ASSOCIATION POUR LE DÉVELOPPEMENT DE L'ENSEIGNEMENT
ET DE LA RECHERCHE EN SYSTÉMATIQUE APPLIQUÉE

MELISSA :

FISRT APPROACH OF MODEL BASED PREDICTIVE CONTROL OF SPIRULINA COMPARTMENT

Contract ESA-ESTEC/ADERSA
P.R.F. n° 132443

Technical Note 21.1

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October 1993

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SUMMARY

I - INTRODUCTION

The contract concerns the study of a **model based predictive control** law for the control of the production of Spirulina in the photo-reactor of MELISSA, by acting on the light intensity.

The results obtained during the first part of the study concern respectively :

- The identification of the dynamic transfer between the light intensity and the biomass production (when the concentration is constant), and the identification of the dynamic transfer between the light intensity and the biomass concentration (when the regulation loop of concentration is open).
- The elaboration of a simulator of the process, according to the identification results and to the physical knowledge of the process.
- Some tests of the predictive control strategy on the simulator.

II - TEST PROTOCOLS

For the elaboration of a model based predictive control, it is necessary to have a model of the transfer between the manipulated variable (action = light intensity), and the controlled variable (biomass production). This model, called the "internal model", is generally a simplified model, as a representation model. It is determined by an identification procedure, based on experimental test protocols. For the identification of this model, the test protocols have to stimulate the process in the same conditions as the control law will do. The process is also stimulated by step protocols of light intensity. During those tests, the other regulation loops (concentration, pH, NO^-_3, temperature, level ...) have to be closed.

To test the control law in good conditions, we have to elaborate a simulator of the process, which reproduces the behaviour of the process in various states of functionning. So, a more complete and precise model, as a knowledge model, is mandatory.

To determine it correctly, we need some other complementary test protocols. The process is stimulated by light intensity step protocols, when the concentration regulation loop is open. Then, the transfer between light intensity and biomass concentration can be identified. The problem of interaction between the concentration loop and the dynamic of production is then eliminated.

All those test protocols must be done for different concentration values in order to identify the influence of the concentration value on the dynamic of production.

III - IDENTIFICATION RESULTS

III.1 - Identification method

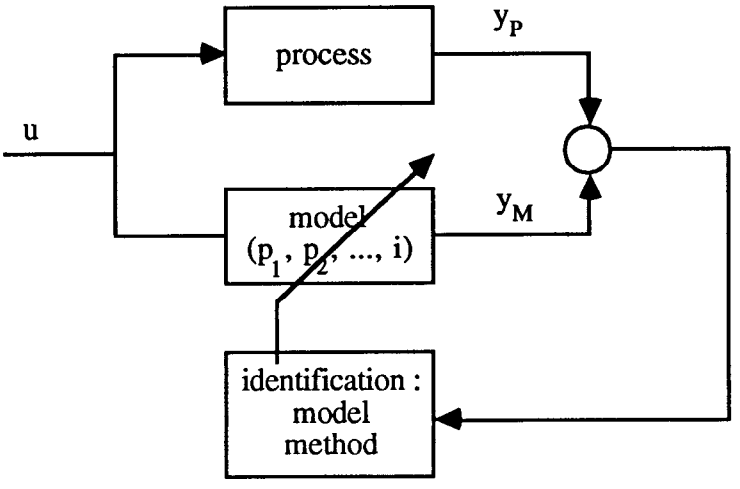
All the results of identification have been obtained with the software GLIDE (Global identification). We describe here after the procedure :

- The input and the output sequences are first analysed, in order to suppress eventually the parts of the signals where there are some problems (saturation, perturbation ...).

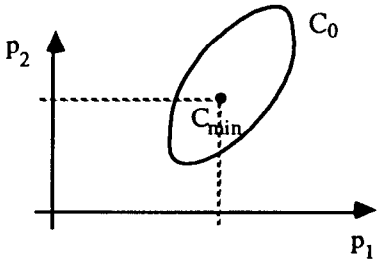
- Those signals are filtered by a parallel filter (low-pass, high-pass filter), to eliminate the high frequency noise, the mean value, and the linear trend on the input and the output sequences.

- The algorithm of local identification is then applied on the filtered signals. We use the analytic model method of "Gauss Newton". The principle of the model method is the comparison between the process and the model behaviours, for the same input sequence. It gives the parameters value (p_1, p_2, ...) that minimizes the state distance criterion between the process and the model.

$$C = \frac{\sum_{i=0}^{h} (y_P(i) - y_M(p_1, p_2, ..., i))^2}{\sum_{i=0}^{h} y_P(i)^2} \qquad [3.1]$$



- Then, the global identification procedure gives the validity domain for all the identified parameters. It analyzes the evolution of the state distance criterion in the parametric space, and allows to test the model validity.



III.2 - Transfer between the light intensity and the biomass production

The results presented here have been obtained with the step protocols of light intensity done at the beginning of July, 1993.

The transfer has been identified under a second order model :

$$H_1(s) = \frac{b_0 + b_1 s}{1 + a_1 s + a_2 s^2} e^{-r.s} \qquad [3.2]$$

Different test protocols have been used for this identification. The input and output sequences are represented on figure 1. The sequences are represented in function of time, expressed in hours. The signal 1119 is the light intensity in the middle of the reactor. The signal 1136 is the speed of production, and the signal 1120 is the concentration of biomass. We can note that the behaviours on the figure 1.a and 1.b are not the same, although the light intensity is the same. On the figure 1.c, we can detect a perturbation on the signal 1136. On the figures 1.d, 1.e and 1.g, we can see that a variation of concentration 1120 creates a perturbation on the speed of production. We can notice that those protocols are not very proper. The results of identification obtained with those protocols may be discussed.

The input and output signals are filtered by a low-pass filter with a time constant equal to 0.3 hour, and a high-pass filter with a time constant equal to 10 hours (figure 2).

The identification is then realized on the filtered data. The results of identification are presented on the figure 3. The criterion is given by the equation [3.1]. A delay is fixed to r = 0.4 hour, according to the file a2906 (figure 3.a). It seems to be justified on files a0207 and b0207. But this delay seems to have desappeared on files a0407, and b0507 (figure 4).

The results of identification are recapitulated in the following table :

		identified parameters				
	Files	b_0	b_1	a_1	a_2	Criterion
r = 0.4	a2906	0.26	1.67	2.52	1.85	3.7 %
	a0207	0.64	0.21	0.94	0.48	0.26 %
	b0207	0.76	0.03	1.08	0.17	0.68 %
	a0407	0.22	0.12	0.65	1.66	10.41 %
r = 0	b0507	0.72	0.52	0.54	0.35	1.35 %

In conclusion, the identification of the transfer between light intensity and speed of production is not easy to do. The parameters are not constant on the different test protocols. We can observe it on the figure 5 which represents the iso-distance surface for the different protocols. The iso-distance do not intersect. There is a great variation of parameters. Is it due to problems during the experience, or to the quality of the measures ? Those results of identification seem not sufficient for the determination of an internal model for the control. Some complementary tests are necessary to validate the results, but before doing those complementary tests, it seems very important to improve the quality of the measures.

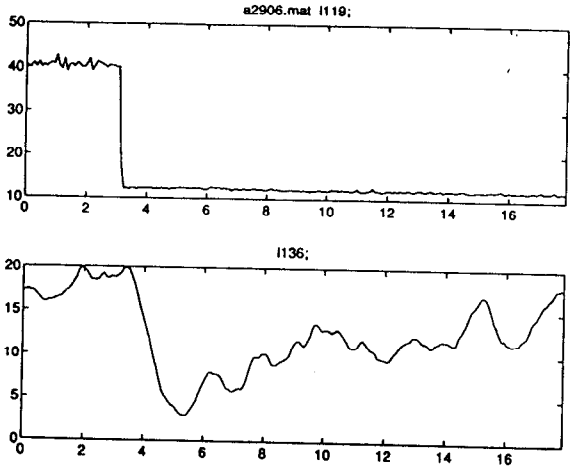


figure 1.a

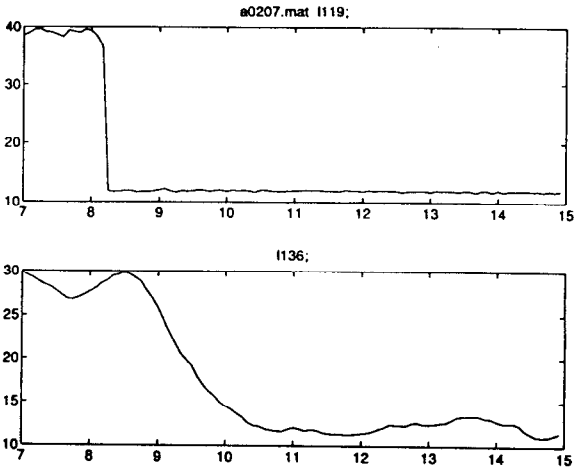


figure 1.b

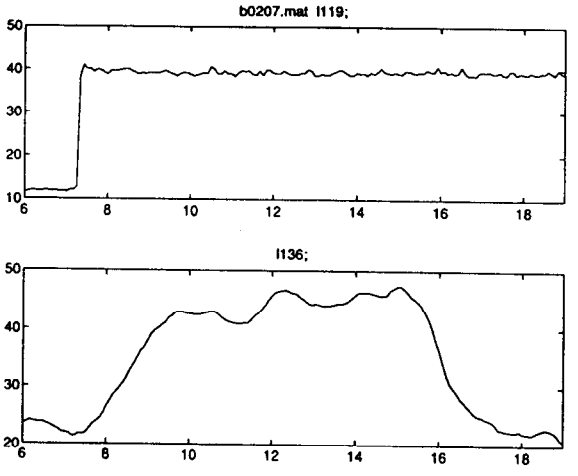


figure 1.c

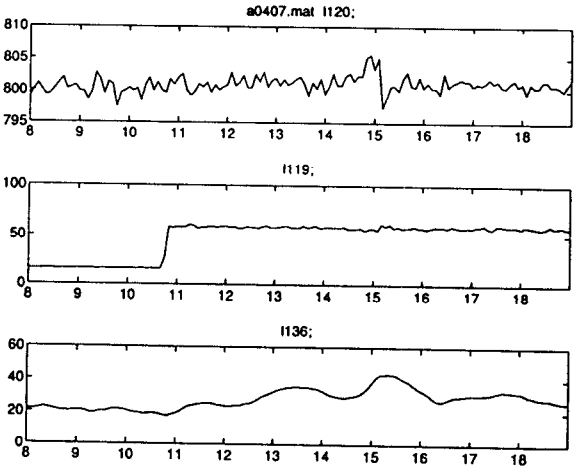


figure 1.d

Figure 1 - Step protocols of light intensity in closed loop

l119 : light intensity
l136 : speed of production of biomass

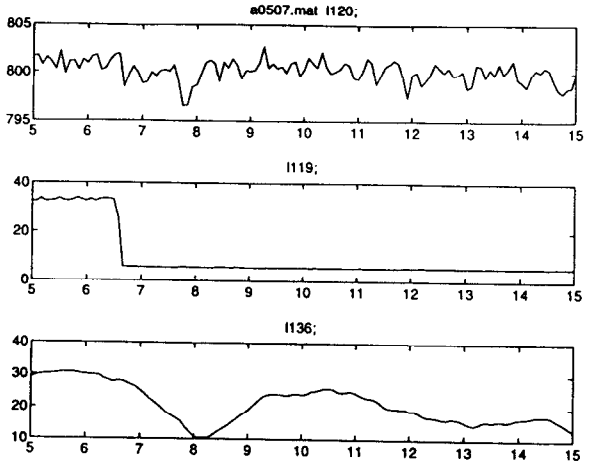


figure 1.e

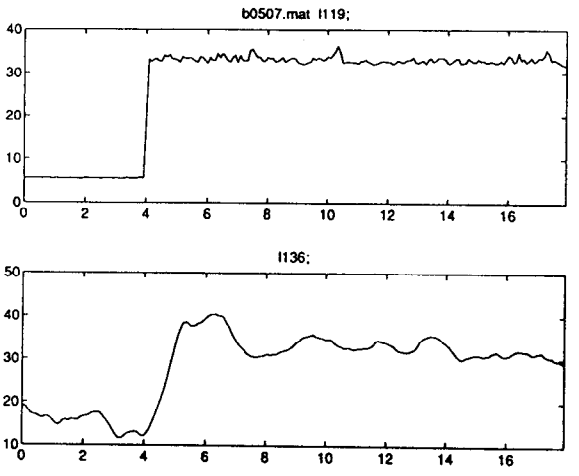


figure 1.f

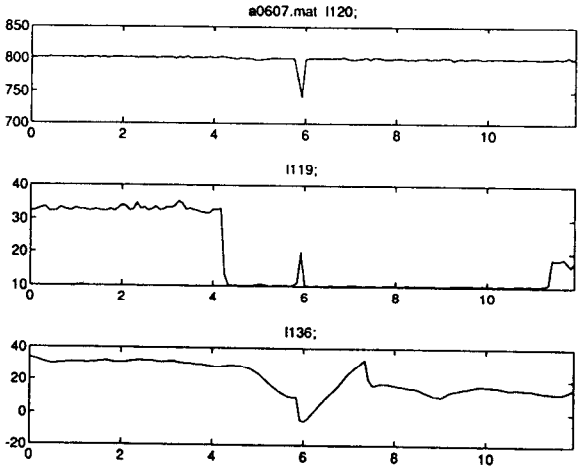


figure 1.g

Figure 1 - Step protocols of light intensity in closed loop

I119 : light intensity
I136 : speed of production of biomass

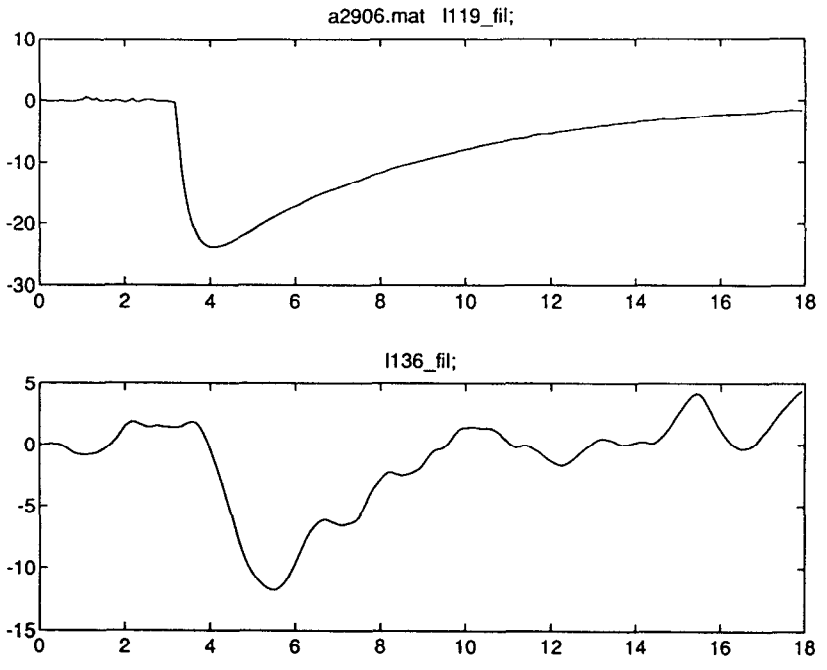


Figure 2 - Filtered data

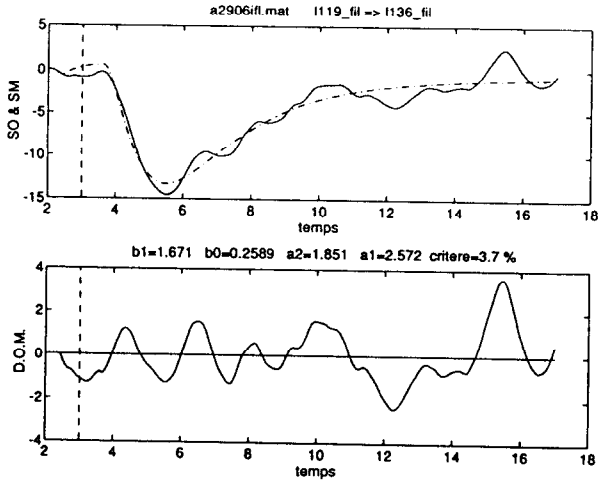


figure 3.a

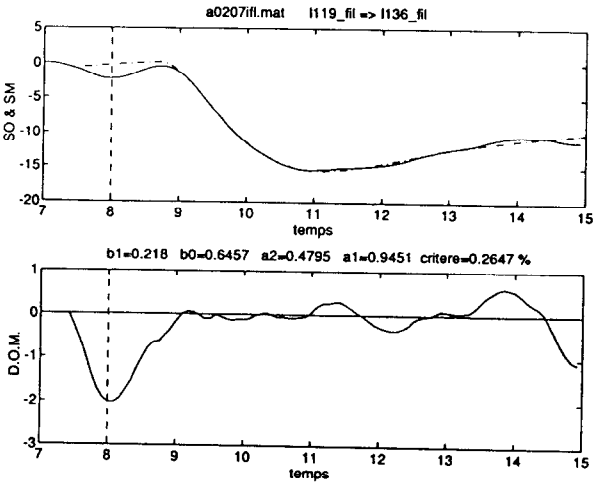


figure 3.b

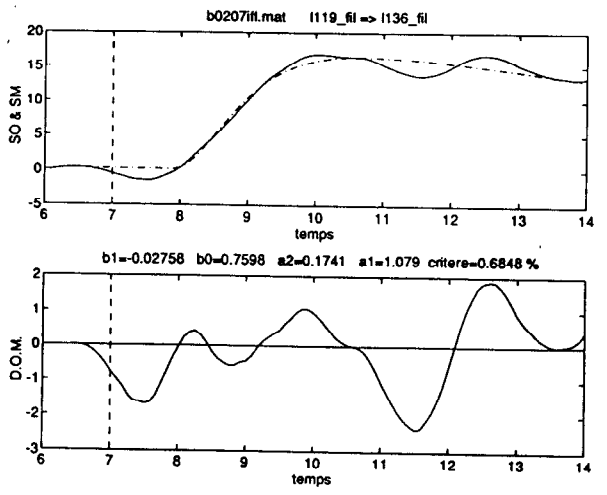


figure 3.c

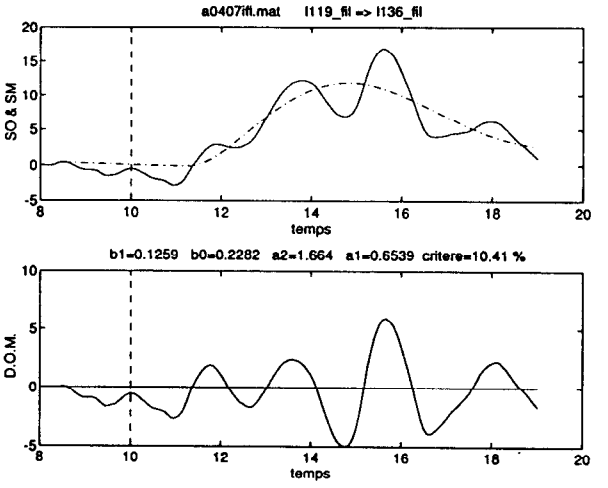


figure 3.d

Figure 3 - Results of identification (delay : r = 0.4 hour)

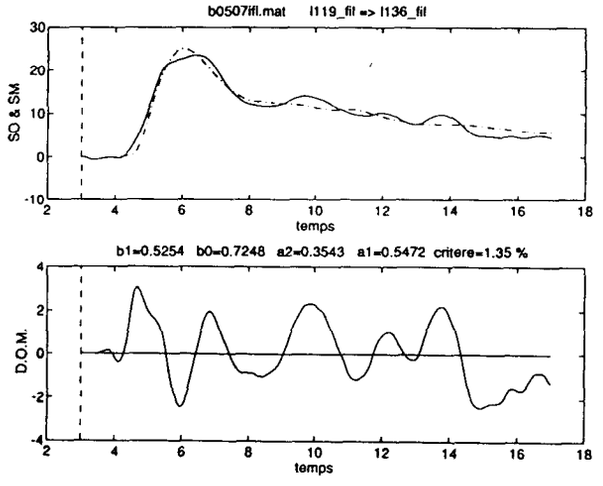


figure 3.e

Figure 3 - Results of identification (delay : r = 0.4 hour)

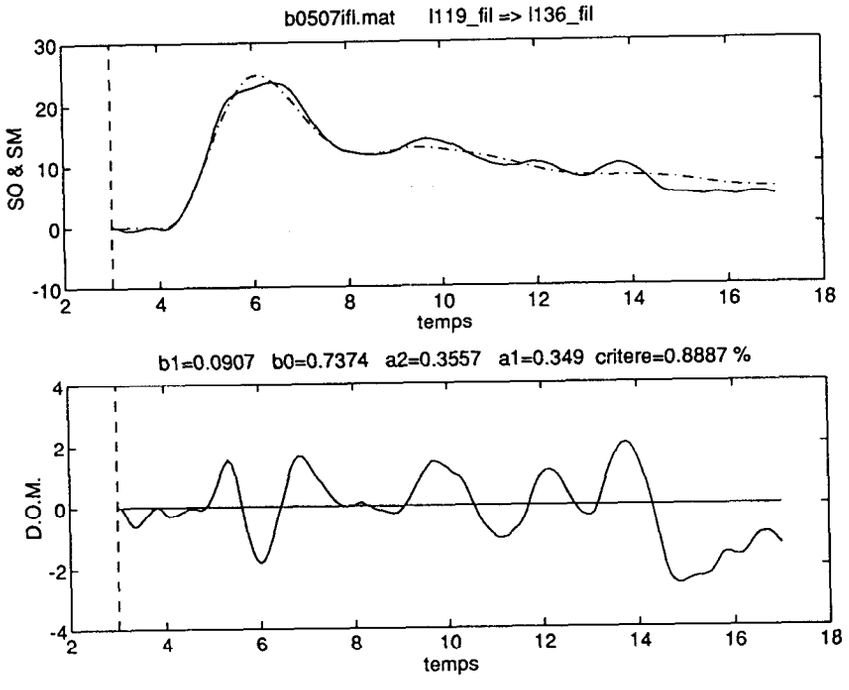


Figure 4 - Results of identification (delay r = 0)

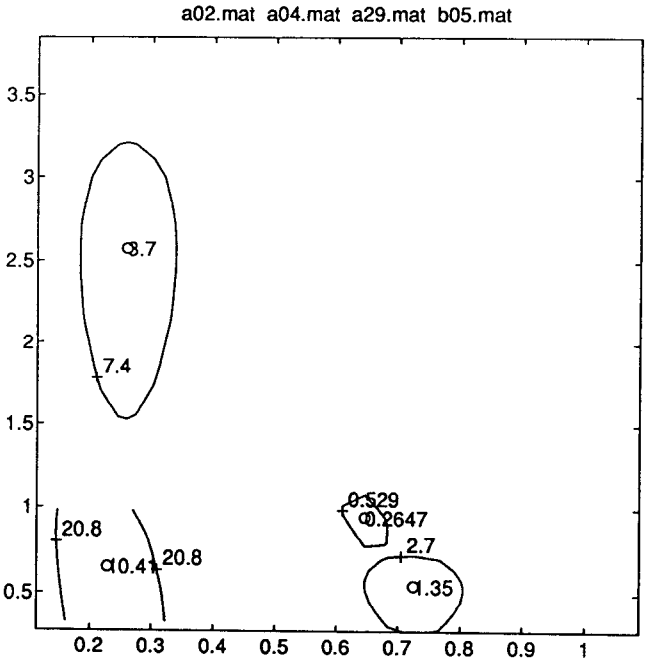


Figure 5 - Global identification (delay r = 0.4)

III.3 - Transfer between the light intensity and the biomass concentration

Those tests have been realized in open loop of concentration at the end of august. They can be used to identify the transfer between light intensity and biomass concentration. It is an integrator transfer. We identify it under the following form :

$$H_2(s) = \frac{b_0 + b_1 s}{s(1 + a_1 s)} \qquad [3.3]$$

The analysis of the test protocols (fbo1, fbo2 and fbo3) shows that the behaviour is not invariant. Those three protocols are realized in the same conditions, and the concentration in the file fbo1 is more oscillating (figure 6).

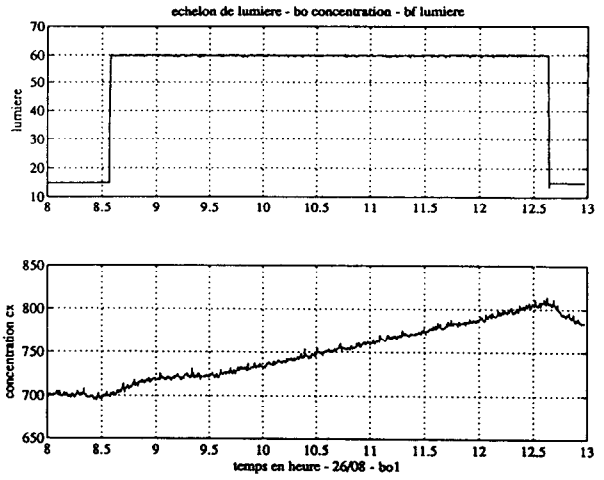


figure 6.a

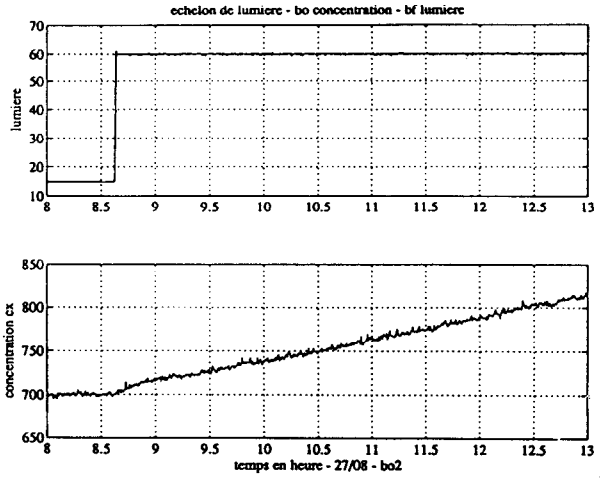


figure 6.b

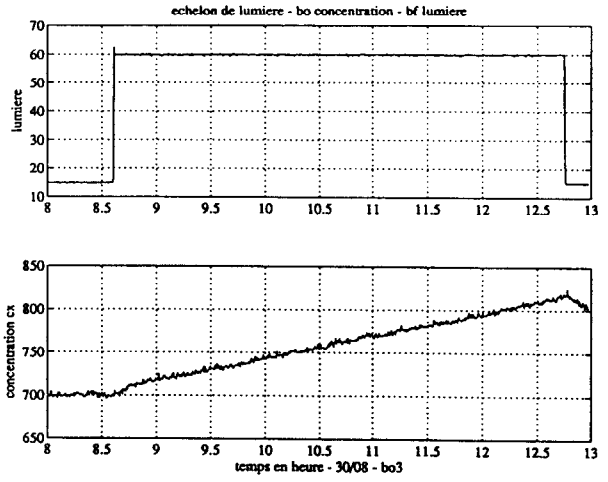


figure 6.c

Figure 6 - Step protocols of light intensity in open loop

The results of identification in open loop are shown on figure 7.

They are recapitulated in the following table :

	identified parameters			
Files	b_0	b_1	a_1	Criterion
fbo1	0.58	0.17	0.04	9 %
fbo2	0.54	0.17	0.03	1 %
fbo3	0.58	0.20	0.08	0.25 %

The identification of this transfer is better than the transfer in closed loop. Indeed, the identified parameters are nearly the same, on the different files. The problem of identification in closed loop is certainly due to the bad quality of the speed estimation, and the not proper signal of the pump extraction.

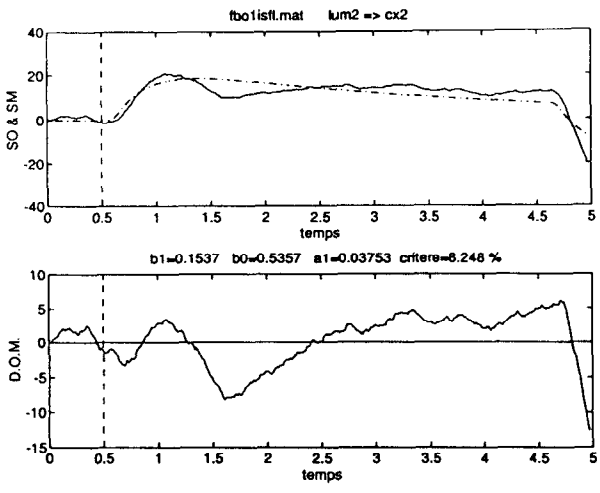


figure 7.a

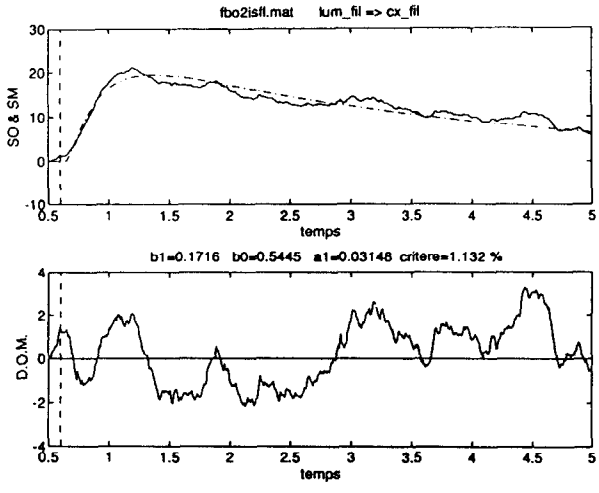


figure 7.b

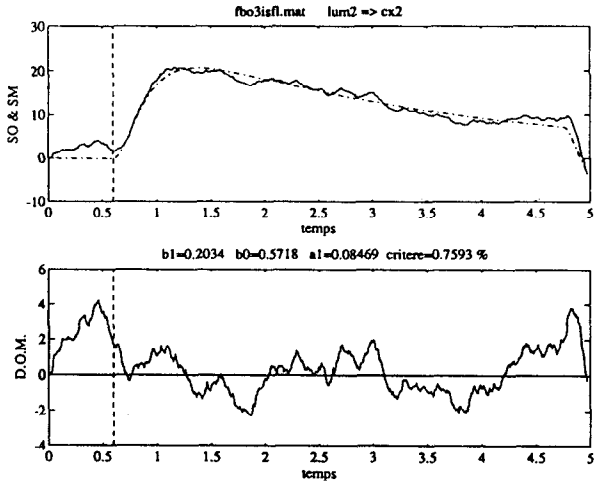


figure 7.c

Figure 7 - Results of identification

With the help of the global identification (figure 8), we can choose a model, and test it on the different protocols (figure 9). Except the overshoot on the protocol fbo1, the chosen model seems to be correct.

This transfer will help us in the elaboration of the simulator, and in the determination of the internal model for the control law.

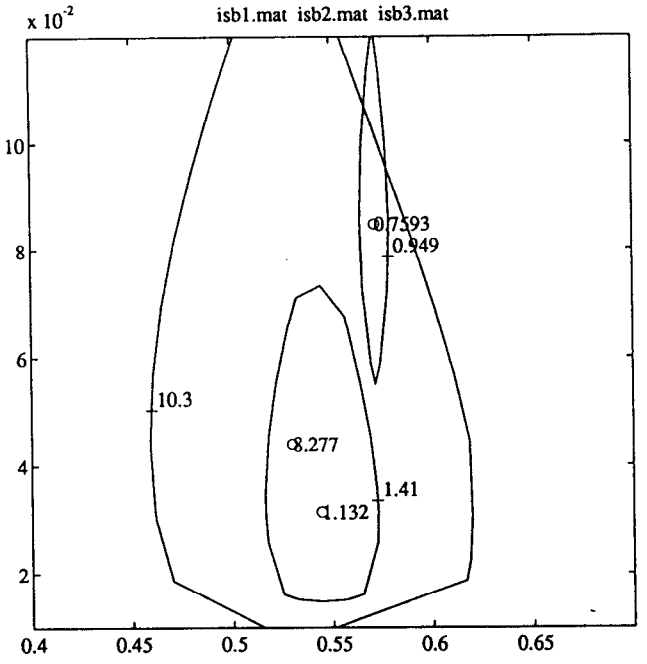


Figure 8 - Global identification

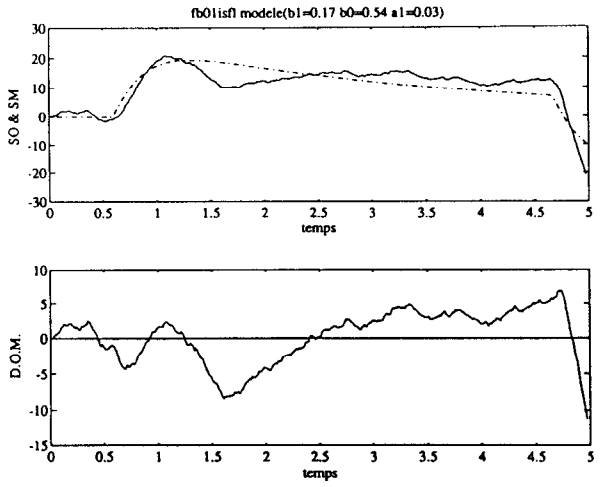


figure 9.a

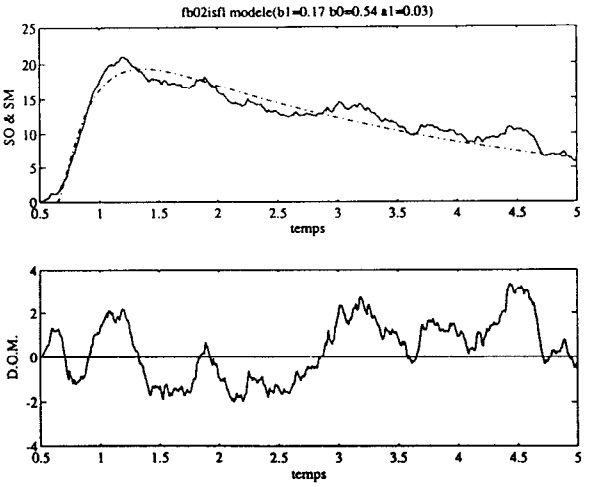


figure 9.b

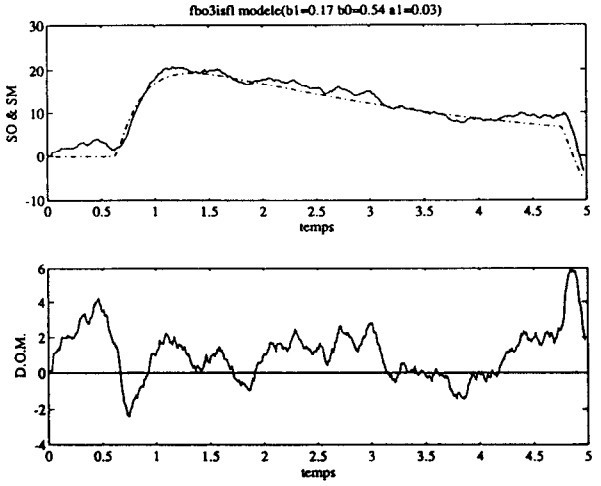


figure 9.c

Figure 9 - Validation of the chosen model

III.4 - Transfer between the light intensity and the counter of action of the extraction pump

Those tests have been realized at the beginning of September in closed loop of concentration. The speed of production was not recorded, but the counter of action of the extraction pump was.

We have tried to identify the transfer between light intensity and the derivative of the counter. The identification results are not very satisfactory. The transfer is identified under a first order model.

$$H_3(s) = \frac{b_0}{1 + a_1 s} \qquad [3.4]$$

The gain b_0 is well identified, but the time constant a_1 is very different on the various protocols. And it remains an important error (oscillation) between the measured signal and the model (figure 10). Is this difference due to a noise or a perturbation or is it really a characteristic of the process ? This question has to be solved in the continuation of the study.

Those results are recapitulated on figure 11, concerning the global identification. We can see that the time constant a_1 is not sensibilized.

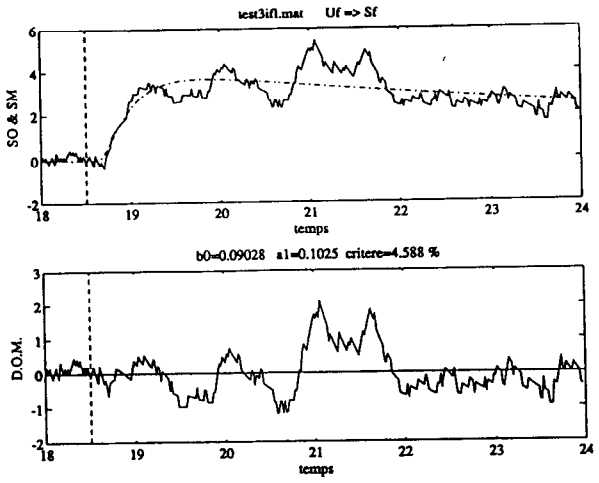


figure 10.a

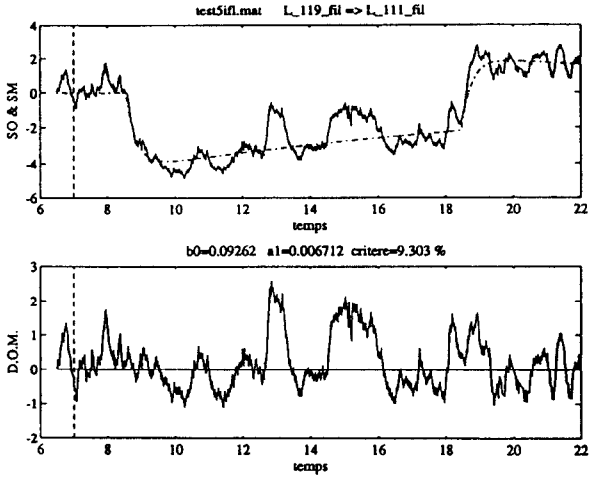


figure 10.b

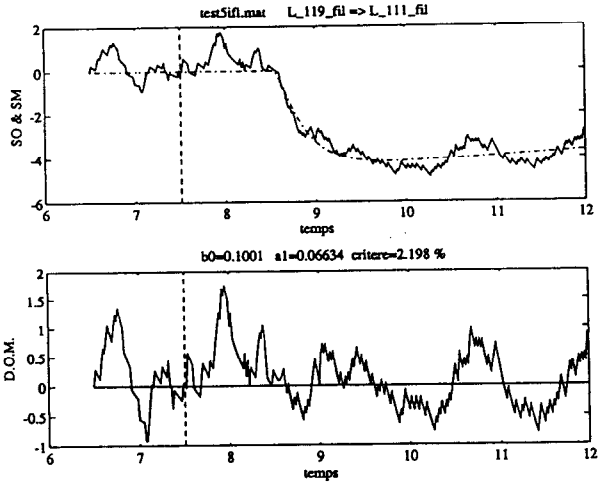


figure 10.c

Figure 10 - Results of identification

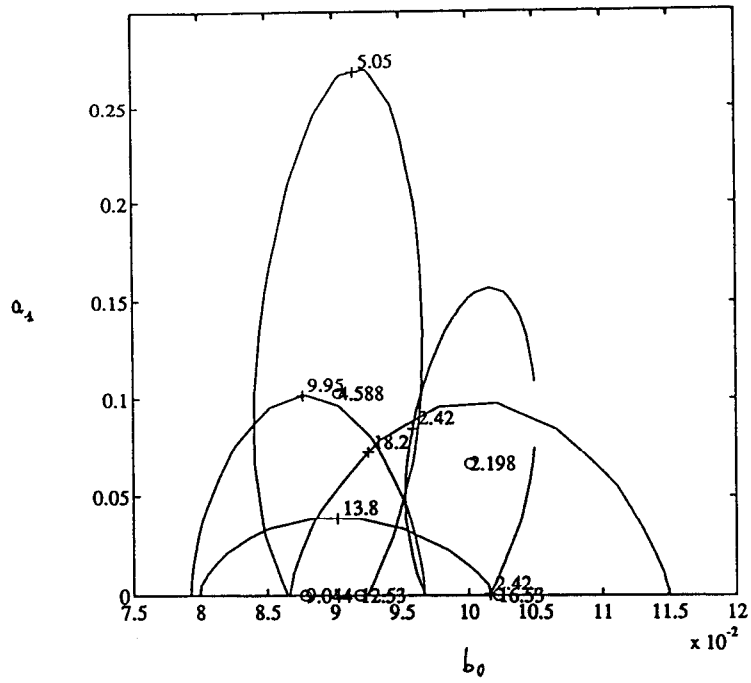


Figure 11 - Global identification

III.5 - Conclusion

Different test protocols have been realized in open loop and in closed loop, at different periods (July, August, September).

They have been used to identify the dynamic influence of a light intensity step on biomass concentration (in open loop), on the counter of pump action, and on the estimated speed of production (in closed loop). The results obtained are not allways coherent. They have to be improved and validated on other protocols.

The complementary protocols have to be done in a stable situation. It seems to be evident that the measure system creates some perturbations on the signals, so it has to be improved before (speed estimator, measure of biomass, ...) ; the control system (concentration regulation) has to be fixed (bang bang of proportional controller) ; all the perturbations that can be identified have to be supressed, or explicitely considered.

In order to identify the influence of the value of the biomass concentration on the dynamic transfer, the protocols have to be realized for different values of this concentration.

New test protocols have been realized in october on MELISSA, with a new measure of the biomass. The results obtained are different. It proves that a part of the problems of identification found at the beginning of the study can be explained with the measure problems.

IV - SIMULATOR

IV.1 - Introduction

The goal of the simulator is to reproduce the behaviour of the process. We are especially interested in the behaviour of the production of biomass. We suppose that the process is well regulated in pH, NO_3^-, pressure, temperature, and we neglecte those loops in the simulator in a first approach. We only consider the level loop and the concentration loop in the simulator.

IV.2 - Level regulation

The level loop is considered with the regulator implanted in MELISSA. There are two level detectors. When the liquid is below the low level, the speed of the injection pump is 10% more than the speed of the extraction pump. When the liquid level is between the low and high level, the speed of the injection pump is the same as the speed of the extraction pump. When the liquid level is above the high level, the speed of the injection pump is 10 % less than the speed of the extraction pump. As the extraction pump and the injection pump are supposed ideal in the simulator, the level is exactly constant, and the deliveries of both pumps are equal.

IV.3 - Concentration regulation

The concentration regulation loop is considered with a proportional regulator and a saturation. The saturation is set according to the real value set on MELISSA (U_{max} = 0.4). The proportional coefficient is tuned in order to have the same behaviour as in experimental tests.

With this tuning, this regulation looks like a "bang bang" regulation. Indeed, it is very often in saturation (figure 12). So, a real bang bang regulator will be tested. It will be perhaps more proper.

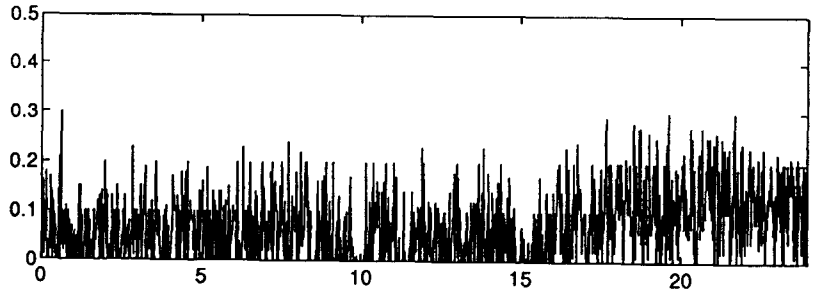


Figure 12 - Output signal of concentration controller

The gain of the pump, equal to 1.85 is calculated with the data given by ESA. An action of the pump equal to x % ($0 < x \leq 100$) corresponds to a delivery of :

$5.14 \cdot 10^{-3} \cdot x - 8 \cdot 10^{-4}$ ml/s [4.1]

$(5.14 \cdot 10^{-3} \cdot x - 8 \cdot 10^{-4}) * 3.6$ l/h [4.2]

$(1.85 \cdot 10^{-2} \cdot x - 2.88 \cdot 10^{-3})$ l/h [4.3]

An action of 100 % corresponds to a regulator output equal to 1, so the regulation between the regulator output u ($u = x/100$) and the delivery of the pump q_s (l/h) is given by the relation.

$$q_s = 1.85 \cdot u - 2.88.10^{-3} \quad \text{for } u \geq 0.0015$$
$$\text{and} \quad q_s = 0 \quad \text{for } u < 0.0015 \qquad [4.4]$$

IV.4 - Physical equations

The elaboration of the simulator is done with the help of the physical equations when it is possible. They are enumerated in the following, they use the following variables :

P_x is the real production of biomass in the reactor (g/h)
P_s is the harvesting production (g/h)
MXbio is the mass of Spirulina in the reactor (g)
Xbio is the concentration of biomass (g/l)
Vol is the volume of liquid in the reactor (l)
q_s is the extraction pump action (l/h)
q_e is the injection pump action (l/h)
C_{pt} is the counter of actions of the extraction pump

$$Xbio = MXbio / Vol$$

$$\frac{d}{dt}(MXbio) = P_x - P_s$$

$$P_s = q_s \cdot Xbio$$

$$\frac{d}{dt}(Vol) = q_e - q_s$$

IV.5 - Speed of production estimator

The estimation of the biomass production is done with the help of a counter of extraction pump actions. This counter is derived. This procedure of integration and derivation has a filtering action.

At the beginning, the derivation was done by difference between the counter at time (t) and the counter at time (t - 1) hours. After, it was replaced by the least mean square trend evaluated during 1 hour.

We have tried to identify it as a continuous transfer. We have obtained the following transfer :

$$H_{est}(s) = \frac{s}{1 + T_{est}\, s} \qquad \text{with} \quad T_{est} = 0.7 \text{ hour}$$

This identification has been done with the protocols realized at the beginning of July, corresponding to the first calculation :

$$P_{s\text{-}est}(t) = C_{pt}(t) - C_{pt}(t\text{-}1)$$

This estimator has a very slow dynamic. It has been tuned like that because the action of the extraction pump was very shattered. If the concentration controller can be improved, it might be interesting to accelerate the speed estimator.

IV.6 - Dynamic of Spirulina synthesis

It has been noticed in experimental situation, and in simulation that the tuning of the concentration regulator was very influent on the dynamic of biomass production. It is due to the fact that the production is not the real production. It is estimated from the action of the extraction pump, which depends directly on the concentration regulation loop (cf Annex A for the expression of the closed loop transfer). The dynamic of production that can be identified from test protocols in closed loop is composed of three dynamics : the proper dynamic of production, the dynamic of the closed loop of concentration, and the dynamic of the estimator.

The proper dynamic of Spirulina synthesis is better identified in open loop. The transfer which can be identified is the one between light intensity and concentration of biomass.

The representation of the Spirulina synthesis is a qualitative approach based on the results of identification in open loop. We have introduced a divergent effect of the mass, that can be justified physically : "the more they are, the more they produce". As there is a divergent effect of the mass, we have to put a stabilizing feedback. It has to be justified or explained. This stabilizing feedback can be explained by the light limitation. It would be interesting to realize some experiments to prove and identify this feedback.

This modelisation has not the pretension to be exact. It reproduces qualitatively the behaviour of the reaction in open loop (figure 13). The gain K = 0.03 has been adjusted to reproduce the behaviour described on open loop protocols : a step of light intensity of 60 W/m^2 applied during 4 hours creates an increase of 100 mg/l of concentration (figure 6).

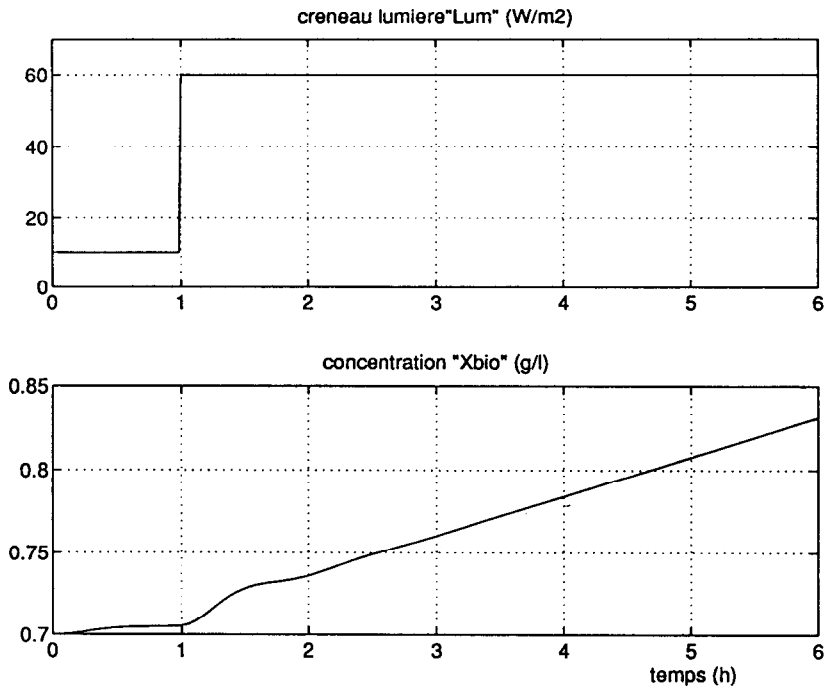


Figure 13 - Simulator in open loop of concentration

IV.7 - Conclusion

The scheme of the complete simulator is given in figure 14. A step protocol of light intensity has been applied on this simulator, in closed loop of concentration (figure 15). Then, a noise is added on the measure of biomass concentration (figure 16). The results obtained on this simulator correspond qualitatively to the results of identification. But this simulator will be improved in the continuation of the study for two main reasons.

The new results of identification (with a new measure of biomass) will certainly be differed from those obtained precedently. So, the simulator will be changed in function of those new results.

We will have to introduce the influence of the concentration value on the parameters of the simulator. This will be done with the help of new test protocols at different values of concentration, and with the help of the knowledge of ESA and LGCB (Cornet's model ...).

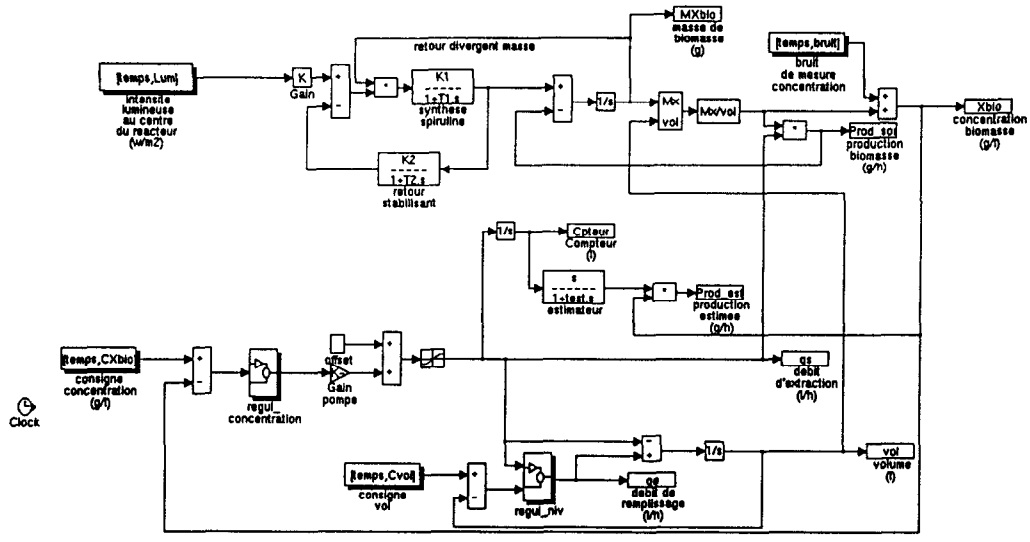


Figure 14 - Simulator

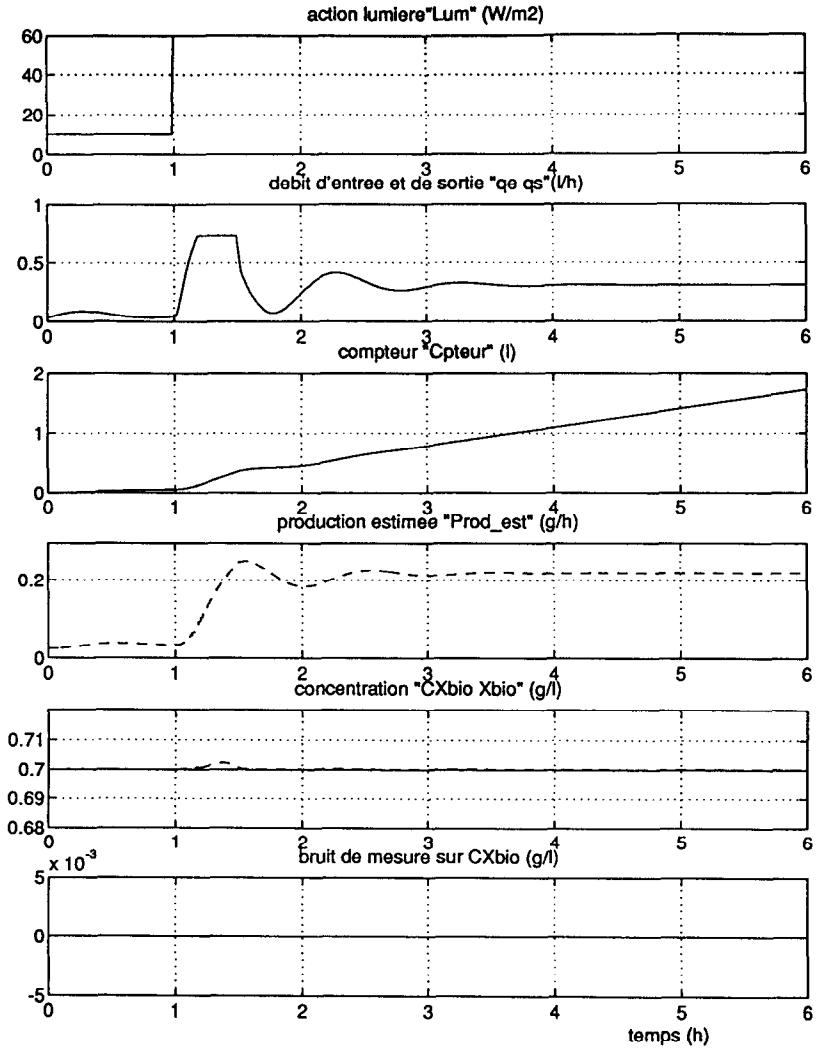


Figure 15 - Step protocol on the simulator

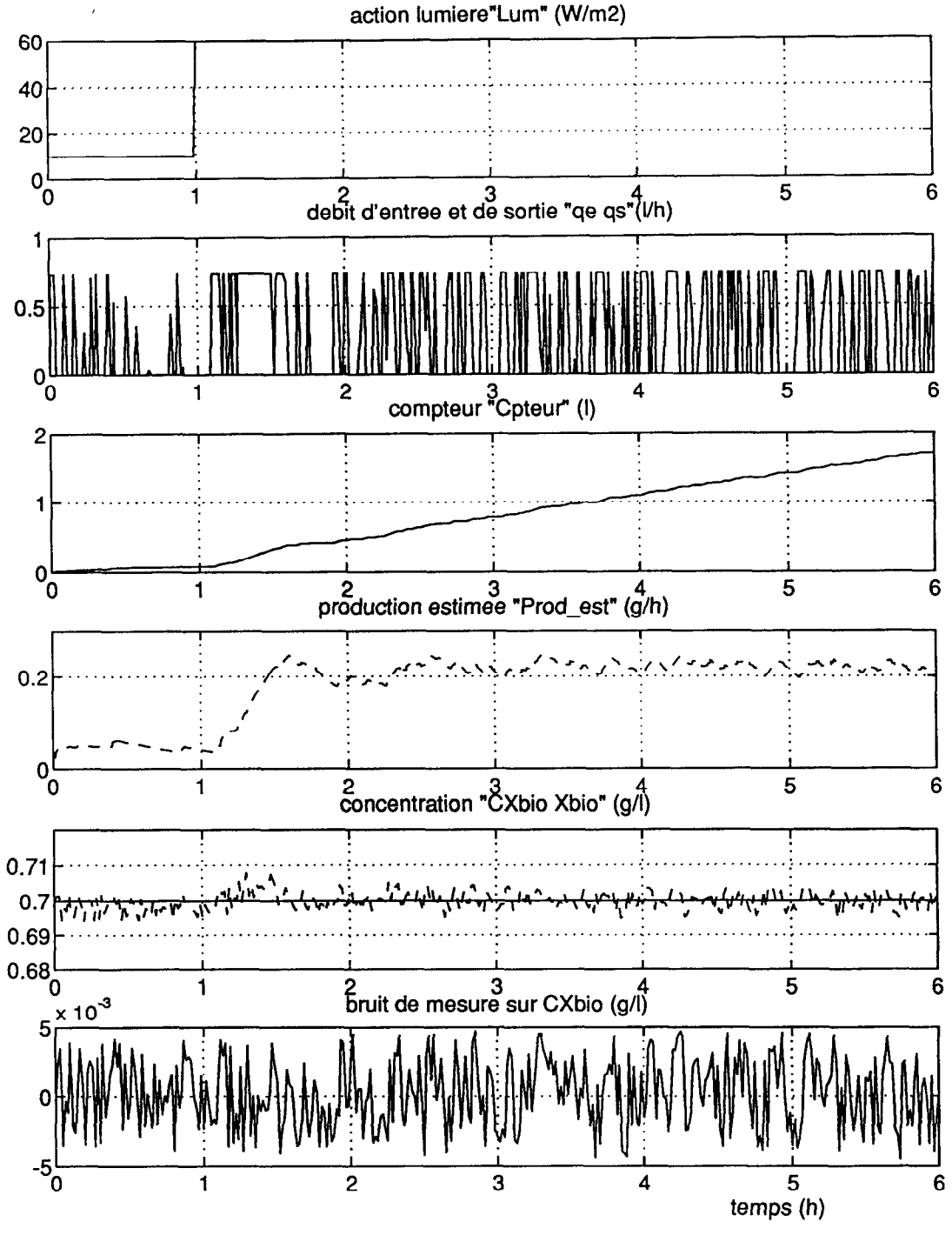


Figure 16 - Step protocol on the simulator (+ noise)

V - PREDICTIVE CONTROL

V.1 - Introduction

The predictive control technic is tested on the simulator of MELISSA, for the control of the speed of production of biomass.

At this stage of the study, the following hypothesis are done on the manipulated variable, which is the light intensity (W/m^2) in the middle of the reactor :

- the level zero of light control is supposed ideal ;
- the light action has a magnitude constraint. This constraint does not depend on the concentration in the present version of the simulator. This will be integrated in the future version.

The controlled variable is the speed of production (g/h). This speed of production is not measured directely. It is estimated from the counter of actions of the extraction pump. The quality of this estimation is very influent on the control performance. It will be interesting to improve this estimator. In the present results, the estimator is modelized as a first order derivator filter (see IV.5).

The control law is tested on the simulator, for different values of the parameters (K, K_1, K_2, T_1, T_2), in order to find the optimal tuning. At present, according to the identification results, it might be necessary to give a great importance to the robustness.

V.2 - Tuning of the predictive control

PFC strategy : the PFC controller is based on four principles :

- the internal model ;
- the reference trajectory ;
- the structuration of the manipulated variable ;
- the auto-compensation procedure.

The PFC strategy consists in minimizing the distance between a reference trajectory and the prediction of the process output. This distance is evaluated on some points of the coïncidence horizon named coïncidence points. The prediction of the process output is computed with the help of the internal model under the action of a structured manipulated variable, and with a prediction of the difference between the process and the model (auto-compensation).

PFC tuning :

- **Control period** :

  It has to be chosen in function of the dynamic of the process in open loop. It is fixed to dt = 1 mn = 1/60 hour.

- **Internal model** :

  It is the main tuning parameter. It is a representation model, which reproduces the behaviour of the process. The results of identification being not satisfactory, we have prefer to identify this model with protocols applied on the simulator. We have chosen a third order model :

$$MI = \frac{0.0027}{1 + 0.22\,s + 0.024\,s^2 + 0.0019\,s^3}$$

- **Time response of the reference trajectory** :

  This parameter specifies the dynamic of the reference trajectory. It corresponds to the desired dynamic of the closed loop system. Different values of this time response are tested. We can choose the best value, in function of the robustness specifications.

  The following table shows the evolution of robustness and dynamic criterions in function of the value of the parameter T_{rep} (time response of the reference trajectory).

MG	:	gain margin
MP	:	phasis margin
MR	:	delay margin
TRBF	:	obtained closed loop time response
DEP	:	overshoot
U_{max}	:	maximum of the input
FC_p	:	cut frequency for the disturbance
$(Y/D)_{max}$	:	maximum of the gain of the transfer Y/D

The definitions of those criterions are given in Annex B.

Traj. Reference		CRITERES OBTENUS							
TRep		MG	MP	MR	TRBF	DEP %	Umax	FCp	(Y/D)max
0.5	1	4.97	69.86	0.3292	0.5333	0	605.7	0.4552	1.391
0.8333	2	6.588	74.94	0.4687	0.85	0	456.9	0.3662	1.28
1.333	3	9.167	79.24	0.6902	1.283	0	366.9	0.279	1.194
1.667	4	10.92	80.99	0.8404	1.583	0	366.6	0.237	1.16
2	5	12.68	82.25	0.9914	1.867	0	365.9	0.2126	1.137

We can see that the robustness margins increase when the time response increase. Two tunings of the controller (T_{rep} = 0,5 hour and T_{rep} = 1 hour) are tested on the simulator.

- **Structuration of the future manipulated variable** :

When the goal of the controller is to track a polynomial trajectory without any static error, the future manipulated variable must be structured as a linear combination of polynomial base functions. But in the case of our study, it is sufficient to take one base function (the step).

- **Coïncidence points** :

The choice of the coïncidence points is influent on the stability/robustness criterion. As there is only one base function, it is sufficient to choose one coïncidence point. With a help procedure based on stability/robustness and dynamic criterions, we have chosen :

$$H_c = 0.23 \text{ hour}$$

- **Control equation** :

$$U(n) = KC \,.\, c(n) - KY \,.\, y_p(n) + VX \,.\, X_{mi}(n)$$

with

c(n) : setpoint	:	$CV_x(n)$
$y_p(n)$: measure :	:	Prod_est(n)
$X_{mi}(n)$	:	state vector of the internal model
KC, KY, VX	:	coefficients of the controller

The value of KC, KY and VX depend on the model and the choice of the tuning parameters.

V.3 - Tests on the simulator

The PFC controller is included in the simulator (figure 17). The setpoint is a speed of production CV_x, the measure is the estimated speed of production Prod_est, and the manipulated variable is a setpoint of light intensity C_{lum}. The controller is tested with a step setpoint of speed of production, with noise on the measure of biomass, and with some desadaptations of the parameters of the simulator. Two tunings of PFC are tested : T_{rep} = 1 hour (figure 18), T_{rep} = 0,5 hour (figure 19).

We can see that when the controller is more dynamic, the robustness is smaller. The controller seems to be more robust to an over-estimation of the time constants T_1 and T_2 (figure 19.c, d, e) and of the gain K (figure 19.f, g), so it would be eventually necessary not to take the mean model.

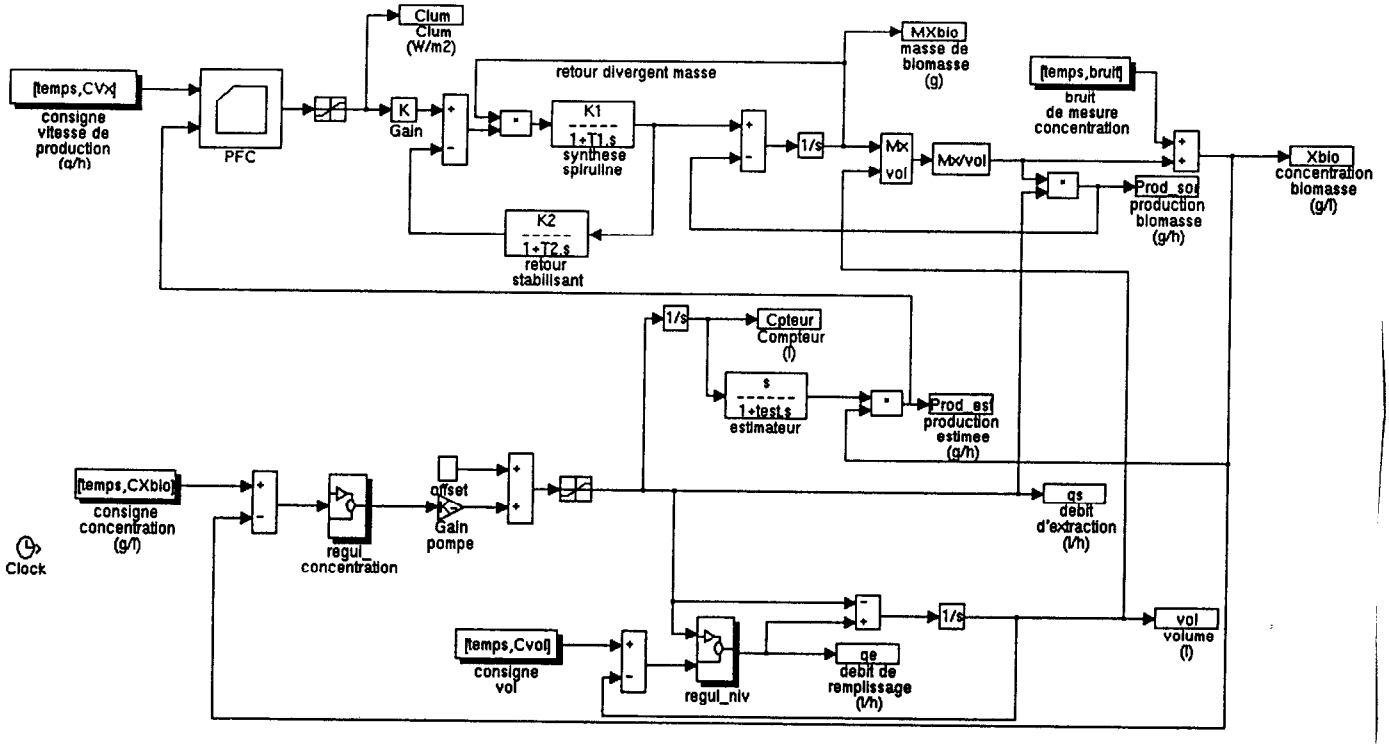


Figure 17 - Simulator with PFC controller

V.4 - Conclusion

Those tests have been done on the actual simulator, which is simplified. It is not sufficient for the test in real dimension on MELISSA. Indeed, the simulator has to be improved according to the new results of identification. The control law has to take into account the influence of the biomass concentration value on the internal model, and on the constraint of light intensity in the middle of the reactor.

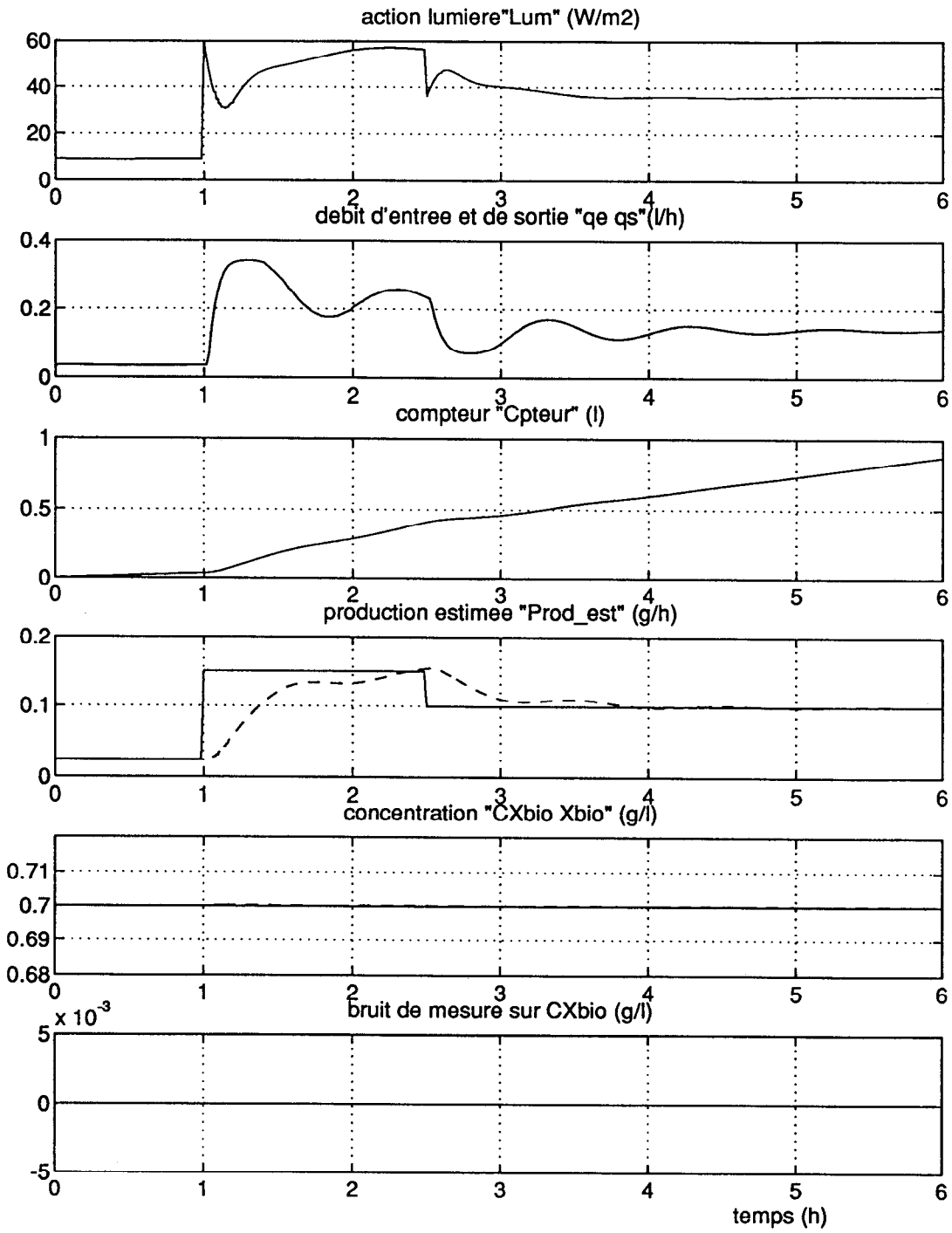


Figure 18.a : Adapted case without noise

Figure 18 - Test of PFC (T_{rep} = 1 hour)

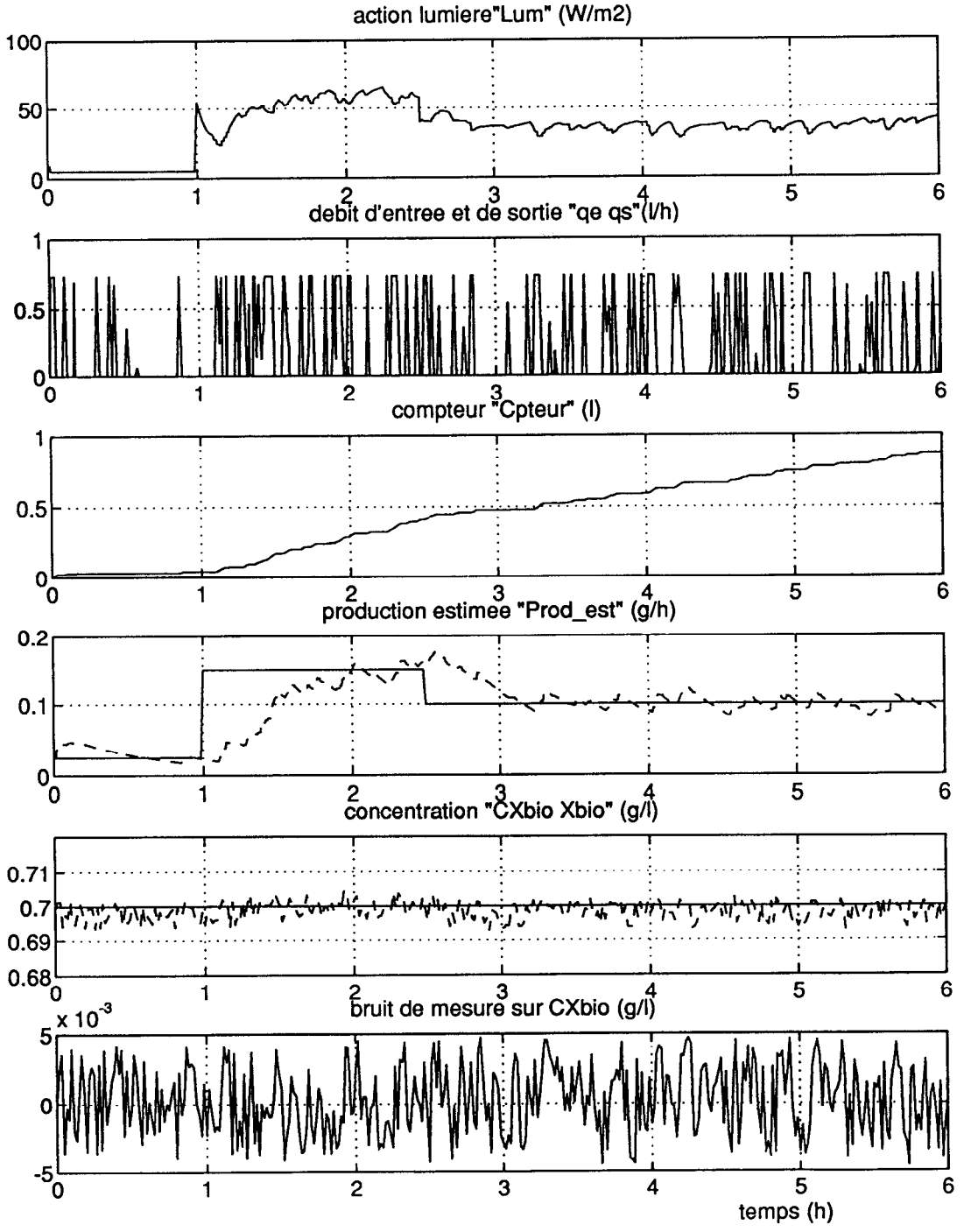


Figure 18.b : Adapted case with noise

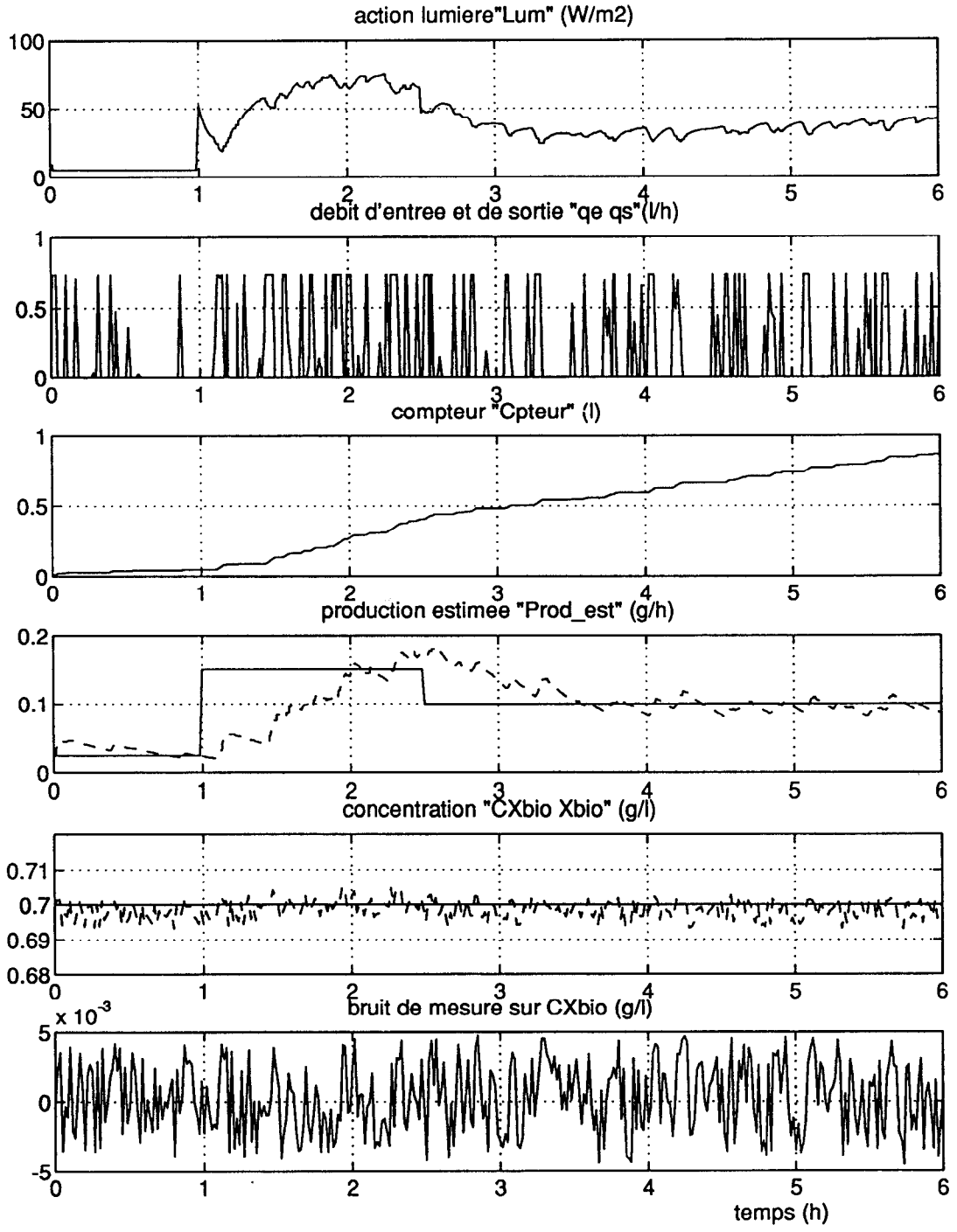


Figure 18.c : Desadapted case with noise - $T_1 = T_2 = 0.25$

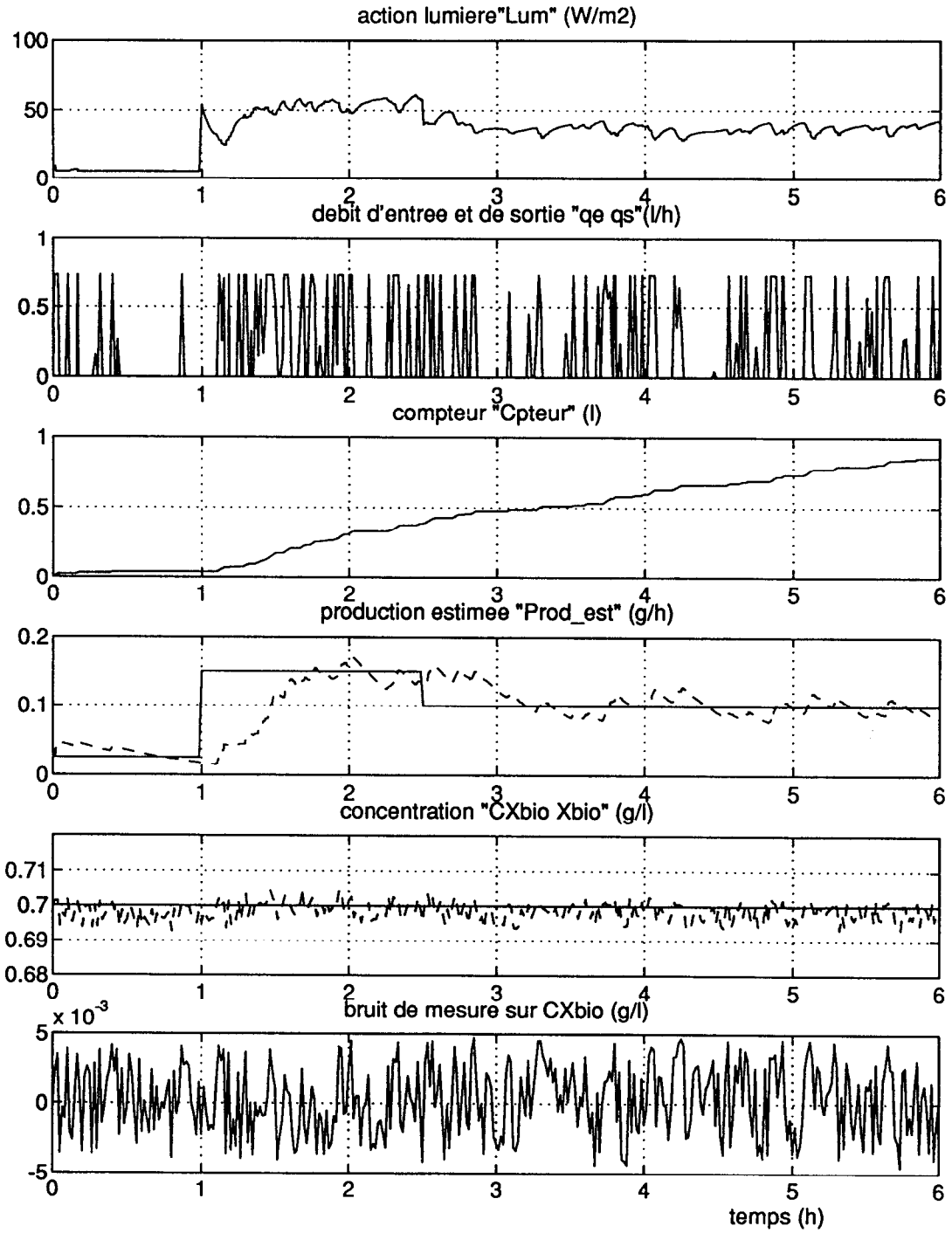


Figure 18.d : Desadapted case with noise - $T_1 = T_2 = 0.6$

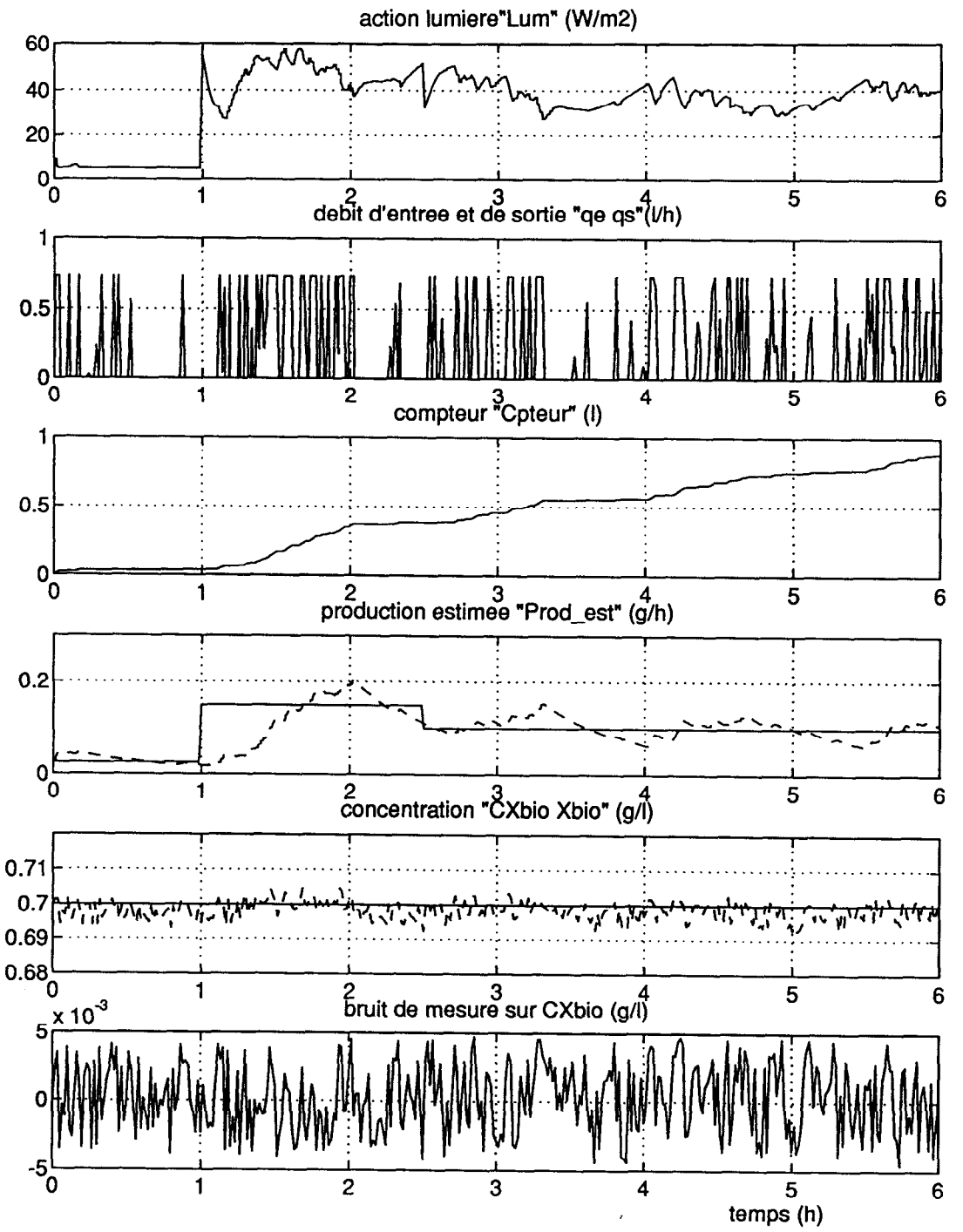


Figure 18.e : Desadapted case with noise - $T_1 = T_2 = 0.75$

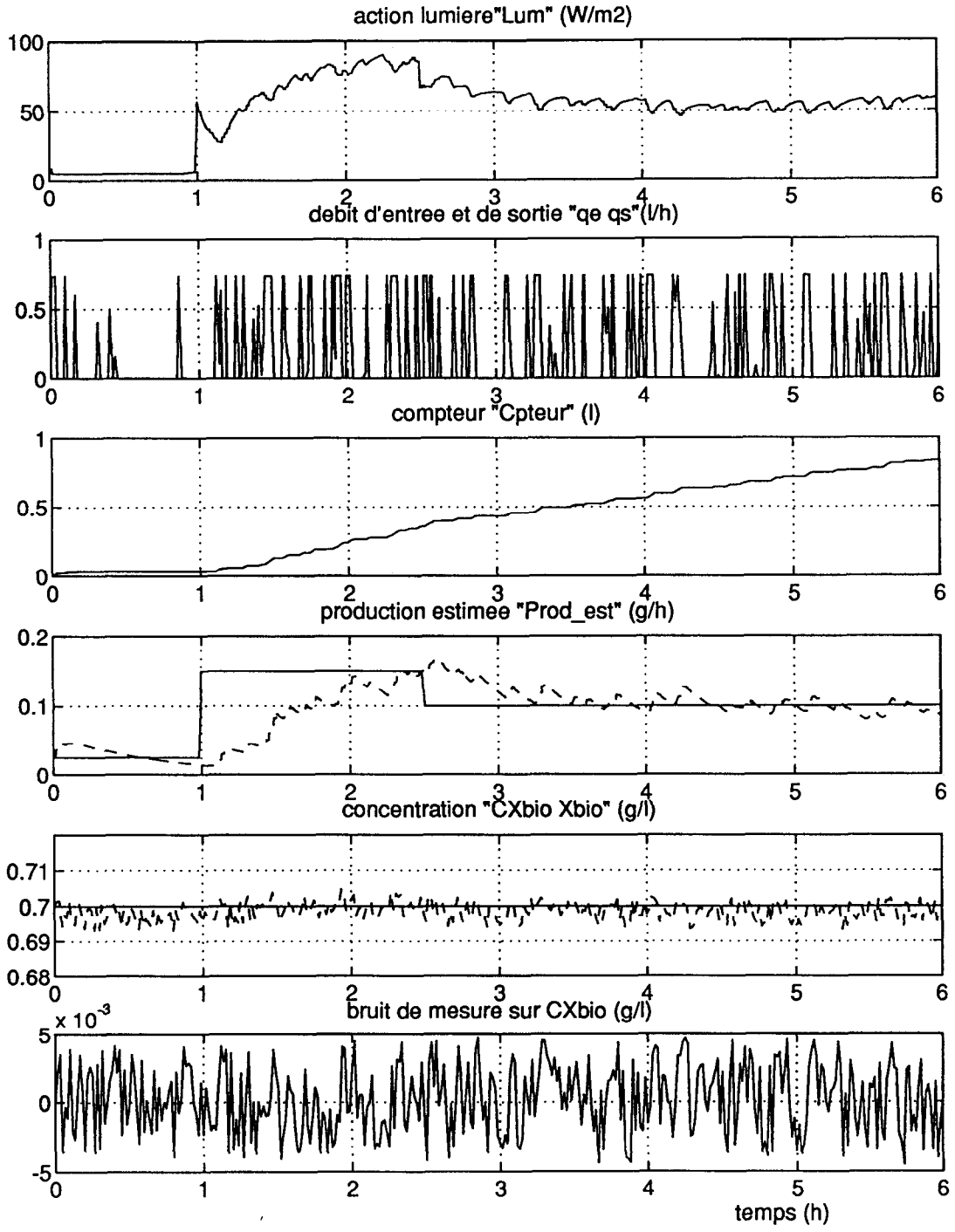


Figure 18.f : Desadapted case with noise - K = 0.02

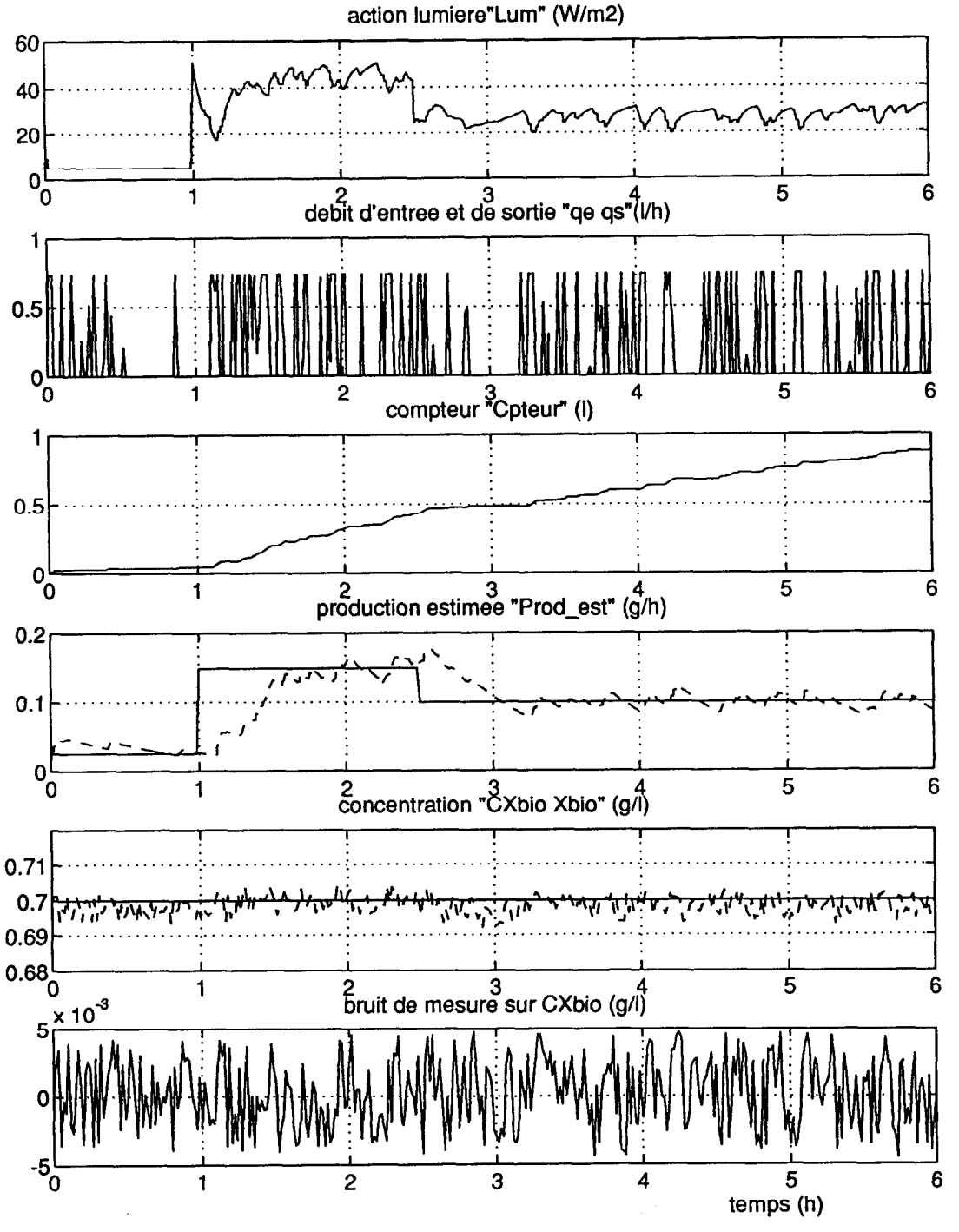


Figure 18.g : Desadapted case with noise - K = 0.04

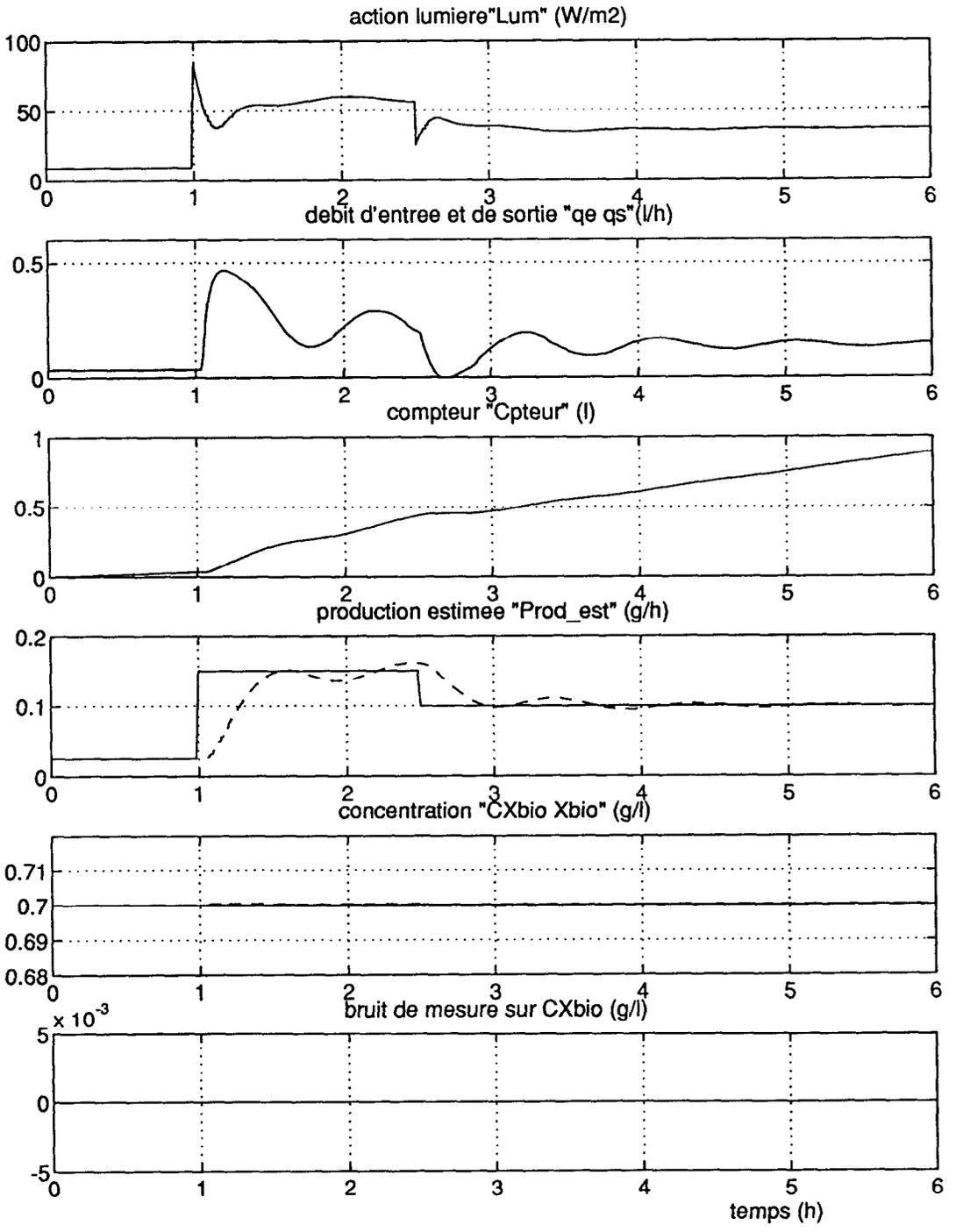


Figure 19.a : Adapted case without noise

Figure 19 - Test of PFC (trbf = 0.5 hour)

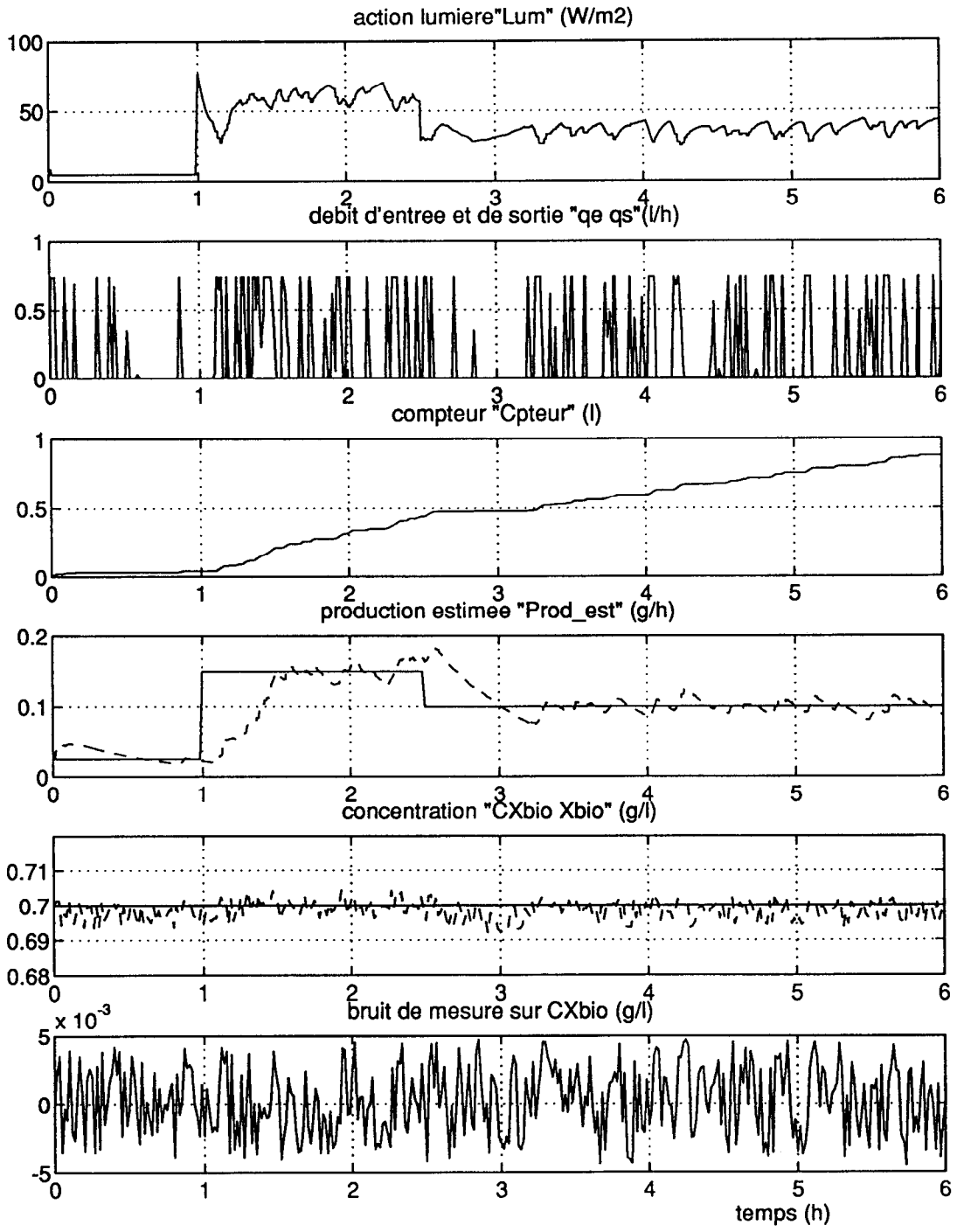


Figure 19.b : Adapted case with noise

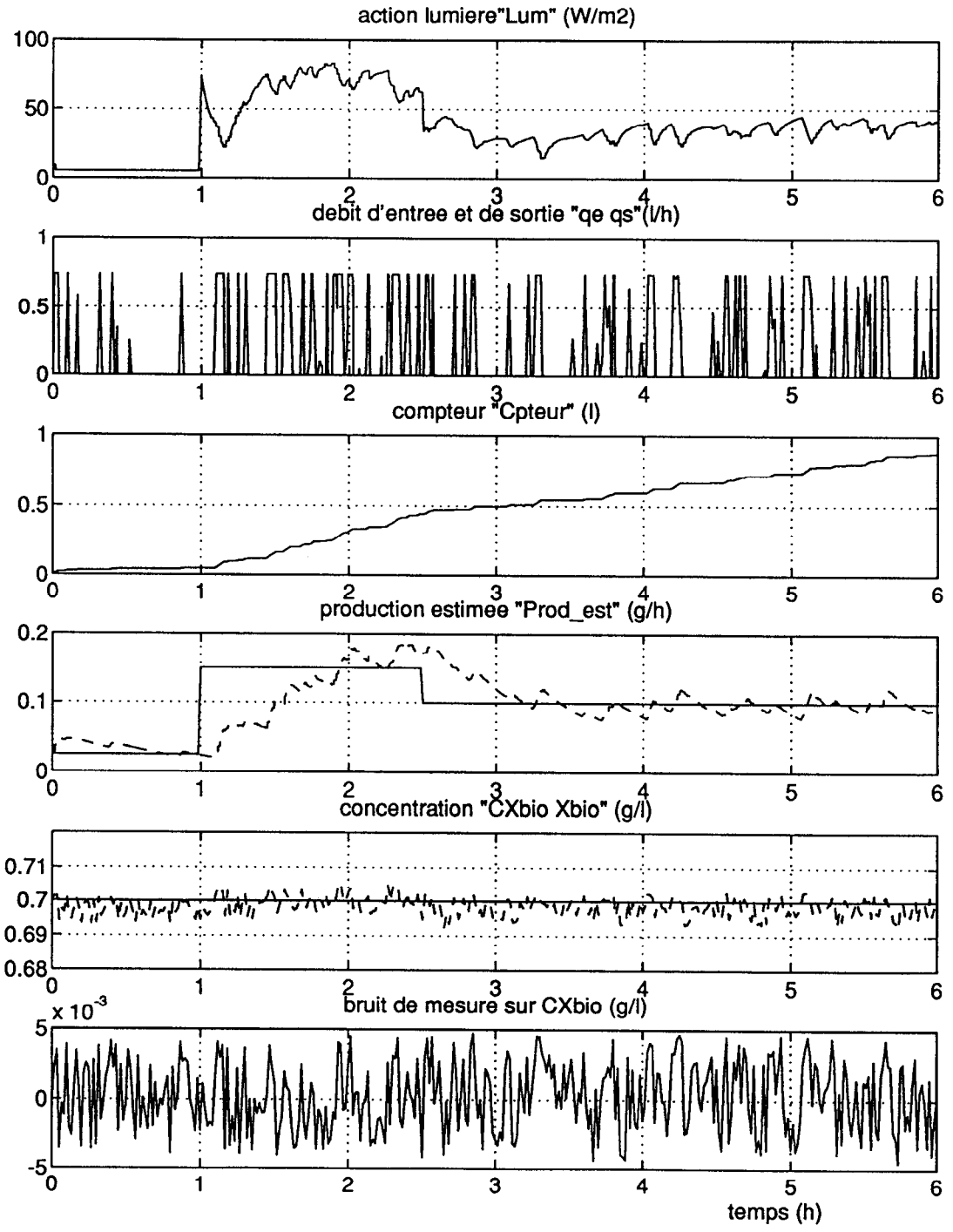


Figure 19.c : Desadapted case with noise - $T_1 = T_2 = 0.25$

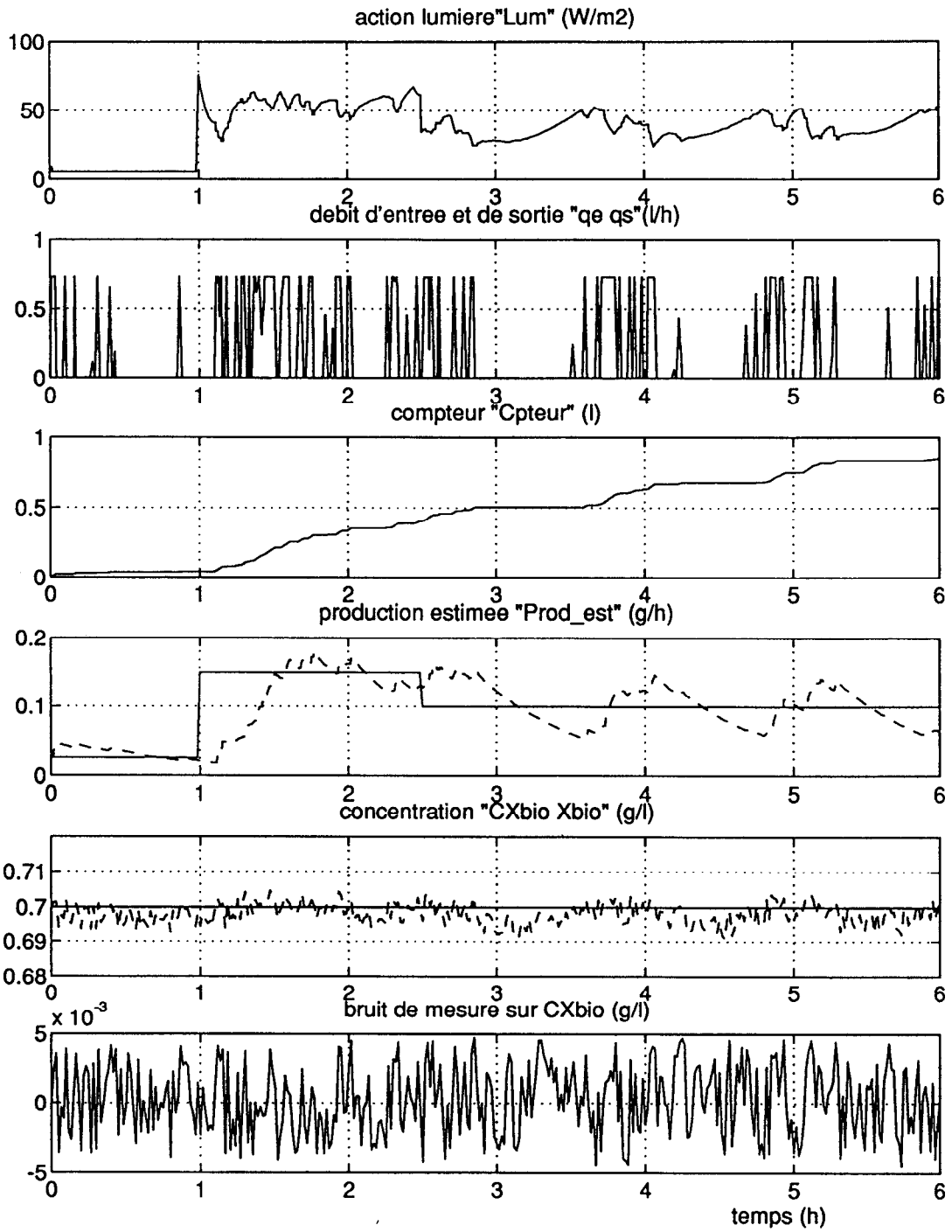


Figure 19.d : Desadapted case with noise - $T_1 = T_2 = 0.6$

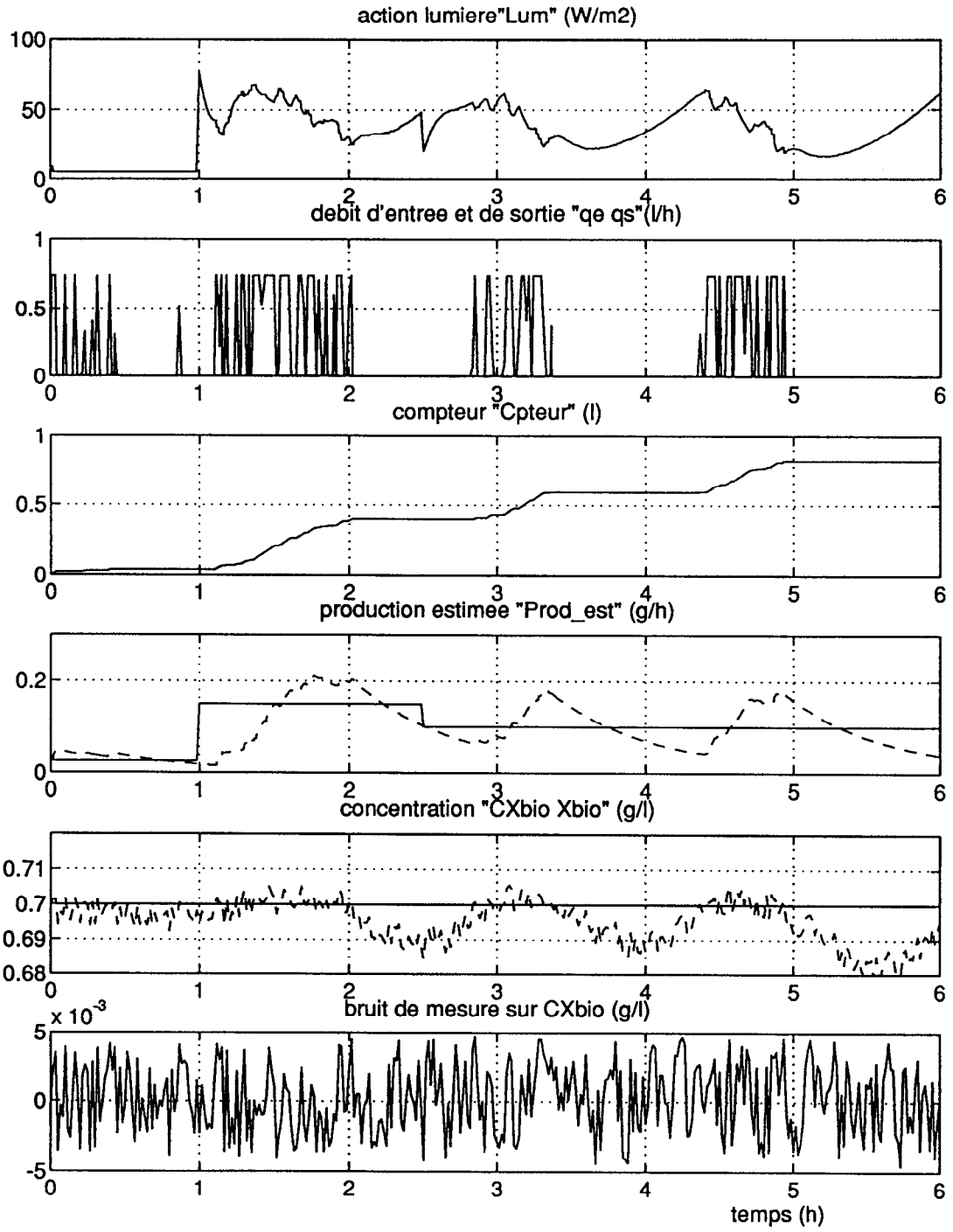


Figure 19.e : Desadapted case with noise - $T_1 = T_2 = 0.75$

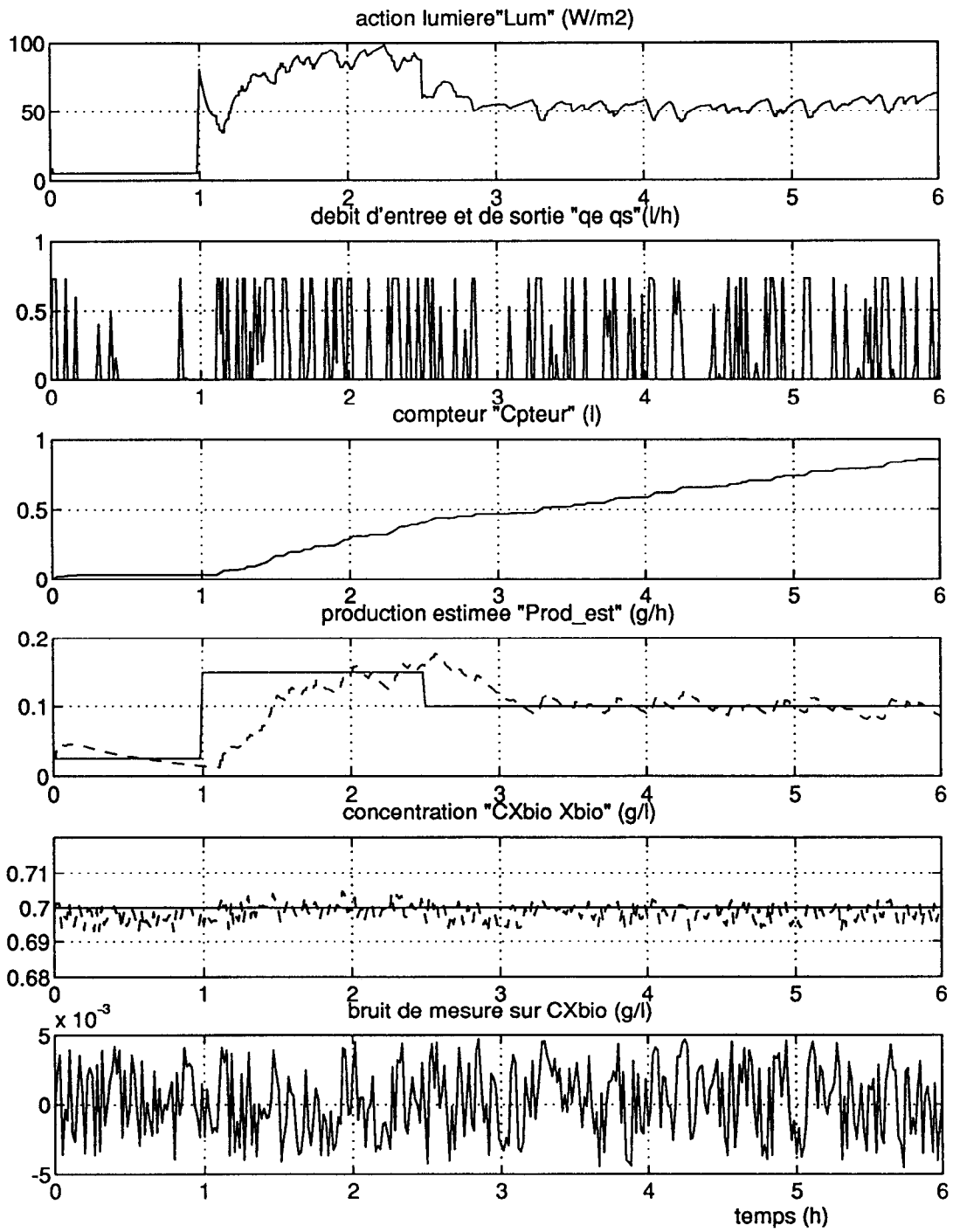


Figure 19.f : Desadapted case with noise - K = 0.02

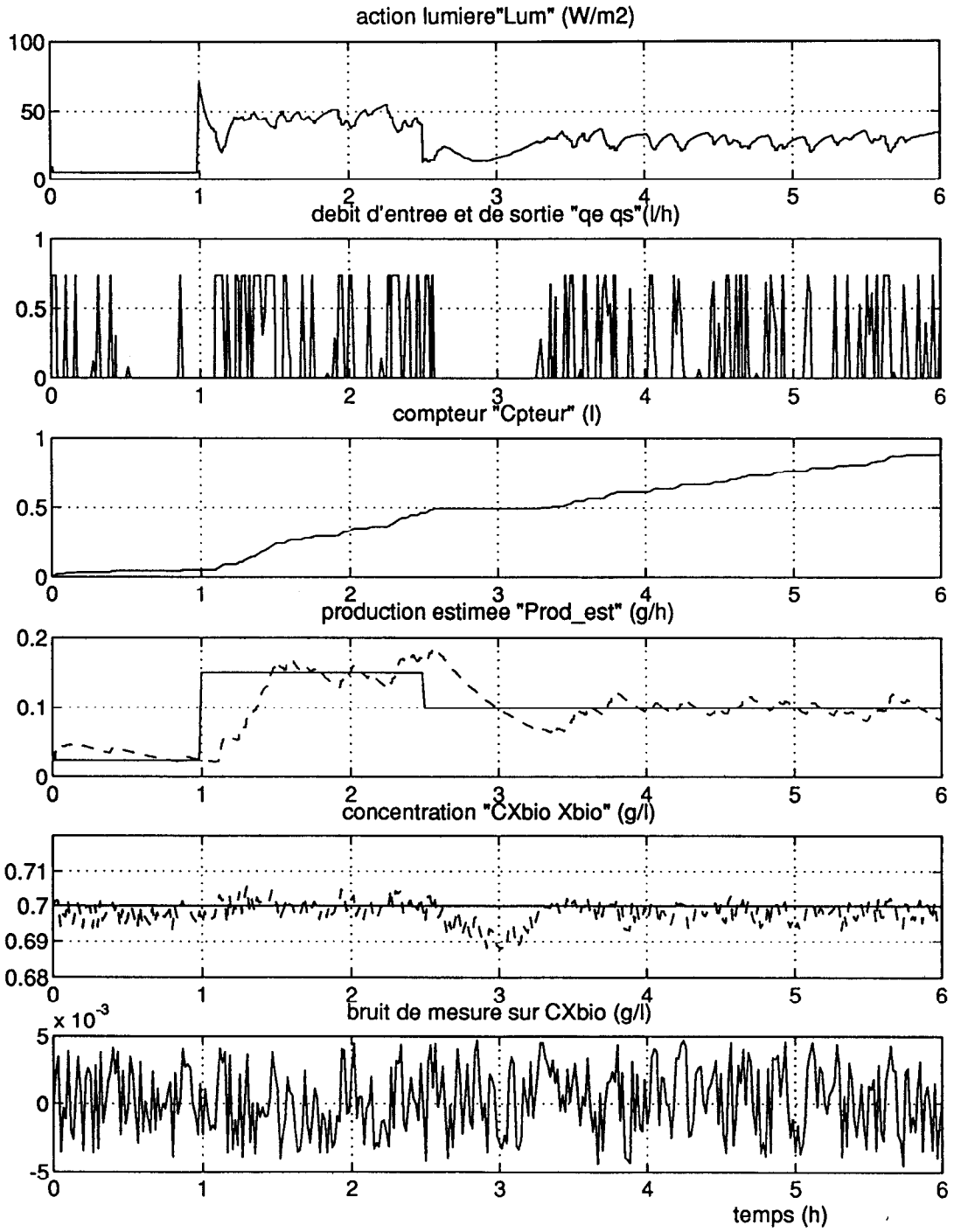


Figure 19.g : Desadapted case with noise - K = 0.04

VI - CONCLUSION

The goal of the study is to test the feasability of a predictive control for the control of the production of biomass, by acting on light intensity. At present, it has been done on a simplified simulator. In the following, this simulator has to be improved. This will be done with the help of other test protocols, and according to the knowledge of the process (ESA - LGCB...). The effect of the biomass concentration value on the parameters of the process must be included in the simulator. The knowledge model developped at LGCB will be included in our simulator.

To go on and progress in the study, the control specifications have to be defined more clearly. What are the real setpoints and the real control specifications ? Which precision is necessary ? Which dynamic ? Then, we will be able to propose a control law to be tested on the photo-reactor.

In the following, it will be interesting to consider MELISSA as a complete system, and to develop a hierarchical control.

The main following actions in this study are enumerated here after :

<u>in 1993</u> :

LGCB/ADERSA :	Integration of the knowledge model (LGCB) in the simulator developped by ADERSA.
ESTEC :	Test protocols on Spirulina compartment to verify and validate :
	- the biomass sensor
	- the calibration of knowledge model (LGCB) in dynamical functionning

<u>in 1994</u> :

ADERSA :	Test of a non linear predictive control law on the simulator (without limiting factors)
ADERSA/ESTEC :	Implantation of this control law on Spirulina compartment.
	Study of the control law with limiting factors.

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Annex A

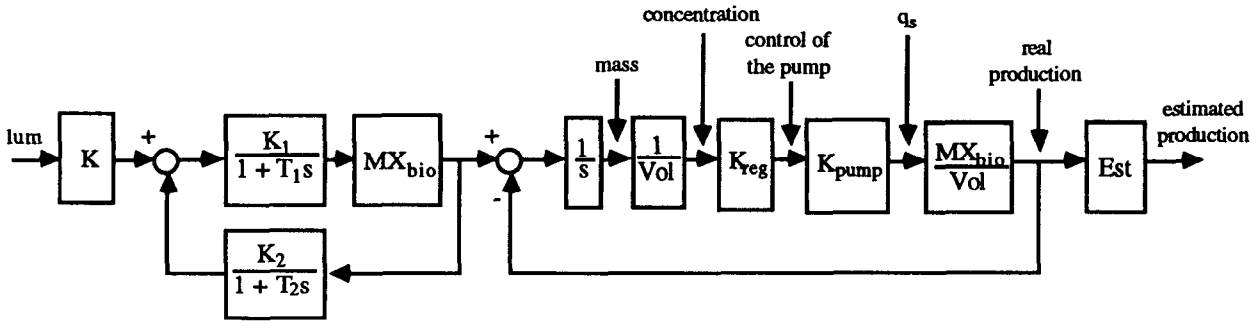
Closed loop transfer

We express the equivalent transfer between the light intensity and the estimated speed of production. This transfer is expressed under the following hypothesis :

- the volume Vol is constant — Vol = 7 l
- the biomass concentration Xbio is constant — Xbio = 0.7 g/l

Then, the mass of Spirulina in the reactor is constant and equal to MXbio = 4.9 g.

The simulator is equivalent to :



$$\frac{Prod\_est}{lum} = \underbrace{\frac{K\,K_1\,MX_{bio}\,(1+T_2 s)}{1+K_1 K_2 \,.\, MX_{bio}\left(1+\frac{T_1+T_2}{1+K_1 K_2 \,.\, MX_{bio}}s+\frac{T_1 \,.\, T_2}{1+K_1 K_2 \,.\, MX_{bio}}s^2\right)}}_{\text{open loop dynamic = proper dynamic of Spirulina synthesis}} \cdot \underbrace{\frac{1}{1+\frac{Vol^2}{MX_{bio}\,.\,K_{pump}\,.\,K_{reg}}s}}_{\text{concentration regulation loop dynamic}} \cdot \underbrace{\frac{1}{1+Test\,.\,s}}_{\text{estimator dynamic}}$$

We can see that the equivalent transfert between light intensity and estimated speed of production is composed of three dynamics : the proper dynamic of Spirulina synthesis, the dynamic of the concentration regulation loop, and the dynamic of the estimation.

Annex B

Definition of stability, robustness and dynamic criterions

1) A system S is represented in the "black representation" (phasis, gain) by the locus S(jw). In the black representation, the critical point corresponds to the point (-180°, 0 dB).

The **gain margin** MG is the gain to be added on all the points of the locus S(jw), to let him passed by the critical point.

The **phasis margin** MP is the phasis to be added on all the points of the locus S(jw), to let him passed by the critical point.

The **delay margin** MR is calculated with the phasis margin

$$MR = \frac{\pi}{180} \cdot \frac{MP}{w_0}$$ where w_0 is the pulsation

where the locus S(jw) coincidates with the critical point.

*More intuitively, the **gain margin** is the value with which the gain of the process must be multiplied to let the closed loop become unstable. The **delay margin** is the value of the delay that can be added in the process to let the closed loop become unstable.*

2) A system is submitted to a unitary step input u(t), the output of the system is y(t). y_∞ is the final value of y(t) and ymax is the maximum value of y(t).

- TRBF, the obtained **cloop loop time response** at 95 % is the time TRBF such as

$$\forall\, t \in [TRBF, \infty[\qquad 0{,}95 \cdot y_\infty < y(t) < 1.05 \cdot y_\infty$$

for the closed loop system, and a unitary step setpoint.

- DEP is the **overshoot** in closed loop, for a unitary step setpoint :

$$DEP = \frac{y_{max} - y_\infty}{y_\infty}$$

- U_{max} is the **maximum of the manipulated variable**, for a unitary step setpoint.

3) The analysis of the Bode diagram of the transfer H between the perturbation δ and the output y(t) allows to define the **cut frequency** FC_p at 3 dB and the **maximal amplification** of the disturbance $(Y/D)_{max}$.

$$FC_p \quad ; \quad \forall f < FC_p \qquad | H(f) | < -3 \text{ dB}$$

$$(Y/D)_{max} = \max_f | H(f) |$$