

DYNAMIC SYSTEM ANALYSIS FOR EDUCATIONAL PURPOSES: IDENTIFICATION AND CONTROL OF A THERMAL LOOP

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ABSTRACT

Phenomena like thermal inertia are difficult concepts to understand for students, because they are difficult to model or to measure. The control theory, on another hand, is often learned in terms of an abstract theory. We have developed a pedagogic cursus, based on the use of a test bench initially dedicated to the test of solar thermal collectors, in order to allow the students to be in real contact with these concepts. The aim of this cursus is to ask them to apply identification techniques and control theory on a real system, with an emphasis on the fact that they have to produce not only theoretical models, but real and proved results.

Keywords: Identification, PID control, pure delay

1 INTRODUCTION

1.1 Framework

The Centre for Energy and Processes (CEP) has developed in his laboratory at Sophia-Antipolis a test bench for solar thermal collectors (fig.1). This test bench operates in an automatic way. It can rotate on itself, in order to follow the sun and to have constant irradiation of the collector during long sequences.



Figure 1. The automatic test bench for solar collectors in Sophia-Antipolis.

According to the norm NFP 50-501, the aim of the test is to measure the collector performance in steady-state conditions. This implies to maintain during long sequences (typically 30 mn) constant operating conditions in terms of incident irradiation and input temperature. This last condition is difficult to satisfy practically. The reason is that the water circulates in a closed loop, according to the hydraulic scheme given in figure 2.

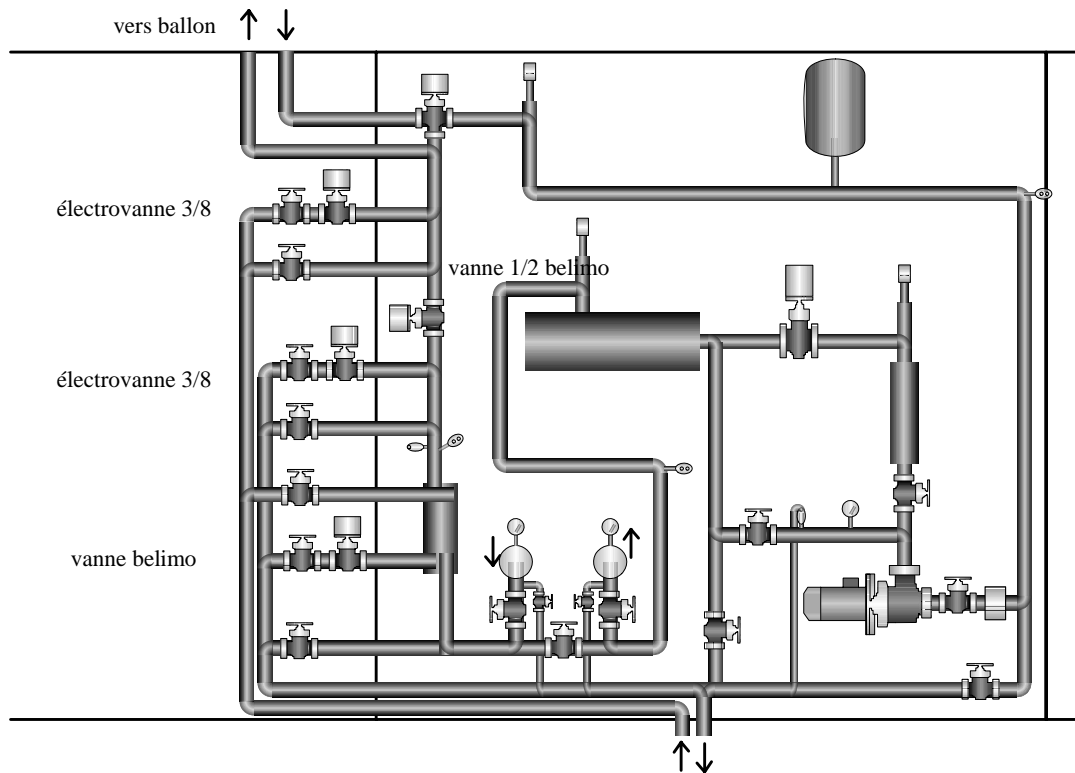


Figure 2. Hydraulic scheme of the water loop.

The water leaves the water loop at a given temperature T_s . This setpoint temperature must remain constant at ± 0.2 °C during the test. After being heated in the collector, the water must be in a first time cooled thanks to an heat exchanger, and then re-heated to its setpoint T_s thanks to an electric heater. Due to the high quantities of metal in contact with the water (pies, pump, vanes, electric heater, ...), the behaviour of the water temperature is characterized by a strong thermal inertia, and the control of the power delivered to the electric heater becomes a very difficult problem to solve in order to maintain the constant T_s setpoint.

1.2 Formalization of the problem

Fig. 3 summarizes the water circulation inside the thermal loop :

- T_s : temperature at the output of the electric heater, supposed to be equal to the setpoint temperature
- T_h : temperature at the output of the collector (the water is hot at this point of the loop)
- T_e : temperature at the output of the heat exchanger, cooled by cold water (about 20 °C)
- T_s : temperature at the output of the electric heater, supposed to be equal to the setpoint temperature
- T_c : temperature before the input of the electric heater

The problem to solve is to manage the electric power P delivered in the electric heater, in order to increase the value of T_c up to T_s . In order to lower the T_c - T_s difference, it is possible to mix partially the cold water T_e with some hot water contained in a storage, thanks to a 3 ways valve.

Two physical phenomena make the control of T_s difficult :

1. The presence of high inertia parts in the loop (copper in the pipes, and steel in the electric heater)
2. The existence of pure delays linked to the physical location of the temperature sensors and the low values of the flow during the test (typically 150 l/h).

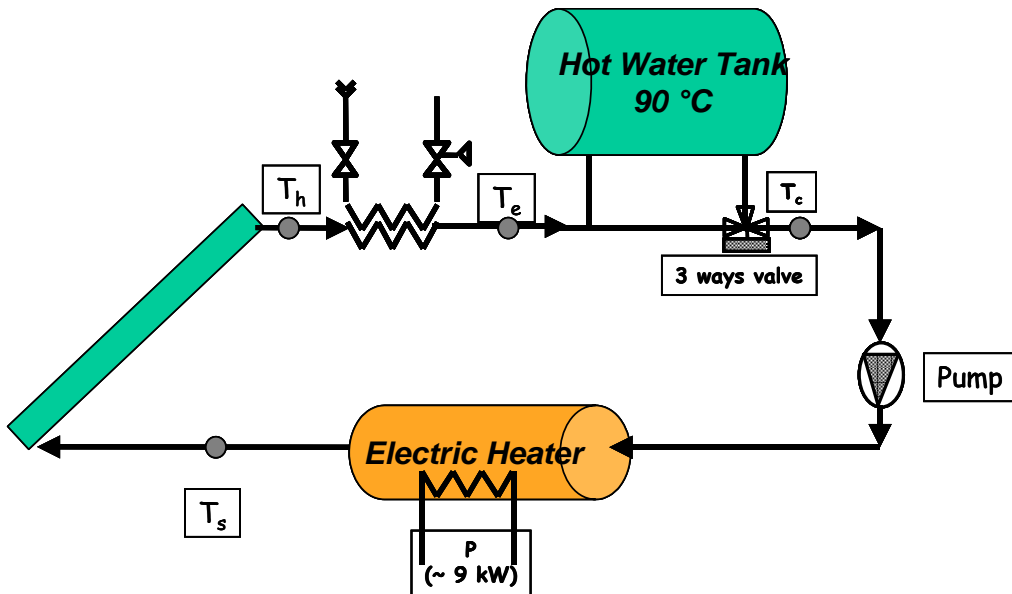


Figure 3. Functional scheme of the thermal loop.

In fig. 4 we can visualize the elements mentioned above :



Figure 4. The electric heater.

Finally, fig. 5 gives a representation of the "electric heater" system in the classical system analysis formalism.

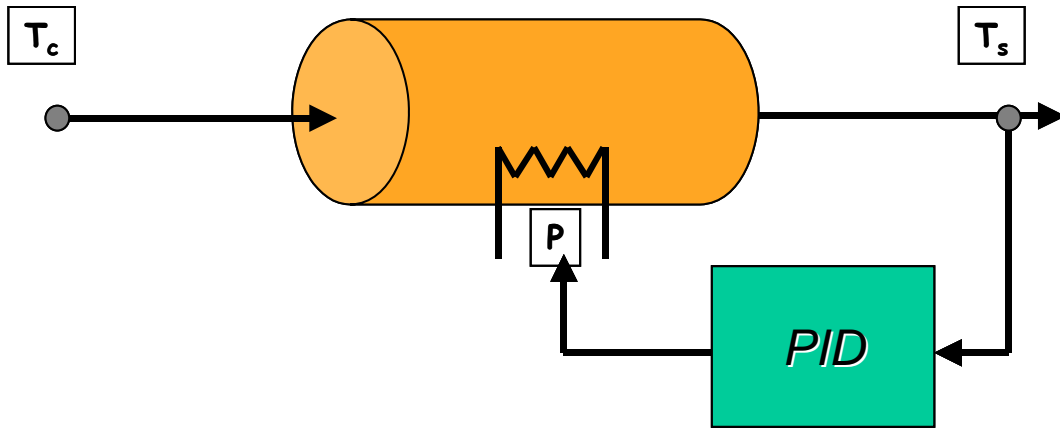


Figure 5. The electric heater on a system analysis point of view.

The electric heater is considered as a dynamic system with the following characteristics :

- The system has two inputs : T_c and P
- The system has one output : T_c

The goal is to control the output of the system T_s near a setpoint value T_{set} , using a single input/single output controller, that measures the output value T_s and modulates the value of the electric power P in a limited range $[0;P_{max}]$.

1.3 Methodology

It is proposed to the students to solve this problem according to a five step methodology summarized in fig. 6:

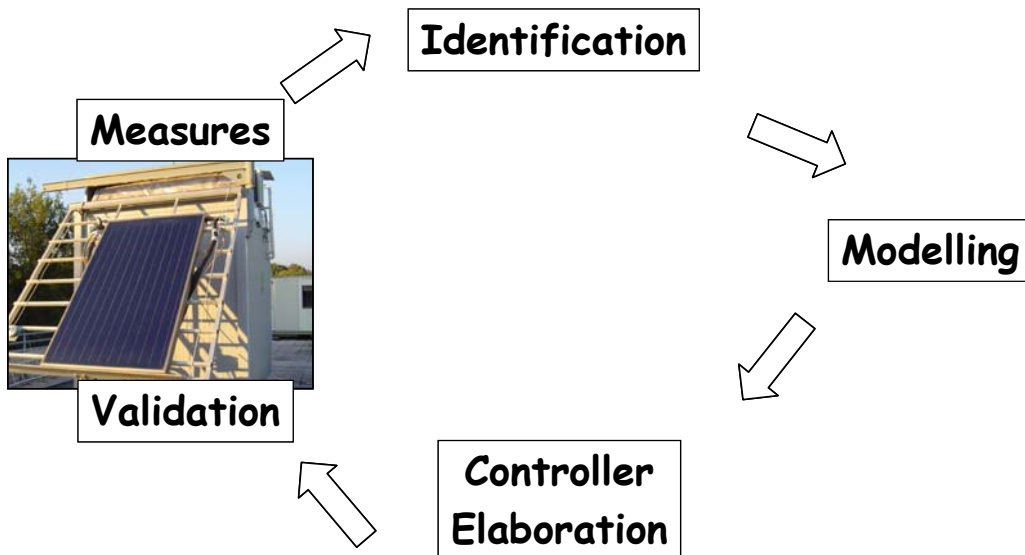


Figure 6. The five steps of the methodology.

- Measures : using a specific strategy for the management of the input values (typically steps), the students have to produce input-output series adapted to the dynamics of the system.
- Identification : system identification techniques are used in order to provide a reduced order model of the dynamic system.
- Modelling : the dynamic model identified in the previous step is included in a simulator of the behaviour of the thermal loop with a PID controller.
- The simulator elaborated is used in order to tune the parameters of a PID controller suited to the characteristics of the system.

- Validation : the parameters of the PID obtained in the virtual environment are introduced in the SCADA of the test bench, and the real performance of the PID are measured.

The next section give details on each of these steps.

2 METHODOLOGY DESCRIPTION

In this section, the 5 steps of the methodology are described using results obtained by a group of students in the final year of Ecole des Mines de Paris.

2.1 Measures

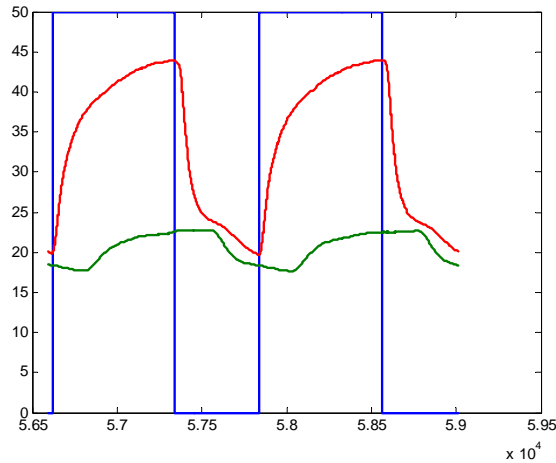


Figure 7. A typical measurements sequence.

Fig. 7 here over shows a typical input/output sequence. The blue curve shows the electric power input P , that is managed following a on/off strategy : the power is on (50 % of its P_{max} maximum value) during 750 seconds, then is set to off for 500 seconds.

One can observe that this management is adapted to the system's dynamics : the output temperature T_s (in red) follows a step response curve, allowing its dynamic characteristics to be identified on the next step. One can remark that the measurement sequence is rather long (~ 30 mn), and that the students have to make numerous tests before to obtain the right sequence.

2.2 Identification

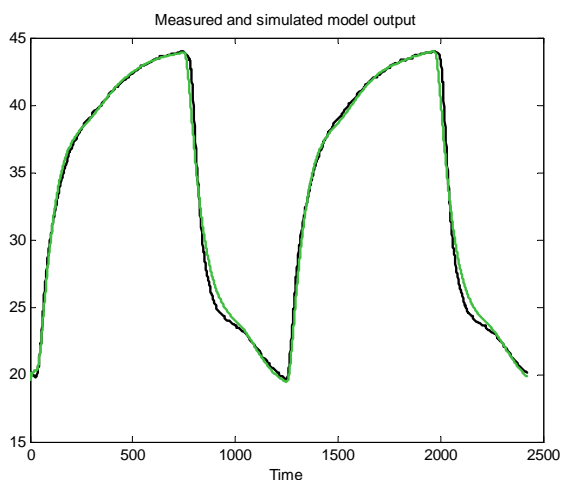


Figure 8. Measured and simulated output signal.

Fig. 8 shows the output simulated by an identified model, compared to the measured signal. For this exercise, we use the matlab® "ident" toolbox, that allows the students to test and to compare different types of models : discrete or continuous models, state space or transfer function,

The question of pure delays is also a difficult one. Theoretically, some options in the ident toolbox allow to identify these delays. However, since pure delays are highly non linear phenomena, and since the delays in this loop are very high (between 1 and 2 minutes), it is preferred to manually determine these delays (by using specific measurements sequences), and to remove the delays from the signals given to the identification algorithm.

2.3 Modelling

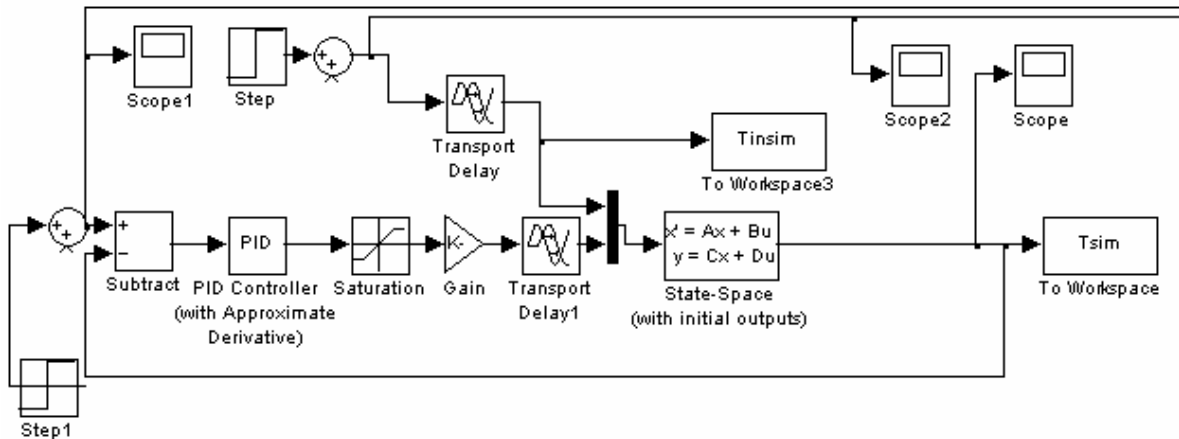


Figure 9. The thermal loop in the simulink® environment.

The model obtained in step 2 can now be included in a global simulator :

- The electric heater and its dynamic behaviour is modelled thanks in the upper illustration to a "state-space" block, whose parameters are the ones obtained in the identification step.
- The pure delays, that were removed for the identification step, are added as "Transport Delay" blocks.
- A PID block is added, which measures the output temperature T_c (T_{sim} in the fig. 9 scheme), and compares it to a setpoint temperature
- The output of the PID is limited by a saturation block, in order to take into account the physical limitations of the heater, that can not produce negative power and is bounded by a P_{max} value.

Beside the simulation exercise, that has by itself a pedagogic interest, the building of the simulator is necessary for the next steps, since it is a virtual representation of the thermal loop, with the particularity that the behaviour of the loop during one hour can be obtained in a few seconds.

2.4 Controller set up

The simulator is then used in order to properly set the p, I, and d parameters of the PID controller. Depending on the context, many methods can be used. One of the most commonly used is the well known Ziegler-Nichols empirical method.

In this method, the PID controller is in a first step used in proportional mode only. The p parameter is increased step by step up to the critical value (called critical gain p_c) that puts the output signal in a regular oscillating mode.

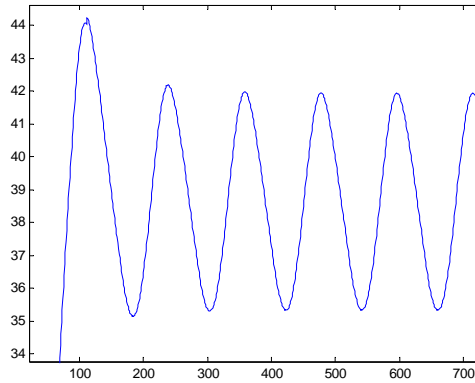


Figure 10. The output temp. T_s in regular oscillating mode.

Then the values of the critical gain p_c and the period of the oscillations T are used in empirical formulas that give values adapted to a PI or o PID control of the loop.

These values are entered in the PID block, and one can verify that the Ziegler-Nichols tuning works properly on the simulated system, as illustrated in fig. 11.

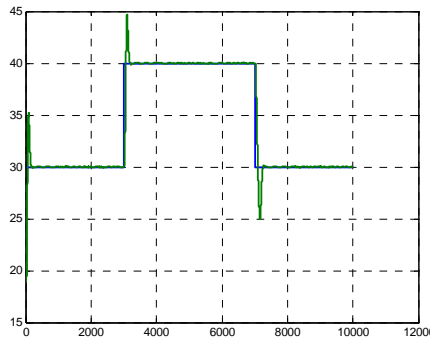


Figure 11. The output temp. T_s controlled by the Ziegler-Nichols PID.

In this example, the set point temperature is 30 °C at the beginning of the sequence, then 40 °C after about 1 hour, and then 30 °C again after another hour. The controlled temperature T_c follows perfectly the set point.

This phase of controller tuning is easy to do in the virtual simulated environment, and we have to note that due to the inertia of the systems, many experiments of many hours, or in another words many days would be necessary to make the same tuning on the real system.

2.5 Validation

Finally, one of the utmost interest of the exercise is to show that these theretical phase of identification and modelling have very practical consequences. The pid parameters obtained on step 4 are thus introduced in the Scada system of the test bench, and the behaviour of the real system is observed :

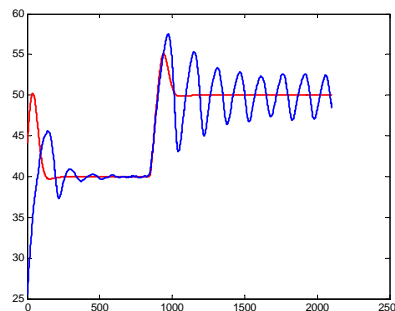


Figure 12. Measured output temp. on the test bench.

In the first part of this test, a set point temperature of 40 °C is used. The real temperature reaches this set point after about 10 minutes of oscillation. The 0.2 °C accuracy around the set point is observed. But in the second part, the set point is increased up to 50 °C. Then the system enters in an oscillating state and the set point can not be reached.

In this example, the students have learned how identification can help in this exercise of controller set up, but also that the model is not a perfect representation of the real world.

3 CONCLUSIONS

The problem solved by the students using identification techniques is a real problem that has taken many months to the CEP engineers to be solved when the test bench was build. As explained in section 2.4, the use of empirical methods on the real system leads to days and days of tests, and the results are not absolute, since they have to be revised for any change in the loop, like water flow for instance.

Thus it is a good illustration of the fact that analysing a system in transient conditions and using identification techniques is a quick and accurate way for the characterisation of a system, even if the final wish is to maintain this system in steady state conditions.