MELISSA

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TECHNICAL NOTE : 44.1

Model Based Predictive Control of the biomass production of the 77 litres photoautotrophic compartment

Version : 1
Issue : 1

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Document Change Log

Version	Issue	Date	Observation
0	0	December 1999	Draft
1	0	June 2003	Original version
1	1	July 2003	Revised version

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1. INTRODUCTION

The Model Based Predictive Control of the Spirulina production has already been elaborated and tested on the 7 litres reactor (report in TN's 24.1 , 24.2 , 38.1 and 38.2).
In the present study, a few parameters of the control, relative to the light supply and to the geometry of the reactor, will be adapted to the new 77 litres reactor. Then this up-dated controller will be tested directly on this new reactor.

2. UP-DATING OF THE CONTROLLER

2.1 Geometrical parameters of the 77 litres reactor

In comparison with the 7 litres reactor which was constituted of 2 concentric cylinders, the 77 litres reactor is composed of 2 cylinders connected in U; the radius of each cylinder is equal to 0.076 m (UAB data).

2.2 Up-dating of the control software

The previous control software (V3.0 of TN 38.1) is modified in order to take into account the new light supply and the new geometry. The modifications are located in 2 subroutines (*lspc* and *dercx* of the source file *lspc.c*) whose previous and new versions are described hereafter.

2.2.1 Up-dating of the subroutine 'lspc'

<u>Previous version :</u>

```
double  Fr_max=400.;    /* max constraint on FR (in W/m2) */
```

<u>New version :</u>

```
double  Fr_max=223.;    /* max constraint on FR (in W/m2) */
```

<u>Modifications done :</u>
Modification of the maximum light intensity according to UAB data (TN 37.2 ; April 1998) reported in annex 1. The minimum value of 10 W/m^2 is unchanged because it is the minimum required to the good functioning of the reactor.

2.2.2 Up-dating of the subroutine 'dercx'

<u>Previous version :</u>

```
double  RT=0.048;       /* external radius of the reactor */
double  R1=0.0302;      /* int radius of the external cylinder */
double  R2=0.02585;;    /* ext radius of the internal cylinder */
```

```
/*
Computation of rx (biomass growth rate)
Integration interval : [z0, 1]
This interval is divided into 'nstep = 1/jstep ' equal parts
Integration : rectangle method
*/
z0 = 1.e-6 / RT;
kstep = (1. - z0) * jstep;
sX = 0.;
for (z=z0; z<1.; z+=kstep)
  {
  if(( z<= R2/RT)||(z >= R1/RT)) /* concentric cylinders */
    {
    pijz = 2*Fr/z*cosh(delta*z)/(cosh(delta)+alpha*sinh(delta));
    if (pijz>=Fmin)
      sX += z * pijz / (Kj+pijz);
    }
  }
rx = 2. * muM * cx * sX * fI * zpc * kstep;
```

New version :

```
double  RT=0.076;       /* external radius of the reactor */

/*
Computation of rx(biomass growth rate)
Integration interval : [z0, 1]
This interval is divided into 'nstep = 1/jstep ' equal parts
Integration : rectangle method
*/
z0 = 1.e-6 / RT;
kstep = (1. - z0) * jstep;
sX = 0.;
for (z=z0; z<1.; z+=kstep)
  {
  pijz = 2*Fr/z*cosh(delta*z)/(cosh(delta)+alpha*sinh(delta));
  if (pijz>=Fmin)
    sX += z * pijz / (Kj+pijz);
  }
rx = 2. * muM * cx * sX * fI * zpc * kstep;
```

Modifications done :

First, the radius `RT` is set to its new value.
Then the instruction :

```
  if(( z<= R2/RT)||(z >= R1/RT)) /* concentric cylinders */
```

is removed of the previous version because the 77 litres reactor is a cylinder (instead of 2 concentric cylinders).

2.3 Test of robustness on simulator

Tests in simulation are necessary to evaluate the robustness of the control. In the following tests, the tuning parameters are those of the 7 litres reactor control :

- control period : dt = 0.5 hour;
- dynamics of the reference trajectory : λ = 0.88;
- coincidence horizon : nhc = 5 control periods.

All the tests have the same pattern :

- At the beginning of the simulation, the process works in steady state and the biomass production set point is equal to 0.90 g/h (this set point, which is supposed to be fixed by the operator or by the level 2 of the hierarchical control, is called set point -level2 in the figures);
- The level2 flow rate set point is fixed to 0.675 l/h (dilution = 0.0877 h^{-1}). One recalls that the level2 controller is allowed to move the process flow (also named measure of flow on the figures) within a range of 10 % around the level2 flow rate set point.
- At time t = 10 h (simulated time), the set point is increased to 1.15 g/h, which is higher than the maximum production allowed by the maximum flow rate (computed to 0.7425 = 1.1 * 0.675 l/h) and the maximum biomass concentration (1.5 g/l). So the control computes the set point -level1 : 1.1138 = 1.1 * 0.675 * 1.5 g/h;
- Then at time 100 h, the set point is decreased to 0.9 g/h;

<u>Test 1 (figure 1) :</u>

The internal model of the control matches the simulated process.

At the increasing set point (t = 10 h), the control moves the two actions :

- the light intensity (FR_ctrl) is set to its maximum constraint : 223 W/m^2 . Due to this constraint, the dynamics is limited and the set point is reached in about 45 h ;
- the water flow rate is set to its maximum value (computed by the level2 controller) : 0.7425 l/h .

When the measured production reaches its set point (at about t = 52 h), the light intensity, FR_ctrl, decreases smoothly to its steady state value (133 W/m^2) and causes no overshoot of the set point.

At the decreasing set point (t = 100 h), the controller moves the 2 actions as previously :

- the light intensity (FR_ctrl) is set to its minimum value : 10 W/m^2 and the dynamics of the closed loop is due to the dilution phenomenon. The set point is reached in 20 h;
- the water flow rate is set to the level2 flow rate set point : 0.675 l/h .

When the measured production reaches its set point (at about 115 h), the light intensity, FR_ctrl, increases smoothly to its steady state value (82 W/m^2) and causes no overshoot of the set point.

The maximum constraint on the biomass concentration (1.5 g/l) is respected.

<u>Test 2 (figure 2) :</u>

The internal model of the control does not match the simulated process : the light intensity received by the process is assumed to be 50 W/m^2 lower than the action FR_ctrl computed by the control, with a minimum value of 10 W/m^2 because the lamps cannot be turned off.

In that case, the behaviour of the closed loop system is nearly unchanged, except that the dynamics of the first step is a little bit longer (75 h instead of 45 h) and that the set point is slightly overshot (about 1 % of the step) at the end of the decreasing step (at t = 120 h).

<u>Test 3 (figure 3) :</u>

Another mismatch is simulated : the illuminated surface ratio of the process, f_I_process, is supposed to be 90 % of the illuminated surface ratio of the internal model, f_I_ctrl . In comparison with the matched control, this is equivalent to a decreasing of 10 % of the biomass growth rate.

In that case too, globally the behaviour of the closed loop system is identical to the one of the matched control, except that the dynamics of the first step is longer (85 h instead of 45 h) and that the steady state is not reached because the next step occurs.

<u>Test 4 (figure 4) :</u>

This test is a simulation of bad calibration of a sensor : the flow rate of the process is assumed to be 80 % of the flow rate measured and given as input data of the internal model .

In that case too, globally the behaviour of the closed loop system is identical to the one of the matched control, except that the dynamics of the first step is shorter (it takes about 30h, compared to 45h, because of overestimation of the production) and that the dynamics of the last step is longer (because of a smaller dilution).

<u>Test 5 (figure 5) :</u>

In this test, the biomass concentration of the process is assumed to be 80 % of the measured biomass concentration.

In that case too, globally the behaviour of the closed loop system is identical to the one of the matched control. The dynamics takes about 25 h compared to 45 h.

<u>Conclusion of these tests :</u>

The robustness of the control is quite correct. It has to be confirmed on the real process.

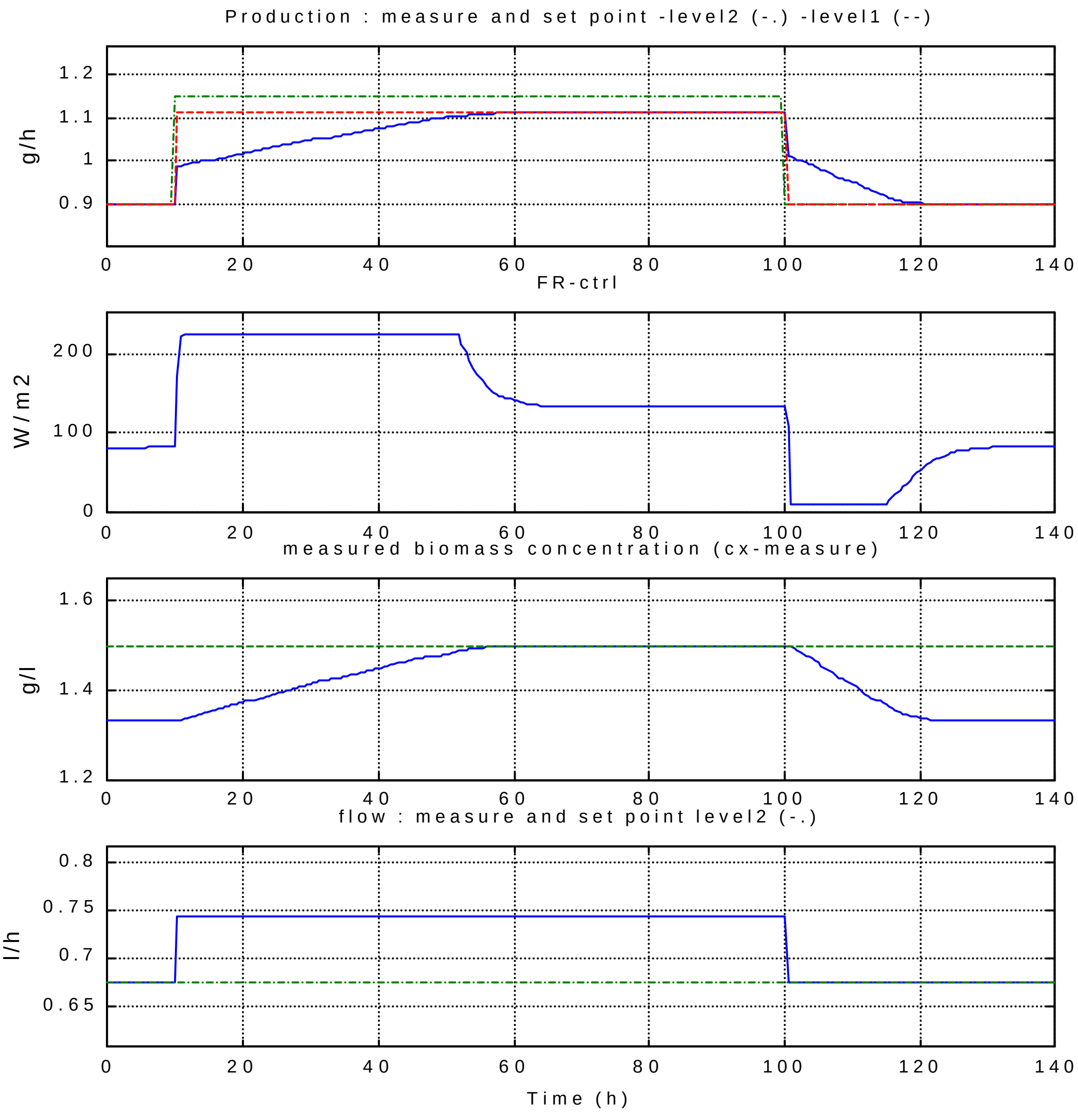

Figure 1 : Matched control

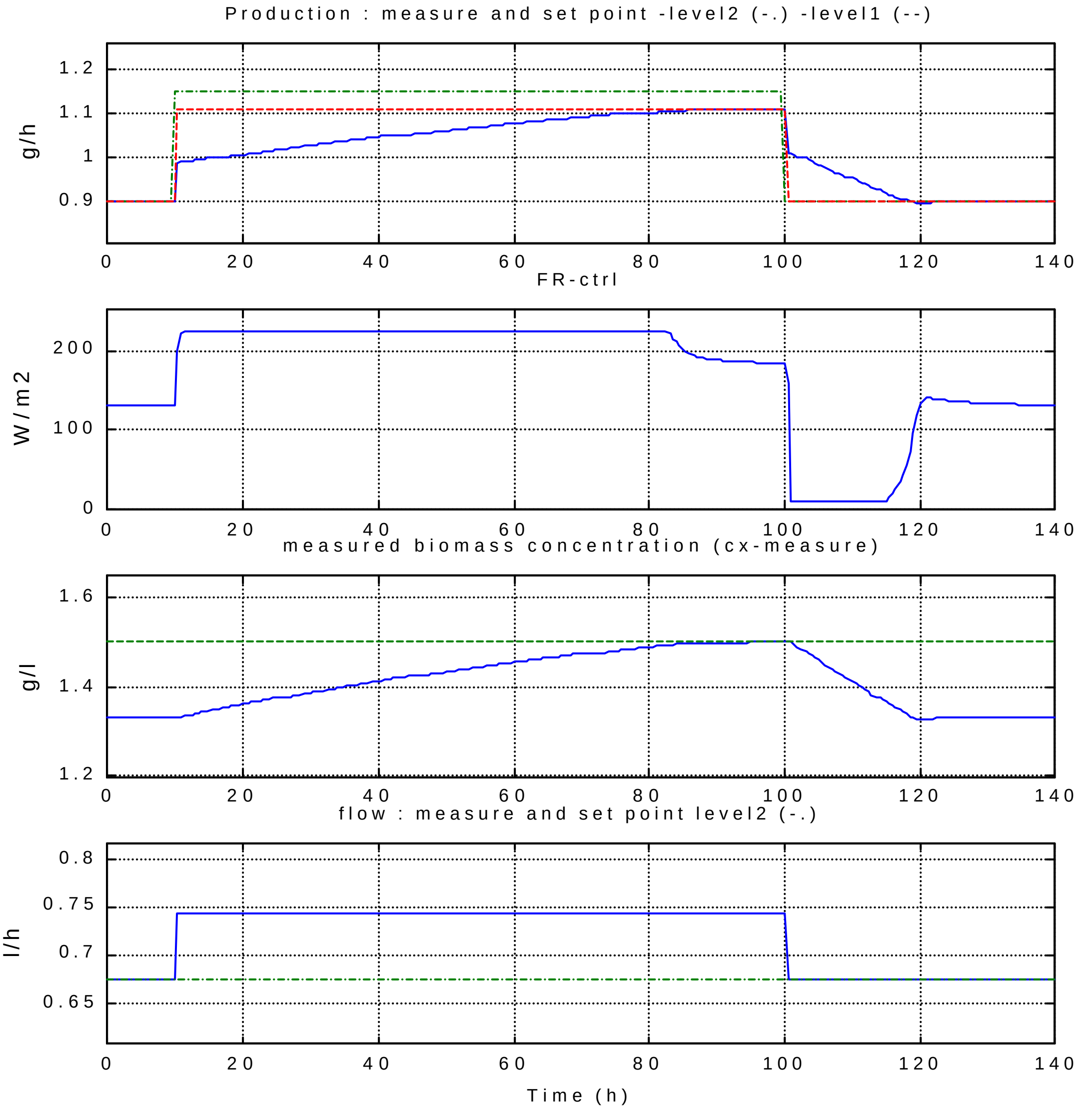

Figure 2 : Mismatched control : F_R_process = F_R_ctrl - 50

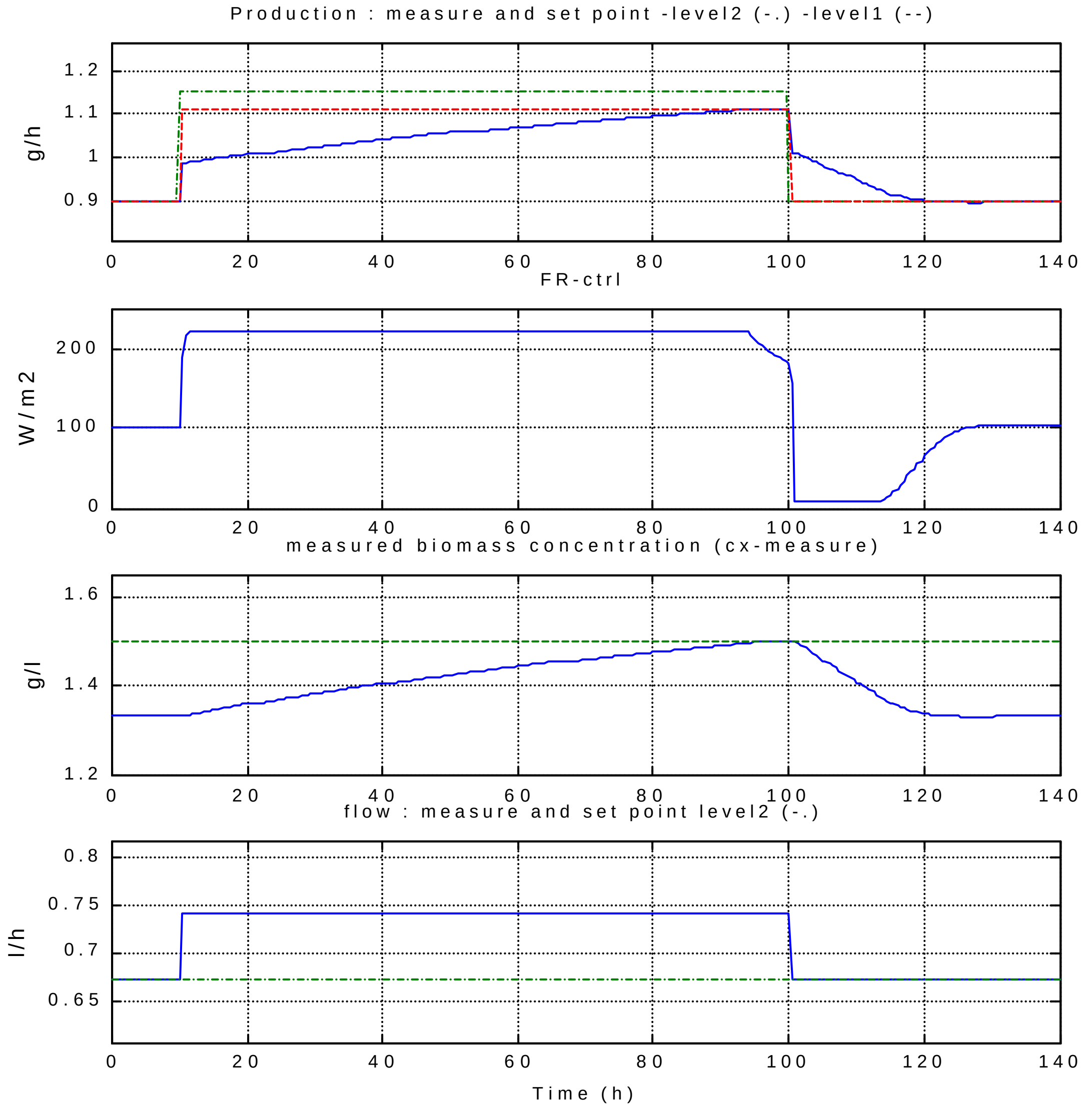

Figure 3 : Mismatched control : f_L_process = f_L_ctrl * 0.9

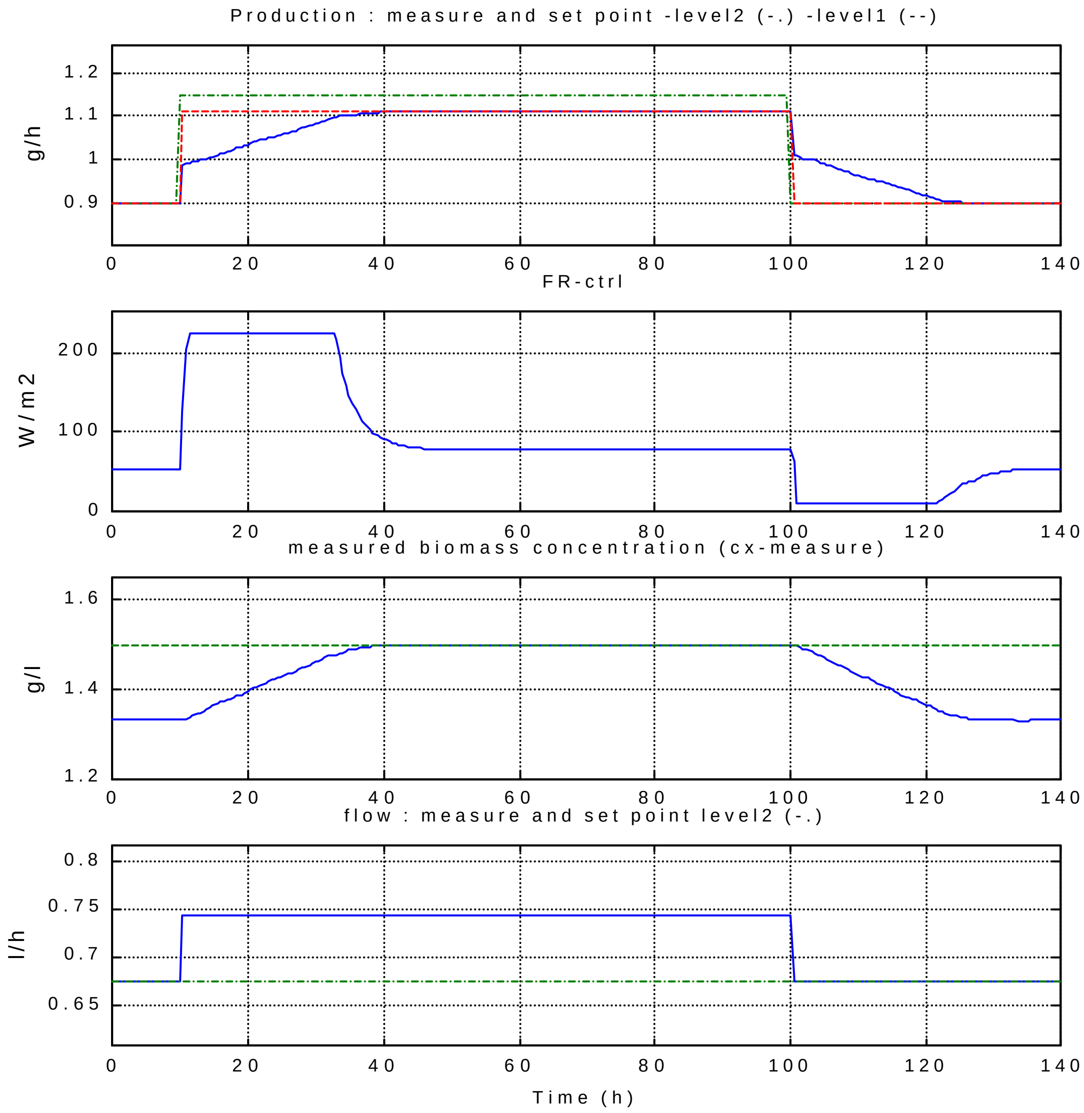

Figure 4 : Mismatched control : flow_process = flow_measure * 0.8

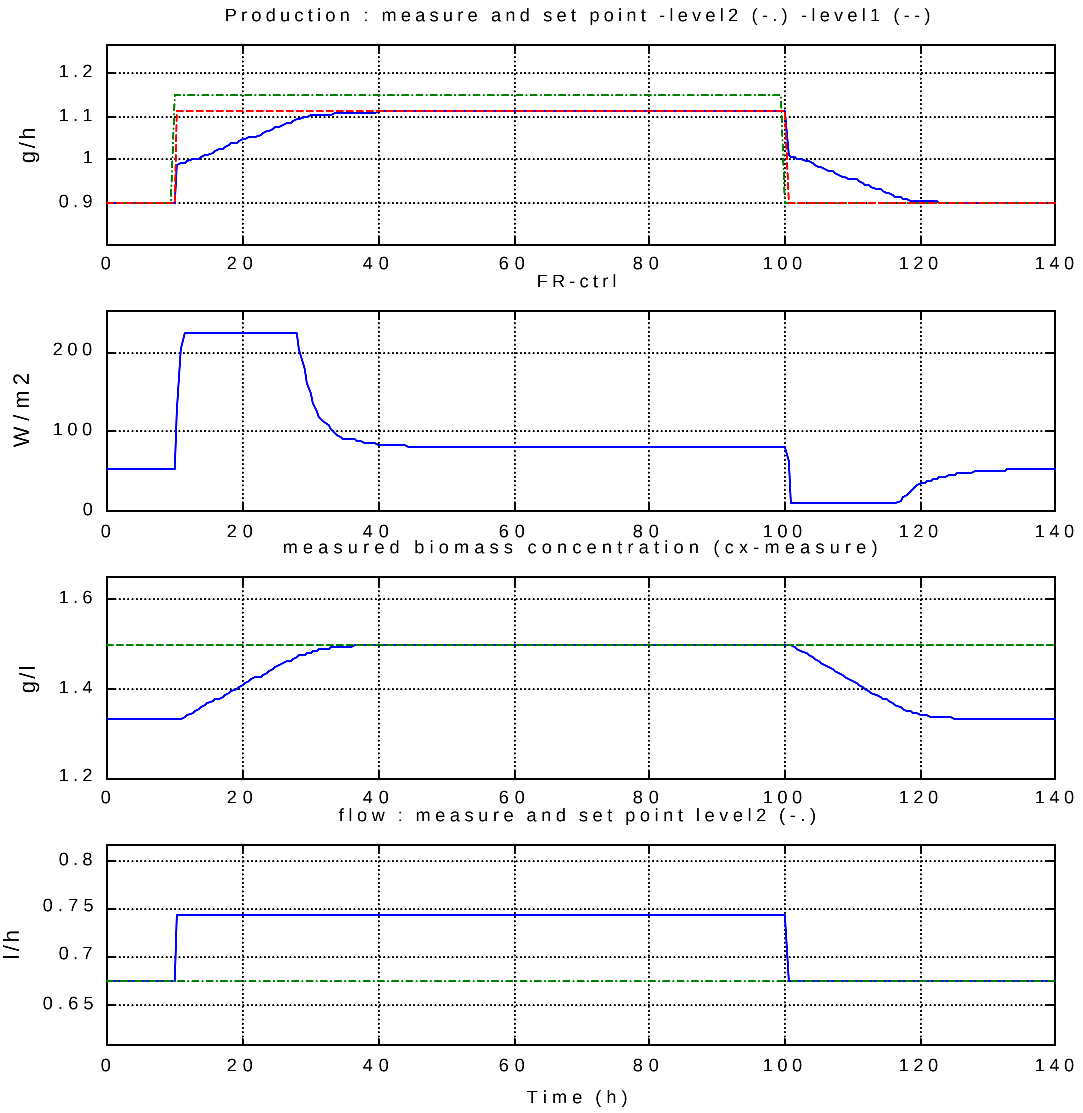

Figure 5 : Mismatched control : cx_process = cx_measure * 0.8

3. UP-DATING OF LIGHT CALIBRATION

The conversion of the Manipulated Variable (the light intensity, FR, computed by the control *lspc*) into the Action Variable 'light controller action' , which is specific of the light supply, is done by a subroutine outside the control programme *lspc*. So, the conversion can be changed when necessary (in case of new equipment, for example) without modifying the control programme *lspc*.

The subroutine of light calibration, *lightcal*, is given in annex 2.

4. CONTROL TESTS ON THE PILOT PLANT

4.1. First test

A first test was done at UAB from October 13th to 18th 1999.
At the beginning, the production setpoint is set to 0.38 g/h, identical to the measured production (upper graph of figure 6). The light intensity, F_R, is then 44 W/m^2 (second graph from top).
A sampling period later, the value of the measured production is 0.42 g/h. So F_R decreases to its minimum 10 W/m^2 .
At time t = 18 h, the flow rate (bottom graph) is increased from 0.4 to 0.7 l/h, which increased the production to 0.68 g/h . So F_R remains at its minimum.
Due to the dilution, the production decreases slowly until t = 100 h. Then F_R increases smoothly to 25 W/m^2 so that the production remains on its set point.
During all the test, the biomass concentration (third graph from top) never goes under its minimum constraint.

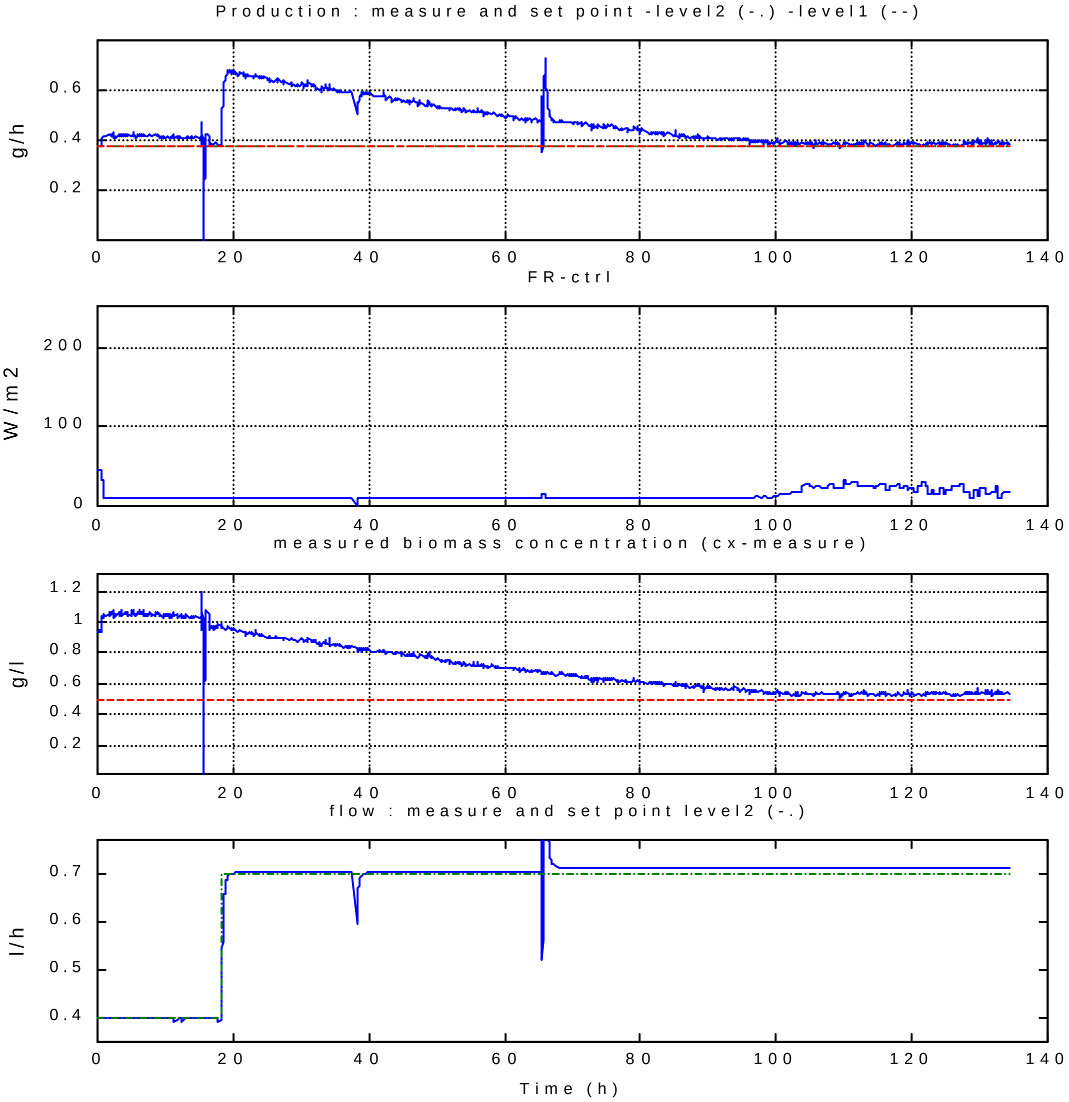

Figure 6 : UAB data from October 13th to 18th

Remark (figure 6) :

After October 15th 17:26 (time = 65.525 h), the measured flow rate (equal to 0.711 l/h) is different from the feasible flow rate (equal to 0.7 l/h) : this problem is due to a lack of precision of the data collection.

4.2. Second test

The second test was done from March 11th to 14th 2000 (figure 7).

At time t=18h, a set point step is applied from 0.55 to 0.77 g/h (top graph). At that moment, the manipulated variable increases to its maximum constraint (220 W/m^2) and stays there until the process output is approaching its set point at t=67h. Then the action decreases smoothly until its new steady state point. The set point is over-shot of about 4%. Due to the max constraint on the manipulated variable, the closed time response is 50 h. The control works as expected.

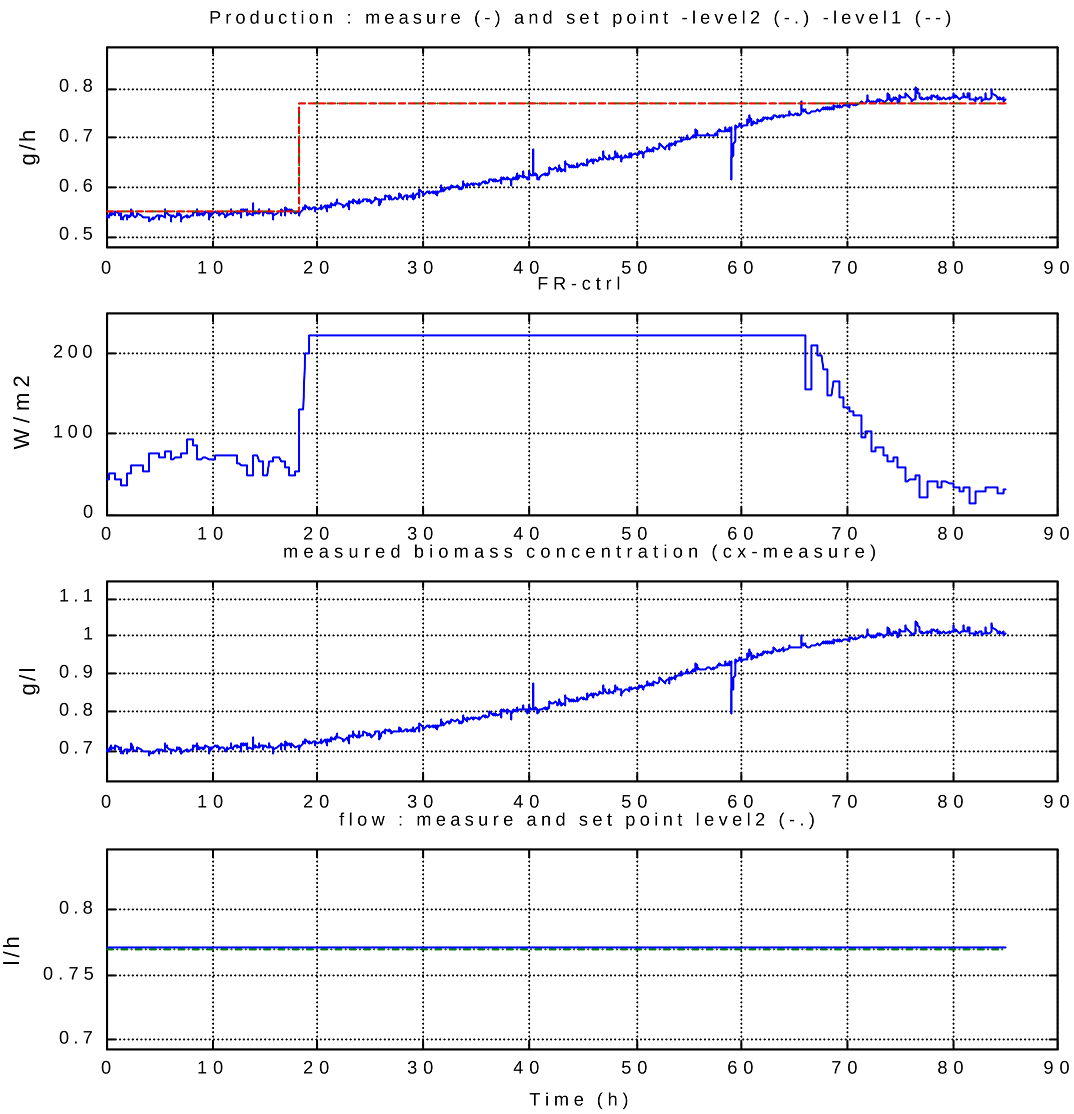

Figure 7 : UAB data from October 11th 1:37 to 14th 14:37

4.3. Third test

4.3.1 Description and results of the test on the pilot plant

The third test was done from March 29th to April 22nd 2000 (figure 8).
The set point (feasible production set point) and the Controlled Variable (biomass production) are represented, respectively, by the red (or dashed) and blue (or continuous) lines of the top graph.
The Manipulated Variable (light flux) is represented on the second graph.

The test is composed of a positive level2 set point at time t = 42h, followed by 2 negative level2 set points at time t = 300h and t = 330h. A negative step of flow rate set point is realized at time t = 428h (bottom graph).

Due to the maximum constraint on the Manipulated Variable, the closed loop response time is about 100 h, which is the value obtained on the simulator (see next section).
When the Controlled Variable is nearly reaching its set point at t = 250h, the biomass concentration (third graph) and the production decreases slightly while no input of the process moves. This phenomenon is due to a non measured disturbance (non measured modification of the flow rate?) as it will be confirmed by the model output given in next section.
The two last set point steps (at t = 330h and t = 428h) cause oscillations (more visible on the first one) of the closed loop. This is due to a mismatch between the internal model and the process. In order to improve the robustness of the control, the closed loop time response will be increased by setting the coefficient of the dynamics of the reference trajectory, *lambda*, to 0.97 instead of 0.88 as it was in the present test. As a consequence of this robustness increasing, the absolute constraints on the biomass concentration could no more be respected so tightly and the closed loop time response will be slightly increased (see section 5).

<u>Remark :</u>

As it can be seen on the bottom graph, there is some problem with the sensor of flow rate : from time to time it indicates an abnormal value, constant to 1.0 l/h all along the test.
It is recommended :

- to cancel the abnormal data through data processing;
- or, if not possible, to soften this phenomenon by computing the average of the flow rate by mean of the following statement in the main programme of the GPS before the call of the *lspc* subroutine :

qe_moy=average_var(&qe_real.value,30);

as it is already done for the biomass concentration.

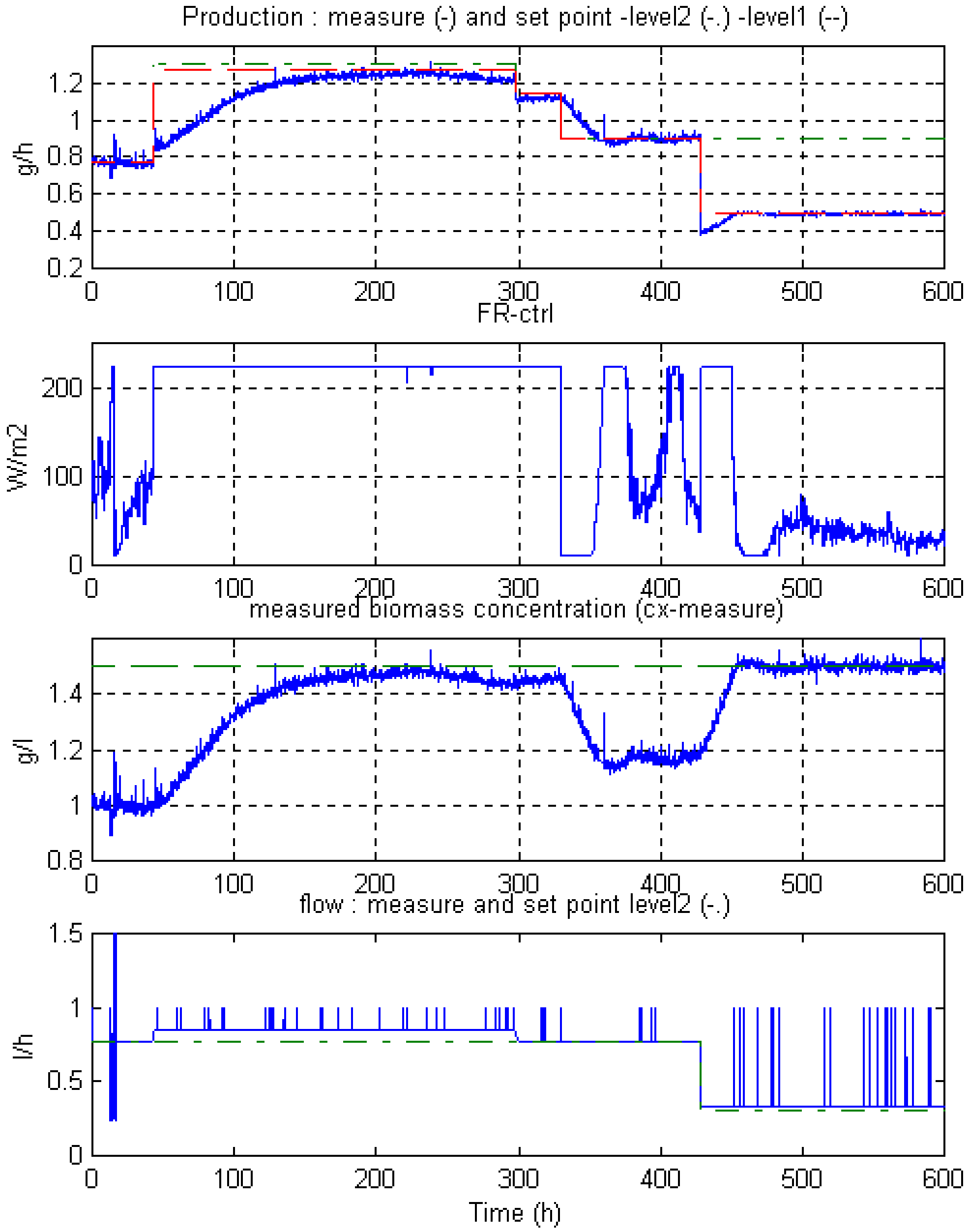

Figure 8 : UAB data from March 29th 0:00 to April 22nd 24:00

4.3.2 Model and process comparison

The figure 9, obtained on simulation by feeding the model with the process inputs (the measured flow is smoothed to cancel the artefacts visible on the bottom graph of the figure 8), allows to compare the model and process outputs for the previous test. For this comparison, the biomass concentration of the model is initialized on the value of a steady state process : 1 g/l, which is obtained on March 30^{th} at 0:00 (i.e. t=24 h on fig.8).

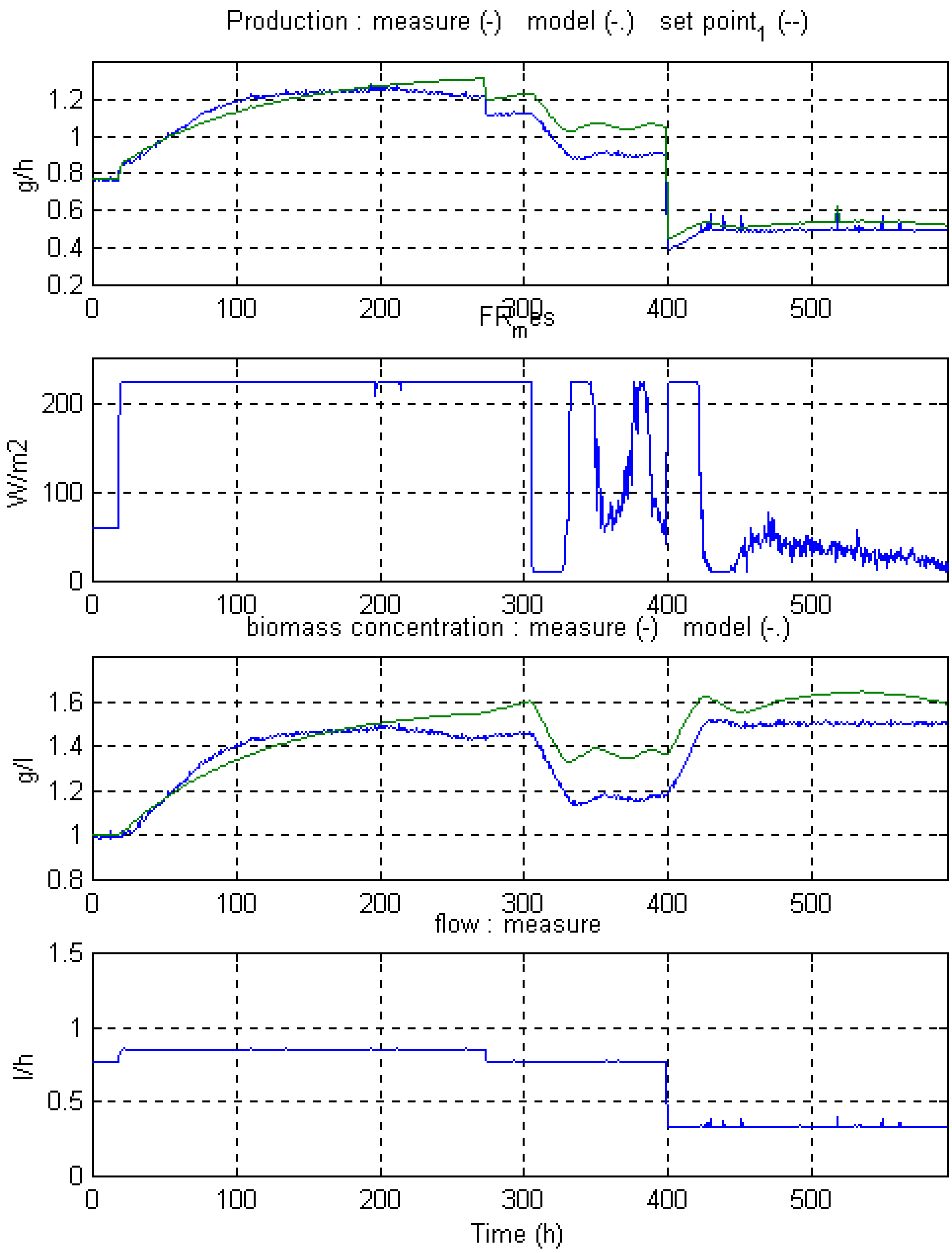

Figure 9 : process and model outputs for biomass conc. and production

Between the beginning and t = 200h, the dynamics and the static gains of the process (biomass concentration and production) and of the internal model can be compared (blue and green curves for the measure and model, respectively) : there is a slight difference for the dynamics and no difference for the gains.

At t = 200h, the process and model outputs begin to differ : the evolution of the process is not expected because there is no change of the measured inputs (light flux and flow rate). That shows that a non measured disturbance appears at that moment. The control is unable to react as the Manipulated Variable is already on its maximum constraint.
Remark: on the first graph of figure 9, the setpoint is not plotted (contrarily to what is mentioned).

5. INCREASE OF THE ROBUSTNESS OF THE CONTROL

The following study is done on the simulator of the closed loop system in order to choose a compromise between the improvement of the robustness and the specified time response.
The dynamics of the simulated process is modified so that to create the oscillations observed on the test : on the figure 10, oscillations are produced on the Controlled and Manipulated Variables between t = 300h and t = 400h as it is on the actual process (figure 8, between t = 330 h and t = 428 h). In this simulation, the value of the coefficient of the reference trajectory, λ, is equal to the value of the present UAB test where $\lambda = 0.88$. The closed loop time response is as short as possible due to the absolute constraints on the Manipulated Variable (light flux).

As a general rule, the robustness is improved by increasing the time constant of the reference trajectory. The best compromise has been obtained with :

$$\lambda = 0.97$$

The figure 11 illustrates the behaviour of the closed loop system with this new value of λ. There is no more oscillation and the time response is still acceptable even if it is slightly increased.

A new test with the new value of $\lambda = 0.97$ has been requested to be done on the pilot plant at UAB. Unfortunately a test has been done again with the old value of $\lambda = 0.88$. This test is reported in annex 4 where slight oscillations can always be seen.

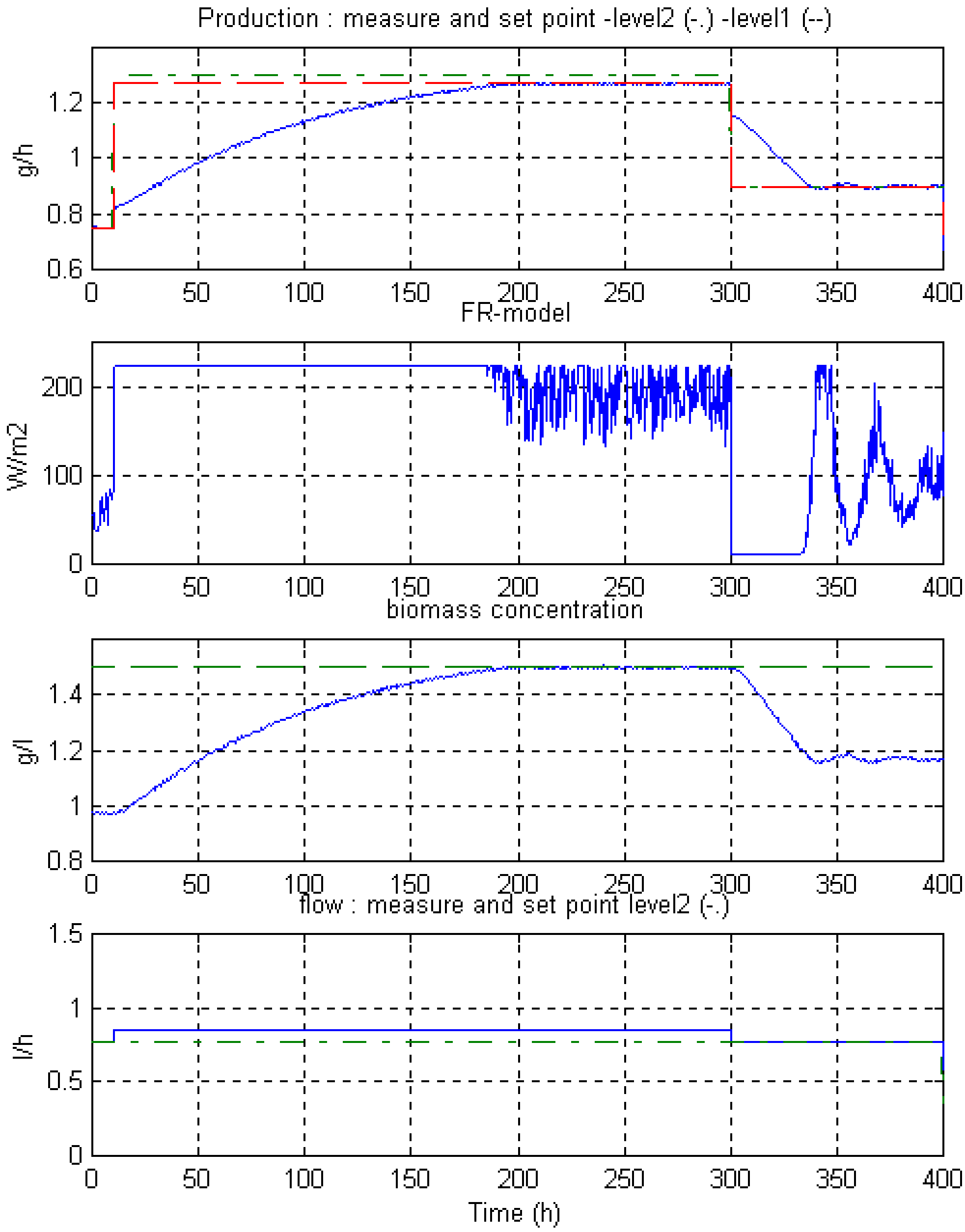

Figure 10 : Simulated closed loop system with l = 0.88

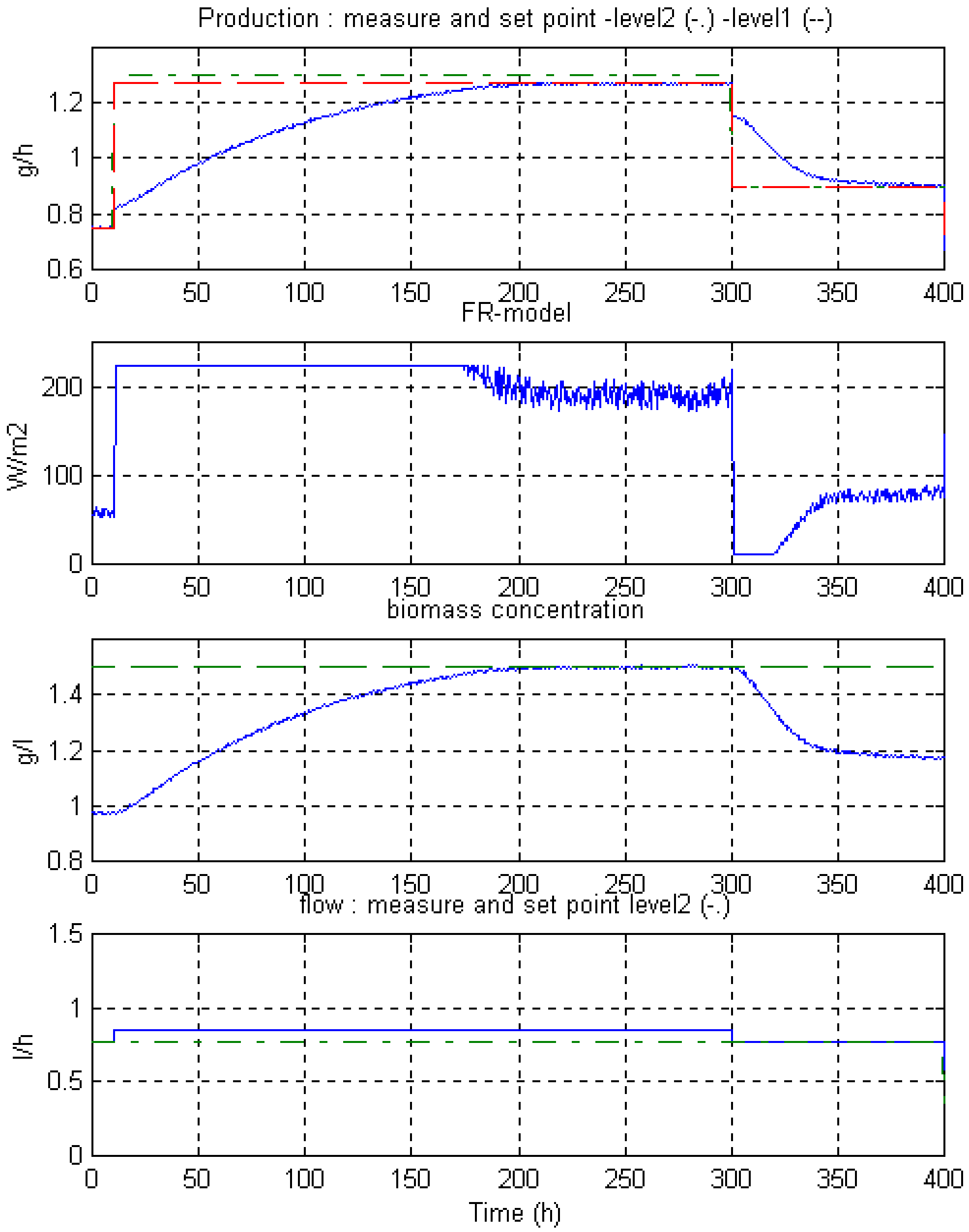

Figure 11 : Simulated closed loop system with l = 0.97

6. CONCLUSION

The tests of the new control software, done at UAB, show that the control is perfectly adapted to the new process despite it is ten times as big as the process on which the control was elaborated first.

Two points are then validated :

- the control itself which is proved to be generic and ready for an industrial photobioreactor;
- the easiness in moving a new control module without any modification into the software of the Global Purpose Station.

6. REFERENCES

CORNET J.F., DUSSAP C.G., GROS J.B. "Modelling of physical limitations in photobioreactors. Adaptation of the light energy transfer model to cylindrical geometry" ESA contract PRF 130820, 1993, TN 19.1 .

FULGET N. "MELISSA. Study for the non linear Model Based Predictive Control of Spirulina comportment using knowledge model". ESA contact PRF 142356. February 1995. Technical Note 24.1.

LECLERCQ J.J. "MELISSA. Final validation of the production control of the 7 litres photoautotrophic compartment". ESA contract PO n° 171686 of 16/07/97. May 1998. TN 38.2.

RICHALET J. 1993. Pratique de la Commande Prédictive. HERMES Edition.

VERNEREY A., ALBIOL J., GODIA F. "Set up of the phothosynthetic pilot reactor". ESTEC contract 11549/95/NL/FG, April 1998, TN 37.2 .

ANNEX 1

Light calibration (conversion function)

A bijective function binding the light intensity 'F_R' and the 'light controller action' is built from the UAB data (TN 37.2 , p.22 , April 1998) and is plotted in figure A1.1 .

Given :
x : controller action (between 0 and 1)
y : light intensity F_R .

The expression of y function of x is :

$$y = a*x^2 + b*x + c$$

The inverse function x versus y is :

$$x = (-b + (b^2 - 4*a*(c-y))^{1/2} / (2*a)$$

with : a = 289.0
b = 54.56
c = -24.19

The parameters a, b and c are identified by means of a least square method on the range :

$$5 \le y \le 223$$
$$0.2371 \le x \le 0.8352$$

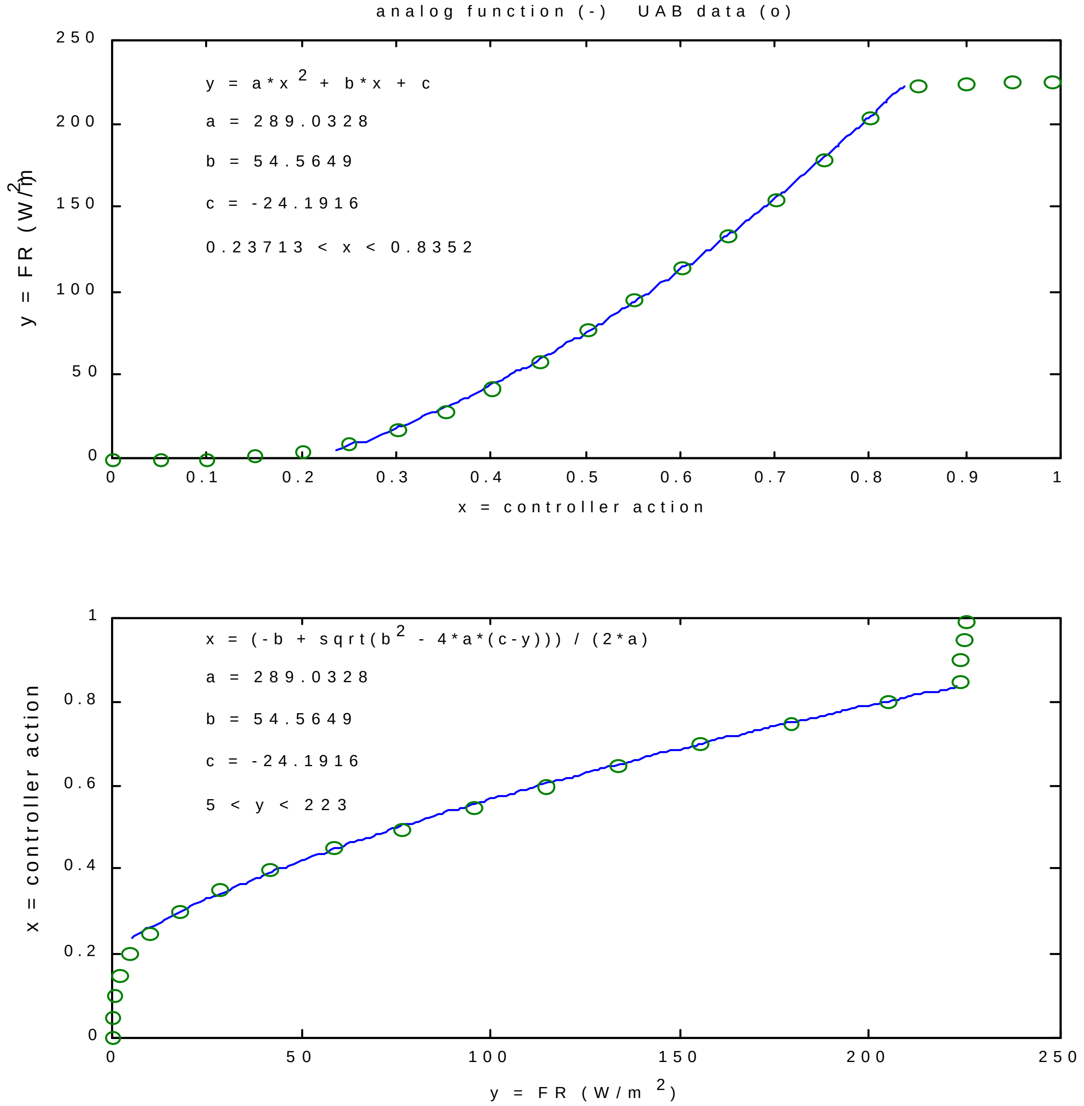

Figure A1.1 : Bijective function binding 'F_R' and 'controller action'

ANNEX 2

Light calibration
(subroutine)

The previous subroutine of light calibration, *lightcal*, in the source file *CtrlSpir.c* is replaced by the following new one.
This subroutine can be tested by *tst_lightcal* whose source file is appended.

```
/*--------------------------------------------------------------------
        light calibration from UAB data  (TN37.2  April 1998)
---------------------------------------------------------------------*/

#ifndef ADERSA
lightcal(REACT *react, int mode)
#else
lightcal(react, mode)
REACT *react;
int mode;
#endif
   {
      /* The following parameters come from ADERSA TN44.1 */
      double  a = 289.0;     double  b = 54.56;     double  c = -24.19;
      double  ymin = 5.;     double ymax = 223.;
      double  xmin = .2371;  double xmax = .8352;

        double  x, y;

        switch(mode) {
                case CAL_FR:
                {
                /*  FR determination ------------------------*/
                x = max(xmin, min(xmax, act_lamp.value));
                react->Fr = a*x*x + b*x + c;
                break;
                }

                case CAL_ACT:
                {
                /*  light controller action determination ----*/
                y = max(ymin, min(ymax, react->Fr));
                act_lamp.sp = (-b + pow(b*b - 4*a*(c-y) , 0.5)) / 2. / a;
                break;
                }

                default:
                {
                display_error("Error in routine lightcal ...\n");
                display_error("*** Program terminated ***\n");
                exit(0);
                }
        }

    }
```

```
/*--------------------------------
Main programme to test 'lightcal'
--------------------------------

        tst_lightcal.c

        September 1999
*/

#include <math.h>
#include <stdio.h>
#include "ctrlspir.h"

extern int lightcal();

main()
        {
        REACT   react;
        short i;


        /* initial value of Fr */
        Fr.value = 0.;

        /* printing results to screen */
        printf("\t Fr     controller_action\n");
        for (i=0; i<=13; i++)
                {

                /* light action sended to output of P100 controller */
                react.Fr=Fr.value;
                lightcal(&react,CAL_ACT);

                /* printing results to screen */
                printf("\t%12.5e %12.5e\n",react.Fr,act_lamp.sp);

                Fr.value += 20.;

                }
        /* initial value of Fr */
        act_lamp.value = 0.;

        /* printing results to screen */
        printf("\t controller_action     Fr   \n");
        for (i=0; i<=10; i++)
                {

                /* light intensity sended to input of control routine */
                lightcal(&react,CAL_FR);

                /* printing results to screen */
                printf("\t%12.5e% 12.5e\n",act_lamp.value,react.Fr);
```

```
        act_lamp.value += 0.1;

        }

}
```

ANNEX 3

Remark relative to the illuminated surface fraction f_I

Up to now, f_I was computed (improperly) in the sub-routine *control_spiru* by the relation :

```
fI = VOLUME_LIGHT / VOLUME_TOTAL;
```

the parameters `VOLUME_LIGHT` and `VOLUME_TOTAL` being defined in *melissa.h* .

What should be done, to be in agreement with the very definition of f_I :

- to remove the parameter `VOLUME_LIGHT` from *melissa.h* , if it not used elsewhere than in *control_spiru* ;
- to remove from *control_spiru* the following statement :

```
fI = VOLUME_LIGHT / VOLUME_TOTAL;
```

- to define f_I in *melissa.h* and to set it to its real value.

ANNEX 4

Test on the pilot plant at UAB (from March 9th to March 23rd 2001)

The test was done with the old value of $\lambda = 0.88$ (instead of $\lambda = 0.97$ as requested).
Only the setpoint, the Controlled Variable (production of biomass) and the Manipulated Variable (light flux) are reported in the following figures A4.1 to A4.3 .
The setpoint and the production of biomass are the red and blue lines of the top graph. The light flux is plotted on the bottom graph.
Oscillations still appear on a part of the test (figure A4.2).
On the figure A4.3, the shutdowns of light flux are due to power failures.

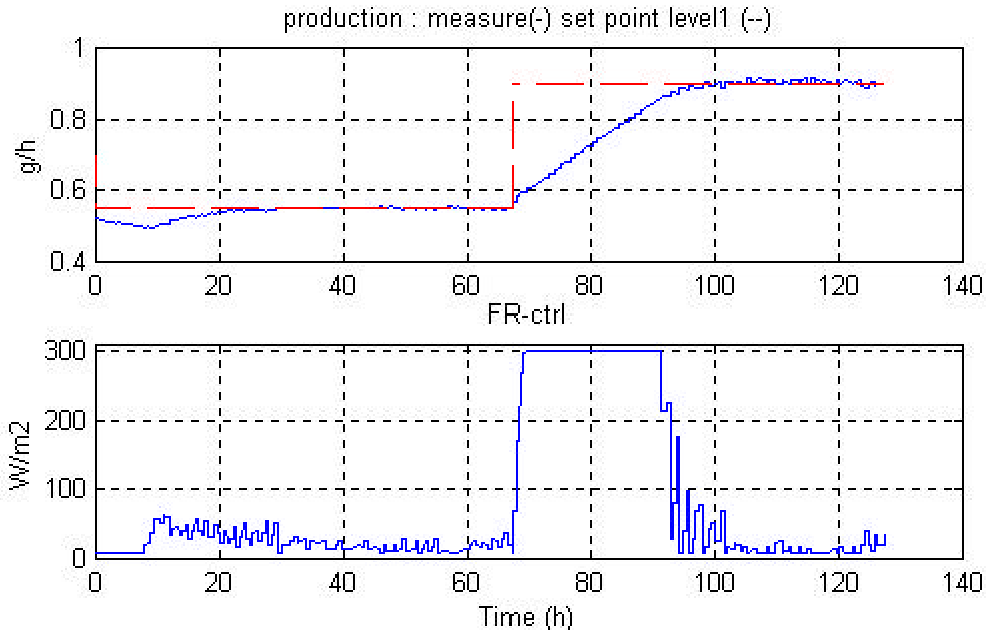

Figure A4.1 : UAB Test from March 9th to 14th

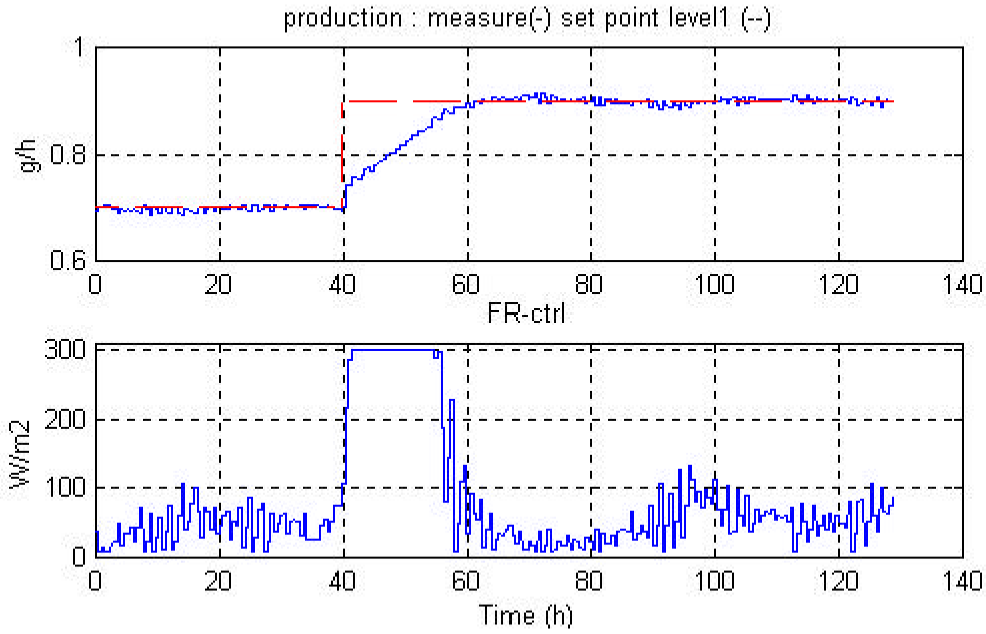

Figure A4.2 : UAB Test from March 15th to 20th

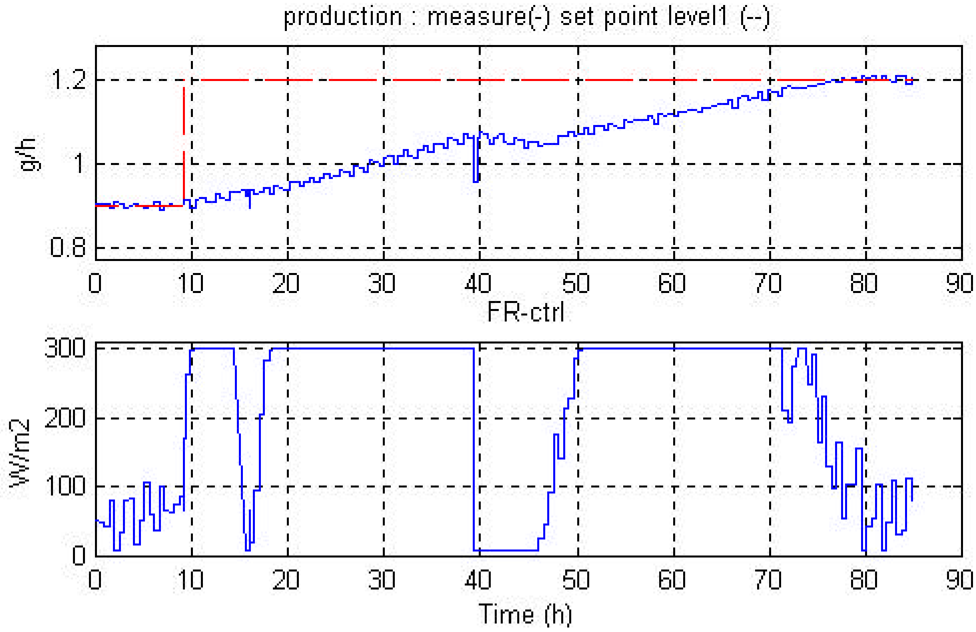

Figure A4.3 : UAB Test from March 20th to 23rd