General presentation

In this tutorial, we are interested in the control of a blower that propels hot air inside a cylindrical tube. The aim is to control both the mass flow rate and the temperature of the air leaving the tube, by acting on the fan speed and the heating power.

We propose to implement :

- A predictive control that responds to network solicitations, more particularly to partial but short duration load shedding requests, without degrading the quality of the regulation too much.

In addition to the wind tunnel model, a PC equipped with the MATLAB-SIMULINK calculation and simulation environment is used to identify a model of the process studied and then to develop the control laws in simulation as well as in real time.

Proposed approach

This practical training is organized in 2 face-to-face/distance sessions and is accompanied by personal work between the 2 sessions.

- **Session 1: Identification of the operative part and experimental validation. The model must be validated by the supervisor before the beginning of session 2.**

- **Homework :** Development of a predictive control strategy. Choice of the optimization criterion, and parameter setting. Validation in simulation.

- **Session 2:** Experimental validation of the 2 strategies developed in sessions 3 and 4. Understanding of the differences between the results obtained in simulation and in experimentation, then adjustment if necessary.

Work to be done

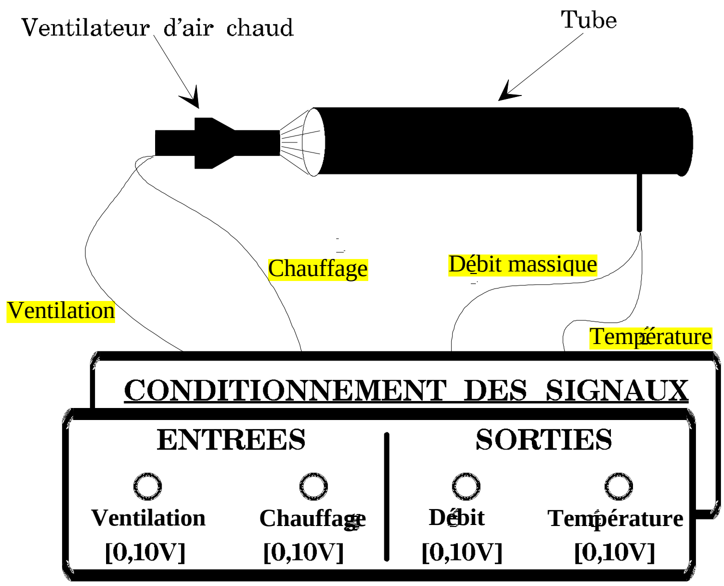
Each session must be the ended with a very short but precise report which attests to the quality of the results obtained and their analysis.

Description of the layout

The LTR 701 equipment is an integrated air flow and temperature control system. Its operating part is a blower that propels hot air inside a cylindrical tube. It is a multivariable process with 2 actuators and 3 sensors. The first actuator controls the fan speed and the second the heating power. In addition, there is a manual adjustment of the angular position of the air intake throttle in the tube. A first sensor allows to measure this angular position. A thermocouple is used to measure the temperature at any of the four measuring points available on the tube. Finally, a mass flow meter allows to measure the air flow at the outlet. It should be noted that the system still foresees the possibility of installing a pressure sensor at the end of the tube, but this one is not present.

In the proposed experiment, only the flowmeter and the thermocouple will be used, choosing for the latter the temperature measurement point located closest to the tube outlet.

Scheme



Physical signals

All signals are operated in the range [0,10V].

Control input

The two controls available on the process are respectively the fan speed and the heating power. These two variables can be adjusted manually by means of potentiometers. They can also be controlled externally by a voltage between 0 and 10 V. To activate the external control inputs (banana jacks), the potentiometers must be in the "off" position.

In order to protect the equipment from possible damage, a safety device automatically switches off the heating when the fan speed is below 10%. Furthermore, it can be observed that each of the processes has a limited operating zone for which the linearity assumptions are satisfied (see below). This must be taken into account in the model by introducing the appropriate saturations.

Sensors

The flow and temperature sensors have a measuring range of 0 V to 10 V.

Operating point

The static study of the operating part reveals the existence of a control zone in which its behavior can be considered as quasi linear. The operating point will be chosen in the middle of this zone, and defined by a ventilation command and a heating command both equal to 5 V. In addition, the throttle opening will be manually adjusted in order to guarantee a maximum excursion of the ventilation command and the flow measurement, while avoiding saturation of the latter quantity. This setting will be maintained for all manipulations.

Session 1: Identification

Organization of the session

The objective is to determine a model of the wind tunnel process in the form of a continuous state model. The identification of this model may be done using the Toolbox Identification of Matlab, from measurements made on the model.

The following steps will have to be carried out:

- Pre-study and choice of operational conditions (signals used, sampling frequency, number of points, ...)
- Acquisition and saving of measurements
- Identification and validation of the model(s) in Matlab.

Deliverables

The report of this first session must recall the chosen measurement protocol, provide the results obtained in terms of models and justify their validation.

Homework 2: Model Predictive Control

The goal of this session is to implement a predictive control to anticipate partial power reduction requests, without degrading the quality of service of the process.

These partial blackout requests have a limited duration of 1.5 seconds, but can be repeated during the experiments.

To do this, at a given time, we assume that we know on the prediction horizon, whose size N_p is to be determined :

- The maximum power available $P_{max}(K|k)$
- Expectations in terms of quality of service, which are reflected in:
    - One temperature measurement (in V) which has to be between $T_{min}(K+1|k)$ and $T_{max}(K+1|k) = T_{min}(K+1|k) + 2$ (only $T_{min}(K+1|k)$ will be given)
    - A flow measurement that must be greater than $D_{min}(K+1|k)$

Modeling the power consumption:

It will be assumed that the total power consumed is equal to the sum of the flow and temperature controls.

Work to be done:

Two steps are required:

- **A development of the optimization problem related to the chosen MPC strategy in Matlab (a Live Script file is provided for you to complete). This step includes among others:**
    - The discretization of the process you identified in session 1 (and therefore implicitly, the choice of a sampling period).
    - Adding the operating points and setting up an observer.
    - The construction of the prediction model and its propagation over the prediction horizon (and therefore implicitly the size of the prediction horizon)
    - Definition of the optimization problem: criteria and constraints
    - The choice of a solver for its resolution, and the associated formatting
    - Obtaining the optimal sequence and validating the obtained behavior

- **The implementation of the closed loop strategy.** This one will have to be implemented in the Simulink file provided that will have to be completed.

Deliverables

The assignment is due before the beginning session 2: **the 11th of May. It will be helpful for the exam!**

- A short report that justifies the different settings chosen, in particular:
- The choice of the sampling period
- The size of the prediction horizon
- The definition of the optimization criterion and the constraints
- The formalisation of this problem to use the adequate solver.
- The Matlab/Simulink file that attests the good behavior of the system in closed loop with the chosen setting.

Session 2: Implementation

In this last session, we propose to implement the different control strategies on the model.

Given the circumstances, the validation will be done on a simulator of the model, made available in Teams.

The objectives of the two control strategies being different, you will find in the session 4 directory two simulink files, one dedicated to the standard state control, the other to the predictive control.

The two models are different, you must specify before launching your simulations the number of the model on which you have made your identifications. This is done by running the 'init.m' script

Session organization

The objective of the session is to compare the results obtained in simulation on the control model and the simulator.

Chances are that the results will be slightly different or even surprising ... that's good, you have time to think ... A hint: it is unlikely that it comes from the identification, even if it is not a problem to exclude ...

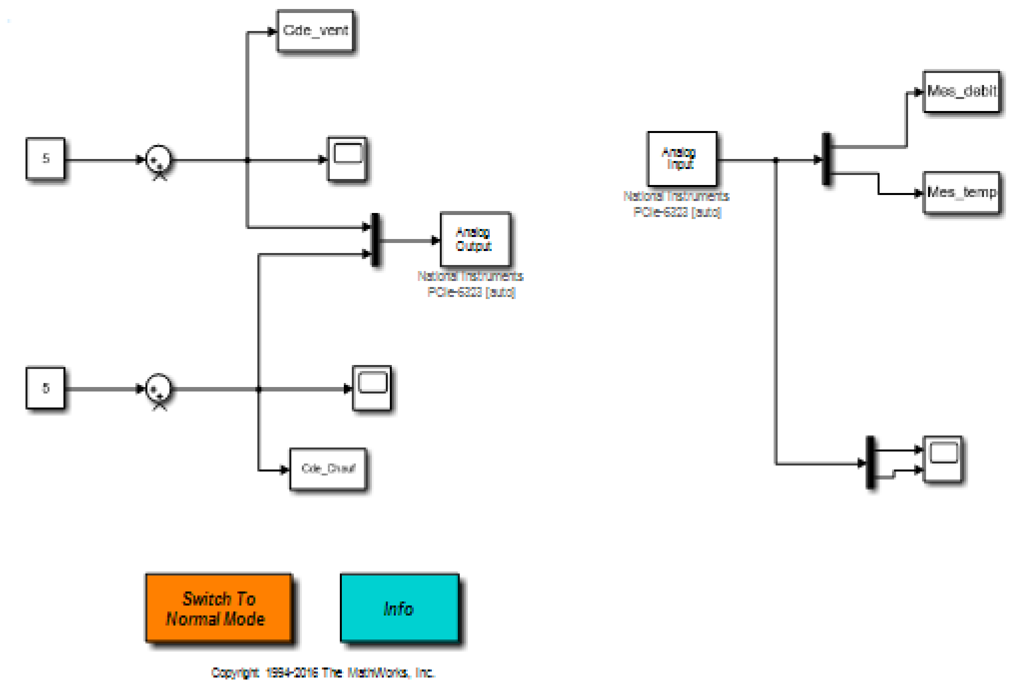
Deliverables

- a well-written AND synthetic Live Script, and a Simulink will do the job for the technical part
- a 5 slide-powerpoint to present the results

Appendix 1: Implementation for signal acquisition for identification

To realize this acquisition, we will use the identification.slx program developed in the real time environment of Simulink associated with the management of the NI PCI 6323 input/output card. This program generates the control signals (ventilation and heating) to the model and allows to recover the measurements from sensors (flow and temperature). Each of these signals is stored in the workspace, and it is advisable to save them in a file (.mat) to use them later during identification.

Before launching the execution of the identification.slx program, it is necessary to initialize at least the sampling period by executing the init_identification.m file (to be completed according to the choice(s) made).



Simulink diagram _ Signal acquisition

$$\begin{cases} x(k+1) = A\,x(k) + B\,u(k) - B\,u_0(k) \\ y(k) = C\,x(k) + y_0(k) \end{cases}$$

$$\begin{pmatrix} \underset{8\times1}{x(k+1)} \\ \underset{2\times1}{u_0(k+1)} \\ \underset{2\times1}{y_0(k+1)} \end{pmatrix} \overset{\text{def.}}{=} \underline{X}(k+1)_{12\times1}$$

$\Rightarrow$

$$\begin{cases} \underline{X}(k+1) = A_a\,\underline{X}(k)_{12\times1} + B_a\,u(k) \\ y(k) = C_a\,\underline{X}(k) \end{cases}$$

with

$$A_a = \begin{pmatrix} A & -B & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{pmatrix}_{12\times12} \quad B_a = \begin{pmatrix} B \\ 0 \end{pmatrix}_{12\times2}$$

$$C_a = \begin{pmatrix} C & 0 & I \end{pmatrix}_{2\times12}$$

Find the observable part:

$[AO, BO, CO, \underset{12\times12}{TO}] = \text{obsvf}(A_a, B_a, C_a)$

Observable part:

$\underset{12\times12}{AO} = TO\,A_a\,TO^T$ $\quad A_{o\,10\times10}$

$\underset{12\times2}{BO} = TO\,B_a$ $\quad B_{o\,10\times2}$

$\underset{2\times12}{CO} = C_a\,TO^T$ $\quad C_{o\,2\times10}$

Observer part:

$$\hat{\underline{X}}(k+1) = A_o\,\hat{\underline{X}}(k) + B_o\,u(k) + \underset{10\times2}{L_o}(y(k) - \hat{y}(k))$$

$$\hat{y}(k) = C_o\,\hat{\underline{X}}(k)$$

$\Rightarrow$

$$\hat{\underline{X}}(k+1) = (A_o - L_o C_o)\,\hat{\underline{X}}(k) + B_o u(k) + L_o y(k)$$

To satisfy the "MPC Controller" in Simulink:

$$\boxed{\begin{aligned} X_{n+1} &= A_{obs}\,X_n + B_{obs}\,U_n \\ Y_n &= C_{obs}\,X_n + D_{obs}\,U_n \end{aligned}}$$

with:

$X_{n+1} = \hat{\underline{X}}(k+1)$ $\quad X_n = \hat{\underline{X}}(k)$

$U_n = \begin{pmatrix} u(k) \\ y(k) \end{pmatrix}_{4\times1}$ $\quad Y_n = \hat{\underline{X}}(k)$

We get:

$A_{obs} = A_o - L_o C_{o\;10\times10}$

$B_{obs} = (B_o \;\; L_o)_{10\times4}$

$C_{obs} = I_{10\times10}$

$D_{obs} = 0_{10\times4}$