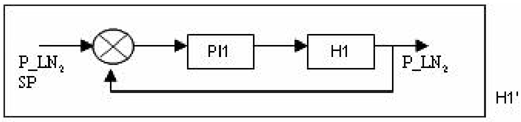

Fig. 5 Closed loop control of liquid nitrogen pressure

Based on the quadratic mean errors analysis, different order model has been compared to the process data. The result has shown that a first order model is sufficient to represent pressure dynamics inside the heat exchanger. The transfer functions in z domain, are characterised by a large time constant, a small gain and a constant time delay as it is shown in the Eq. (1) obtained using Optireg with sampling time of 30s:

$$H(z^{-1}) = \frac{-4.13 \cdot 10^{-4} \cdot z^{-1}}{1 - 0.94 \cdot z^{-1}} \cdot z^{-2} \qquad (1)$$

3.2 Smith controller for time delay compensation based on UNICOS PI controller

The Smith Predictor see Fig. 6 is a PID controller adding an internal model intended to cope with larger delay. The principal aim is to provide a correction to the PID by removing the effect of delay inside the closed loop response. This type of controller can be used for first and second order (double pole) transfer function or an unstable system with delay.

3.3 Discussion

In Fig. 7 the dynamic responses of a simulated controller model are compared using experimental data record. The first controller is a classical PI, tuned from cryogenic operator (cryo-PI, gain=1, Ti=300s), the second is a PI controller also but tuned after the SISO identification process without taking into account time delay and a third controller is based on Smith predictor approach [7] to compensate the time delay.

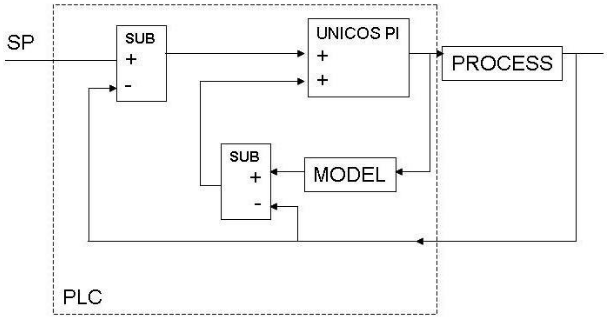

Fig. 6 Smith predictor closed control loop

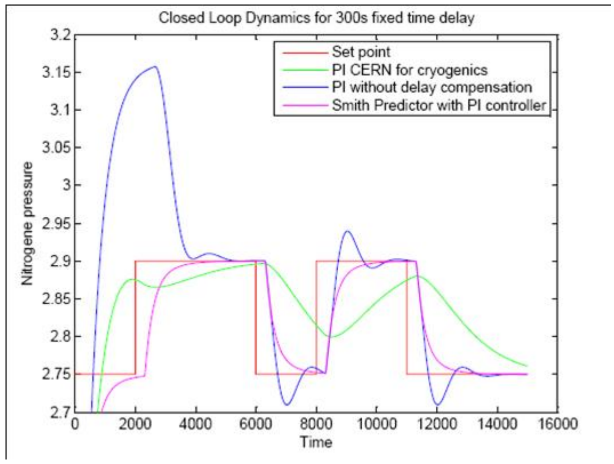

Fig. 8 Closed loop dynamics for 300s fixed time delay

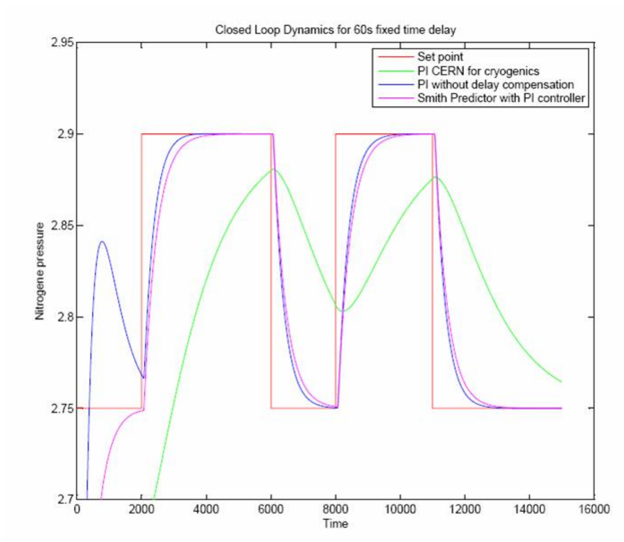

Fig. 7 Closed loop dynamics for 60s fixed time delay

For a time delay less than 2 minutes the optimised PI controller, tuned to obtain a first order response of the closed loop, is adapted to the process as well as the Smith Predictor controller. The cryo-PI controller shows a very slow response to the dynamic excitation.

In Fig. 8 a 300 seconds process time delay has been simulated. The typical tuning of a cryo-PI, done by cryogenics operators, faces time delay or inverted response problems increasing the Ti coefficient. This methodology gives modest dynamic response but combined with dominant slow dynamic processes, very frequent in cryogenics, the final result obtained is acceptable. Only the Smith Predictor keeps its combined precision, velocity and zero overpass, while the optimised PI controller response could bring, if applied, the cryogenic system to an instability operation region. This is shown by the curve of the optimised PI controller with a larger time delay (300s).

4 HIDEN Matlab toolboxe for MIMO model identification of the barrel argon bath temperature

Based on liquid Ar temperature measurements (200) and LN_2 pressure (P_{LN_2}), a multivariable identification process [8], has been studied. HIDEN MATLAB toolbox [9] is a classical scientific multivariable identification toolbox from Valladolid University (Spain). In our work, the identification will create a model which relates directly the P_{LN_2} with the LAr temperatures. The resulting output of the optimized control of the P_{LN_2} will go directly into the transfer function which links the P_{LN_2} and the overall temperature of the liquid Ar in the barrel cryostat (see Fig. 9).

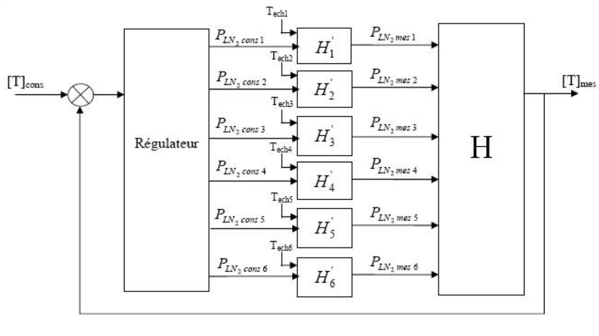

Fig. 9 Temperature multivariable model combined with the pressure closed loop transfer function

An accurate description of the multivariable identification procedure and test description will be reported in the following. The cryogenic process can be classed [10] in a continuous process type around a stability point which uses linear time-invariant dynamic models for control. It is a large scale and complex process, it has 6 MVs (Manipulated Variable or input) and 10 CVs (Controlled Variables or output) with oscillating behavior and time delays. Dominant slow dynamics, time ranges of several hours dictate relative long time for identification test. Identification must respect important constraints as a duration of 10-15 times the longest response time and a wide spectrum test signals.

The test protocol should include that all the inputs have to be uncorrelated between themselves and their autocorrelation should be also close to a white noise. Generally, a white noise cannot be applied on a real process due to the actuators. Hence, the stimulation input chosen is a parameterized Pseudo Random Binary Signal (PRBS). An automatic function has been developed in the supervision system capable to recreate these signals where the amplitudes and switch times are parameterized. This functionality results to be an asset for the procedure of the identification because of the dominant slow time process, the control engineer will not be obliged to organize night-shift in order to follow the test protocol which could last several weeks. Moreover, this functionality is based on the UNICOS supervision system and its implementation will not compromise the security of the control system layer [3].

The temperatures variations of the liquid argon calorimeter and their distributions have been simulated by a numerical estimation using LES method (Large-Eddy Simulation) [11]. Moreover, the constant time of the cryogenic system faces some uncertainties. A preliminary pre-test should be performed on the system permitting the verification of the cryogenic system time constant and delay. The measuring data recording for the studies would stretch over approximately 2 weeks 24 hours per day continuously. The average switch time of all the PRBS signals are set to 120 minutes. Amplitude variation set point for P_{LN_2} would be set in a range of ± 10 kPa (± 0.10 bars) around the stability position, good enough signal-to-noise ratio and not disturbing the stability point of the cryogenic liquid inside the barrel calorimeter see Fig. 10. The first step after the data taking is to remove the continuous component of all signals. A high pass filter with a turn-over pulsation ω combined with a low-pass filter for noise removal.

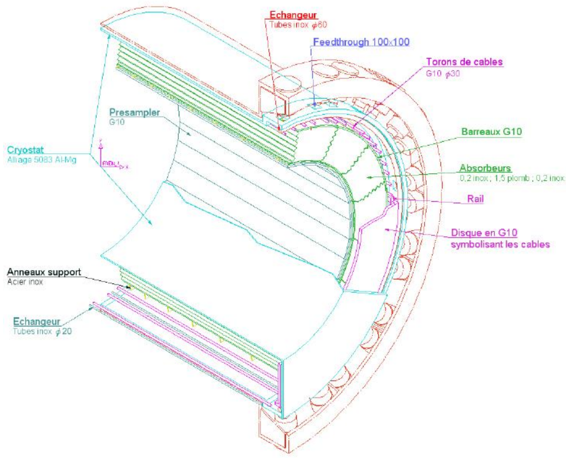

Fig. 10 Cross section of the Barrel Calorimeter

The multivariable process with m manipulated variables (inputs) and p controlled variables (output) will produce, during an identification test, the data sequences as shown in Eq. (2) where u(k) is the m-dimensional input vector, y(k) is p-dimensional output vector and N is the number of samples[8].

$$Z^N := \{u(1), y(1), u(2), y(2)......., u(N), y(N)\} \quad (2)$$

The model chosen will be an ARX model (AutoRegressive with eXternal inputs).

Then, the parameter estimation is performed using a Least-Square (LS) method on MATLAB with a specialized toolbox HIDEN. The LS algorithm allows to minimize the quadratic cost function see Eq. (3):

$$\nu = \frac{1}{N}\sum_{k=1}^{N}\varepsilon^2 = \frac{1}{N}\sum_{k=1}^{N}(y(k) - \phi^T\theta)^2 \quad (3)$$

So if the system to identify has a model $y = \phi \cdot \theta$, where y is the system output, ϕ observation matrix and θ parameter vector; the optimal θ can be calculated with the pseudo inverse of ϕ:

$$\theta = \left[\phi^T\phi\right]^{-1} \cdot \phi^T \cdot y \quad (4)$$

with $[\phi^T\phi]$ invertible. After this step we should proceed in a comparison with Recursive Least Square (RLS) algorithm to see if the resulting parameters change, as well as doing a comparison of results using higher order model. This algorithm takes more calculation time than the LS algorithm but it can provide better results. Then, an analysis of residues is necessary (errors between model and process). Residue values can be estimated by the calculation of the Final Predicted Error (FPE):

$$FPE = \frac{1}{N} \cdot \frac{1+\frac{d}{N}}{1-\frac{d}{N}}\sum_{k=1}^{N}(y(k) - y_m(k))^2 \quad (5)$$

where d is the number of parameters estimated, N the sample number and y_m the model output.

At this stage, a validation of the model has to be proceed with experimental data. If these values are consistent we can consider the identification process done, in the other case a re-identification guideline would be necessary. The tests described will be carried out on the real system when all the calorimeter temperature measurements are available. The architecture necessary for the multivariable identification procedure has been put in place. Based on the LHC long term data archive technology it includes data recording and retrieving tool with several hundred signals record capacity.

5 Conclusion and perspectives

This work presents an identification procedure applied to a large cryogenic process, using UNICOS /CERN standard. Different functionalities have been defined in a specific procedure using scientific identification toolbox(HIDEN) and industrial tools (Optireg) reducing application time and manpower, i.e. automated script for MV movements in the supervision system and the development of an automatic interface for PI tuning with and without delay compensation.

In SISO identification tests, the results have given us an appreciation about the type of control achieved without a proper identification. The response behaviour of the typical cryo-PI controller (with large Ti coefficient) remains acceptable in dominant slow time process very frequent in cryogenic process. The comparisons between different controls resulted in the proposal of a new controller based on Smith Predictor model in order to ameliorate the control of the individual nitrogen pressure in the heat exchangers.

In MIMO identification a specific procedure has been established and it is planned in future, when the ATLAS-DCS supervision system and their very accurate temperature sensors will be operational, to proceed with a multivariable identification.

The multivariable identification of the system will be the base for future scientific studies in advanced controlled field in order to obtain a high efficient advanced controller for the stability and uniformity of the argon bath temperature.

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