# *6. Experiments*

In this chapter we will show results of some experiments realised on different process models and laboratory plants. With these results we would like to show the effectiveness of the proposed anti-windup method - *conditioning technique*.

## *6.1. Experiments on Process Models*

Experiments on process models have been made with program package MATLAB with toolbox SIMULINK.

### *6.1.1. Non-minimal Phase Process*

In this example we used the following representative of the non-minimal phase processes:

$$G_{PR} = \frac{1-s}{(1+2s)(1+4s)}, \tag{6.1}$$

controller

$$K = 4,\ T_i = 7s,\ T_d = 0.5s,\ T_f = 0.05s \tag{6.2}$$

with process limitations

$$U_{\max} = 1.5,\ U_{\min} = 0,\ v_{\max} = 1s^{-1},\ v_{\min} = -1s^{-1} \tag{6.3}$$

The results are shown in Figures 6.1 to 6.3.

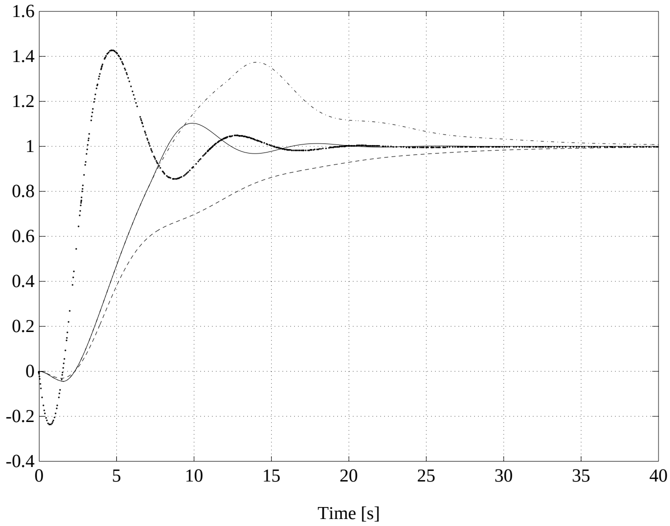


*Fig. 6.1. Process output (y); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

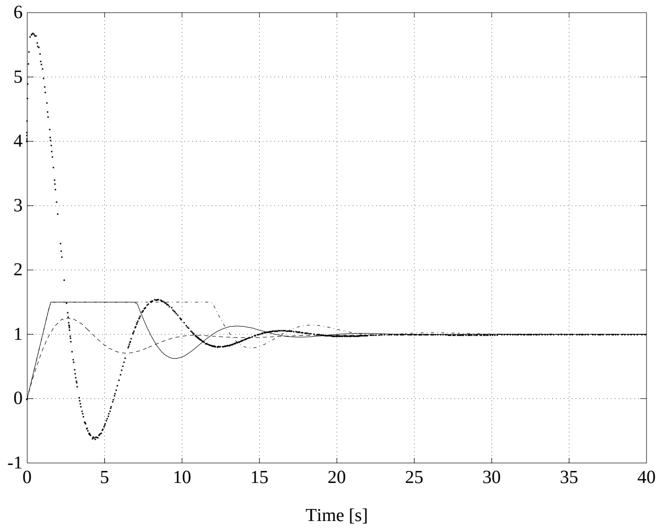


*Fig. 6.2. Process input ($u^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

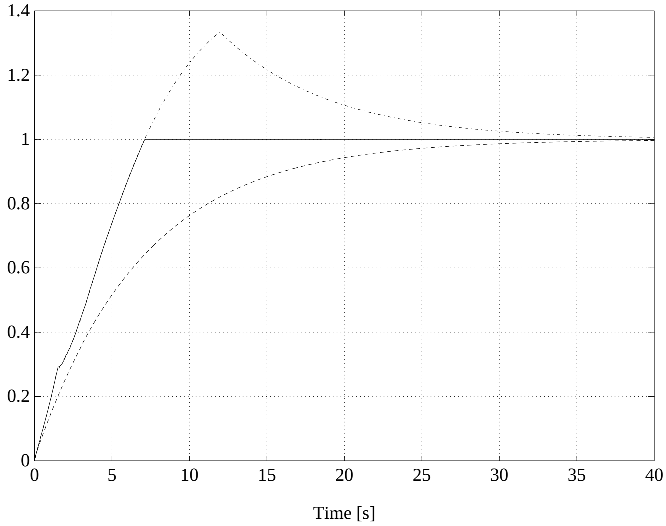


*Fig. 6.3. Realisable reference ($w^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection*

### *6.1.2. Delayed Process*

Here, we added a delay to the previous process (6.1):

$$G_{PR} = \frac{(1-s)e^{-s}}{(1+2s)(1+4s)}, \qquad (6.4)$$

We used controller

$$K = 2.5, \quad T_i = 8s, \; T_d = 1s, \; T_f = 0.1s \qquad (6.5)$$

with process limitations

$$U_{\max} = 1.5, \quad U_{\min} = 0, \quad v_{\max} = 1s^{-1}, \quad v_{\min} = -1s^{-1} \qquad (6.6)$$

The results are shown in Figures 6.4 to 6.6.

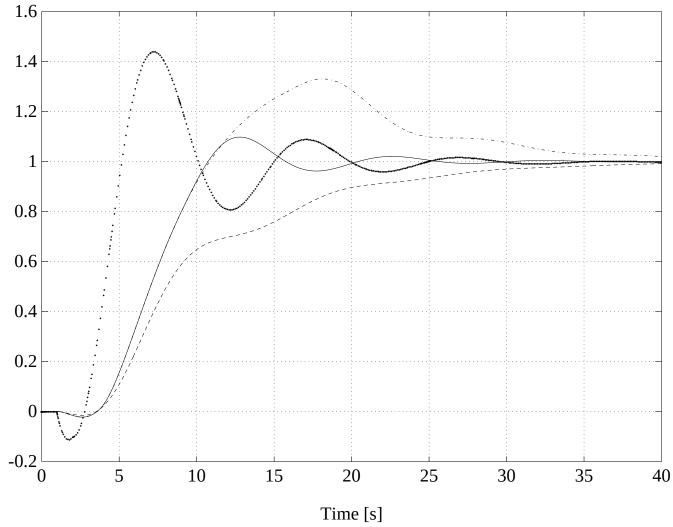


*Fig. 6.4. Process output (y); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

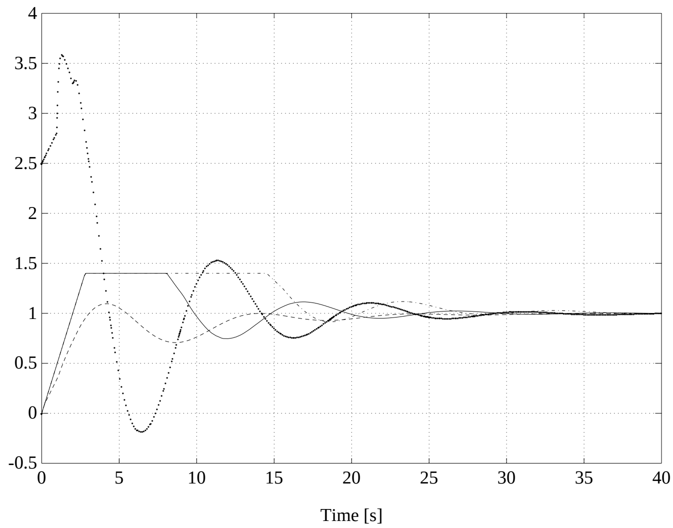


*Fig. 6.5. Process input ($u^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

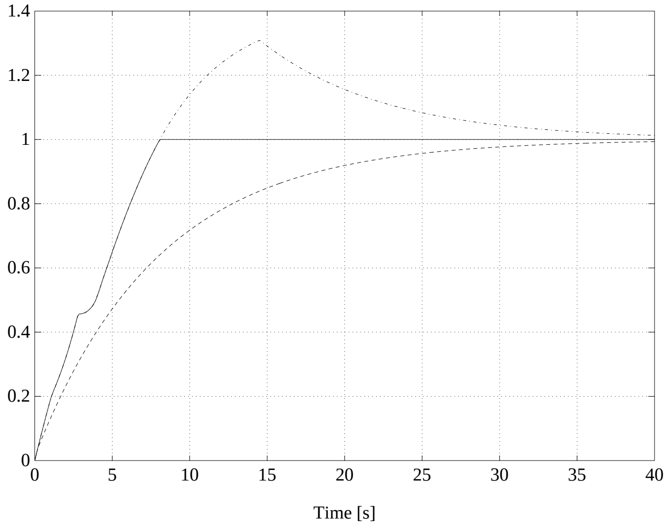


*Fig. 6.6. Realisable reference ($w^r$); __ Conditioning technique, -- Incremental algorithm, -.- Without AW protection*

### *6.1.3. Process With Pole in Origin*

This example was performed with the following transfer function

$$G_{PR} = \frac{1}{s(1+s)}, \tag{6.7}$$

and controller

$$K = 10,\ \ T_i = 20s,\ T_d = 0.1s,\ T_f = 0.01s \tag{6.8}$$

with process limitations

$$U_{\max} = 1,\ \ U_{\min} = -1 \tag{6.9}$$

The results are shown in Figures 6.7 to 6.9.

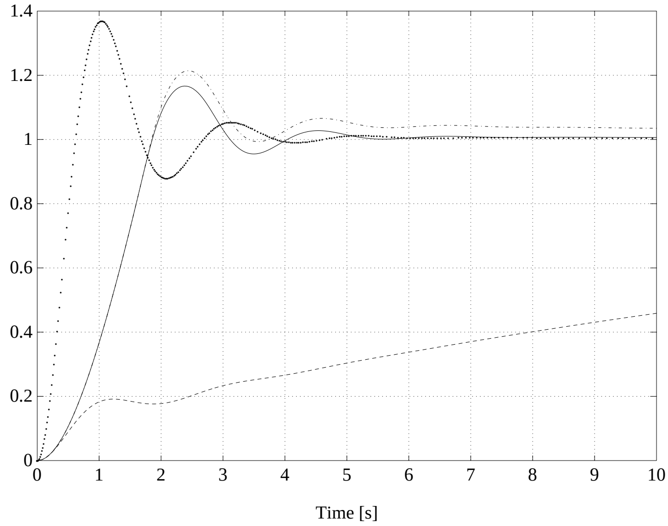


*Fig. 6.7. Process output (y); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

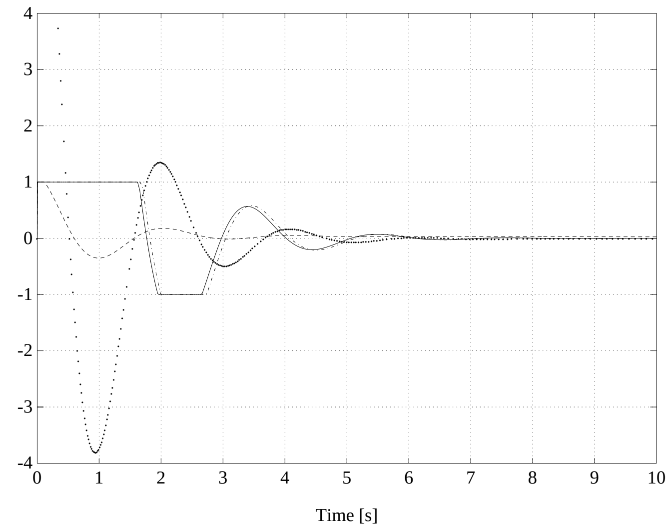


*Fig. 6.8. Process input ($u^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

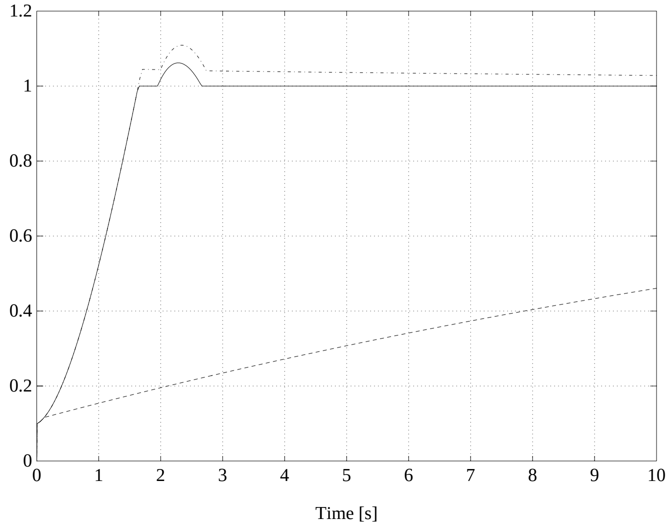


*Fig. 6.9. Realisable reference (w^r); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection*

We can see the offset at process output ($y$) in steady state in unlimited response, which is slowly decreasing. The reason is an integral term of PID controller. If we would use only P or PD controller instead of PID case, the unlimited response would not have an offset. But when using P or PD controllers, another problems can appear. In the case of disturbance in the process, such controller would not be capable to reduce the control error toward zero. This is the main reason why I part of controller is also used in controlling processes with pole in origin.

## 6.1.4. Model of Heat Exchanger

We chose next model of heat exchanger [Balchen and Mumme, 1988]:

$$G_{PR} = \frac{\left(1 - e^{-2s}\right)}{2s(1+s)}, \tag{6.10}$$

and controller

$$K = 0.7,\ \ T_i = 40s,\ T_d = 0.5s,\ T_f = 0.05s \tag{6.11}$$

The simulated process limitations were

$$U_{\max} = 0.1,\ \ U_{\min} = -0.1,\ \ v_{\max} = 0.04 s^{-1},\ \ v_{\min} = -0.04 s^{-1} \tag{6.12}$$

The results are shown in Figures 6.10 to 6.12.

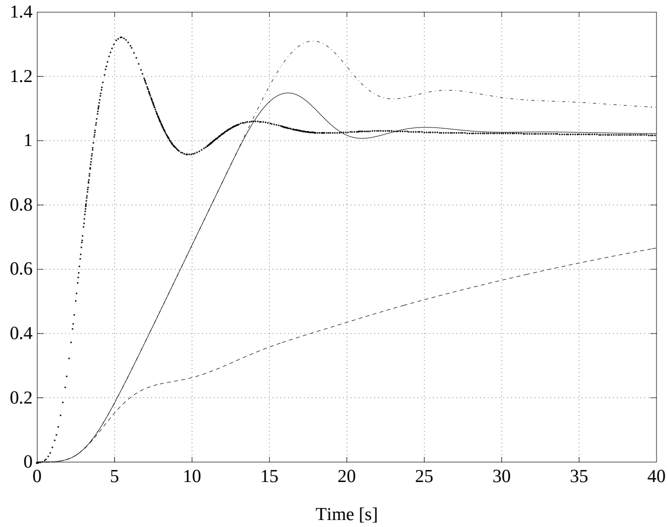


*Fig. 6.10. Process output (y); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

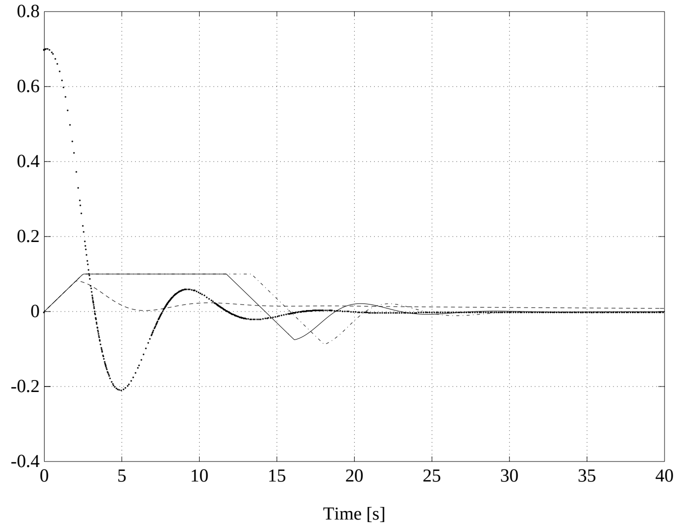


*Fig. 6.11. Process input ($u^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

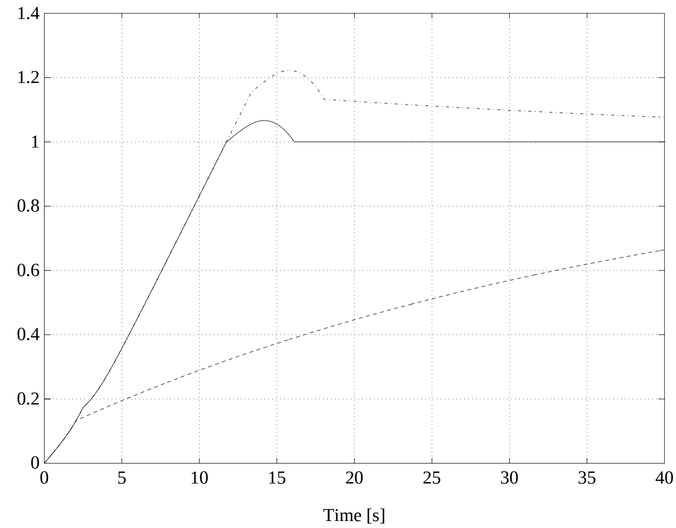


*Fig. 6.12. Realisable reference ($w^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection*

Here we have the same problems as in previous case. The reason is again the existence of the pole in the origin.

### 6.1.5. Model of Distillation Column

From the same source [Balchen and Mumme, 1988] we chose the model of distillation column:

$$G_{PR} = \frac{4e^{-0.5s}s}{(1+2s)(1+4s)}, \qquad (6.13)$$

The chosen controller was

$$K = 37,\ \ T_i = 1s,\ T_d = 0s,\ T_f = 0s \qquad (6.14)$$

and the simulated process limitations were:

$$v_{\max} = 0.35s^{-1};\ \ v_{\min} = -0.35s^{-1} \qquad (6.15)$$

Here we can see, from the process transfer function that there is a zero in the origin. To show the behaviour of such system, we added a disturbance at process input. Disturbance had a value of 1 from 0 to 20s and was 0 from 20s till the end of simulation. The reference value was 0 all the time.

The results are shown in Figures 6.13 to 6.15.

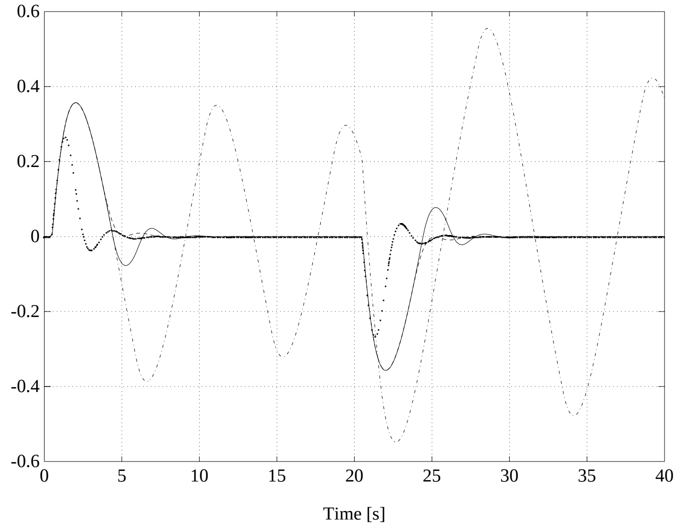


*Fig. 6.13. Process output (y); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

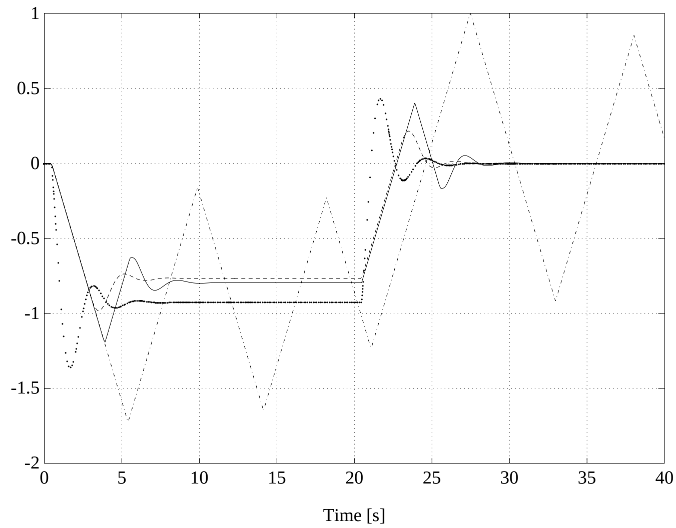


*Fig. 6.14. Process input ($u^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

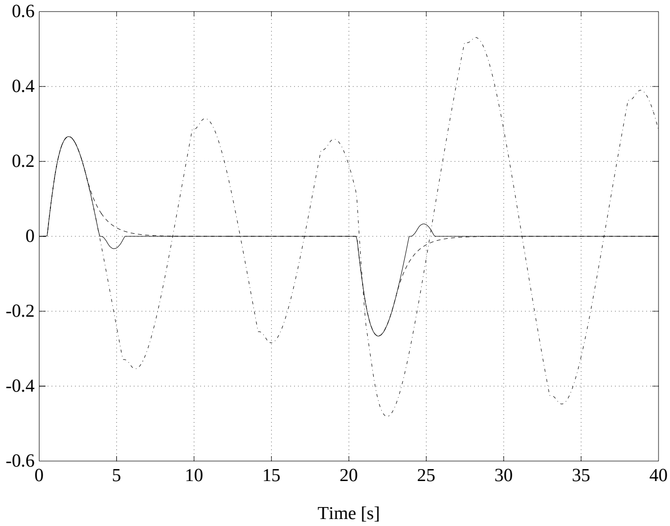


*Fig. 6.15. Realisable reference ($w^r$); __ Conditioning technique, -- Incremental algorithm, -.- Without AW protection*

### *6.1.6. Model of Unstable Process*

As a model of an unstable system we used the following process transfer function:

$$G_{PR} = \frac{1}{(1+2s)(1-2s)}, \tag{6.16}$$

and controller

$$K = -20, \quad T_i = 2s, \; T_d = 0.8s, \; T_f = 0.08s \tag{6.17}$$

The simulated process limitations were

$$U_{\max} = 4, \quad U_{\min} = -4 \tag{6.18}$$

The results are shown in Figures 6.16 to 6.18.

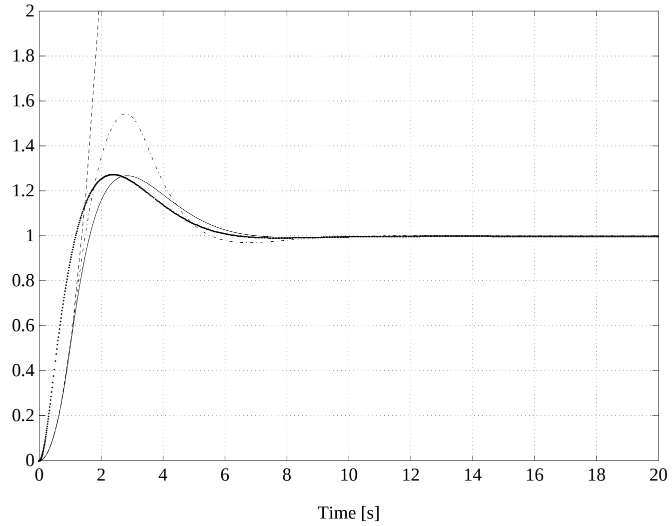


*Fig. 6.16. Process output (y); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

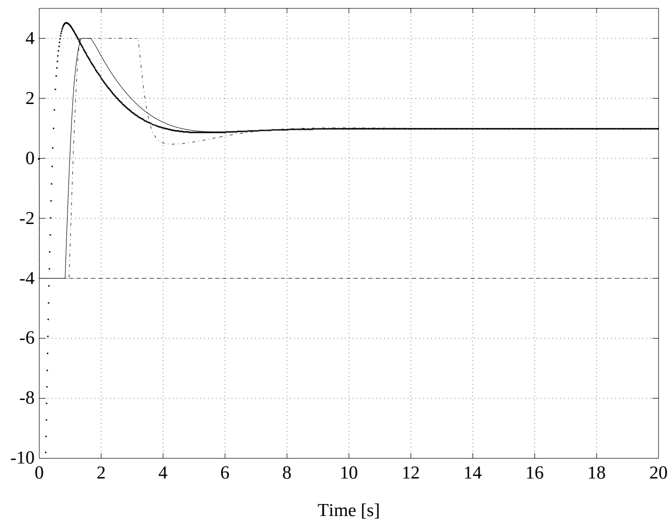


*Fig. 6.17. Process input ($u^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

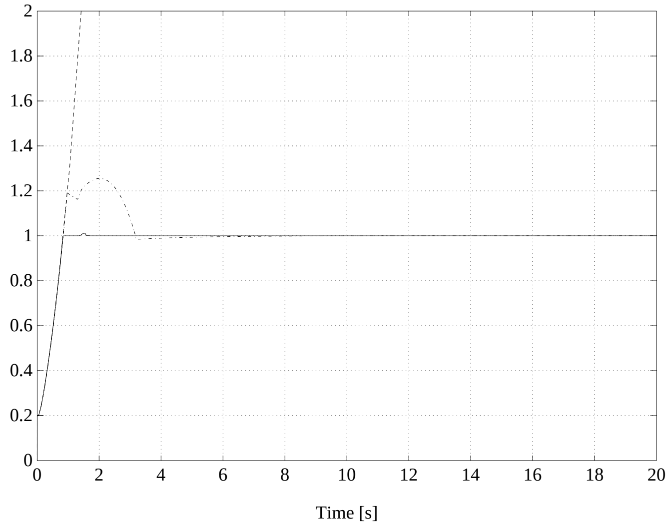


*Fig. 6.18. Realisable reference ($w^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection, ... Unlimited response*

We can see that conditioning technique gives again the best limited response. Note that in the case of limitations which are harder than defined above, the system could become unstable even if using conditioning technique.

## *6.2. Experiments on Laboratory Plants*

In most cases, experiments on process models does not show all the problems which can occur in the real applications. Therefore first step to the real application is to make some experiments on laboratory plants.

We made experiments on water column process and on unstable hydraulic process.

### *6.2.1. Water Column Process*

The water column process is shown in Fig. 6.19.

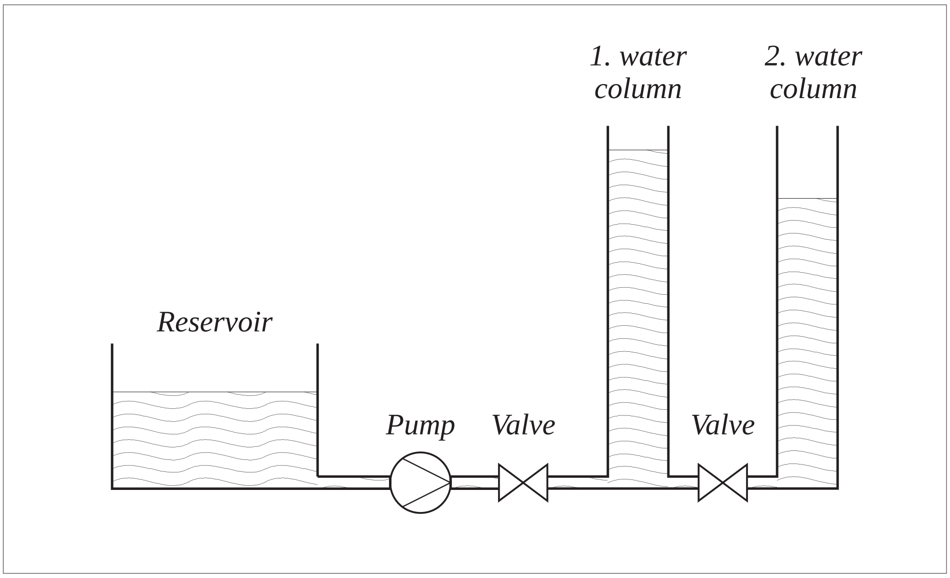


*Fig. 6.19. A scheme of two water column process*

The process input is the voltage on the pump which drives the water from reservoir to water columns. The process output is the water level in the second column. Note that water can go also from columns back to the reservoir.

It is well known that such kind of system has non-linear behaviour. The linear change of input voltage of the pump will produce quadratic change of the water level. When there is no voltage on the pump and system is in steady state, the sensor of the water level shows the value of -0.15V, what corresponds to the level of about -1.8cm. At the desired reference point 3V (corresponds to the level of 36cm), the voltage at the pump must be 2.5V. The non-linearity of the system was therefore estimated as

$$u^r = -0.15 + 0.504 \cdot |u| \cdot u \tag{6.19}$$

The inverse of that estimation (see chapter 5.2) is

$$u_{inv} = \frac{|u+0.15|}{u+0.15}\sqrt{\frac{|u+0.15|}{0.504}} \tag{6.20}$$

The implementation of the estimation and the inverse of estimation is shown in chapter (5.2).

In our experiment, we chose the following controller:

$$K = 10,\ \ T_i = 80s,\ T_d = 0.05s,\ T_f = 0.05s \tag{6.21}$$

and limits:

$$U_{\max} = 6V,\ \ U_{\min} = 0V \tag{6.22}$$

The reference *w* was 3V (36cm) from 0 to 120s and 2V (24 cm) from 120s to the end of experiment.

As an implementation of the controller we have used the program package *MATLAB* with toolbox *SIMULINK* with real-time toolbox and *Burr-Brown* PCI-20000 system. The sampling time was 0.2s.

Figures 6.20 to 6.22 show the results of experiment.

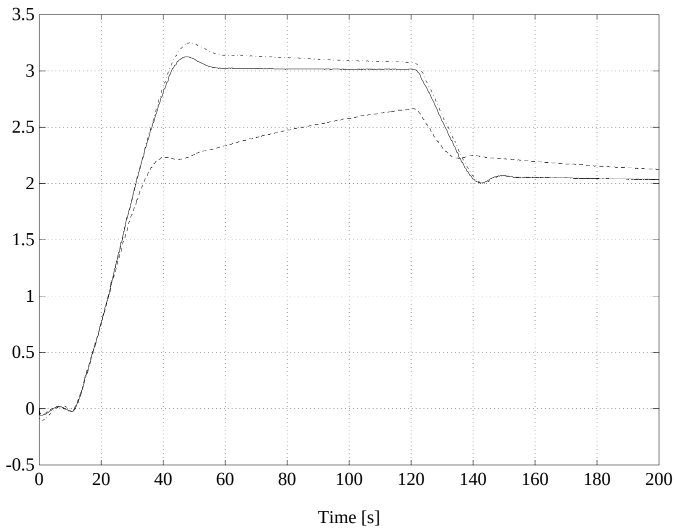


*Fig. 6.20. Process output (y); __ Conditioning technique, -- Incremental algorithm, -.- Without AW protection*

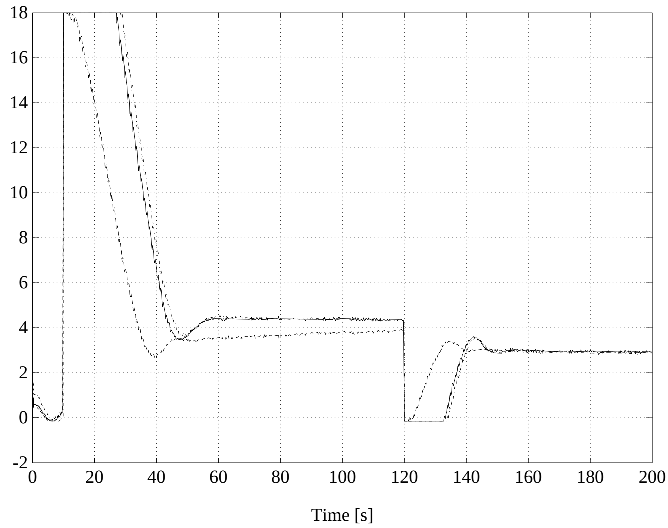


*Fig. 6.21. Process input ($u^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection*

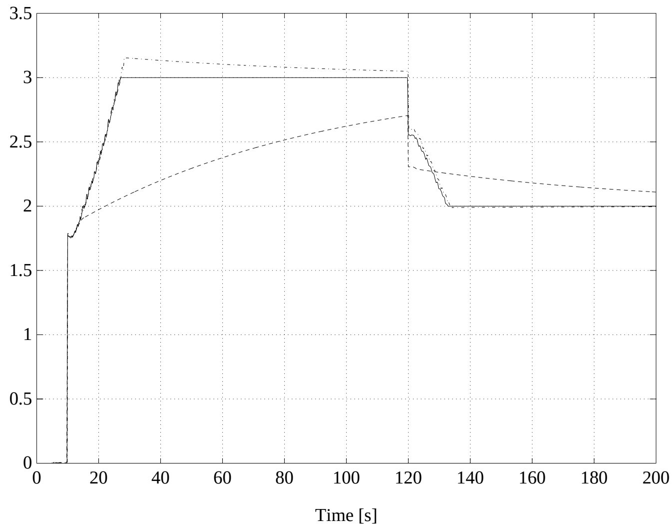


*Fig. 6.22. Realisable reference ($w^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection*

We can see that the incremental algorithm has very sluggish response, while conditioning technique gives most useful result.

### *6.2.2. Unstable Hydraulic Process*

The unstable hydraulic process was the second laboratory plant on which we tested the anti-windup algorithm. It consists of reservoir, pump and closed water column with hollow cylinder, closed on top (rocket). Process input was the voltage on the pump while process output was the position of the rocket.

If the voltage on the pump increases, the pressure inside closed water column increases and it causes that more water comes through the hole at the bottom side of the rocket into it. The rocket becomes heavier and starts to sink. Lower it goes, higher is a water pressure, more water comes into the rocket and consequently the rocket becomes heavier and heavier. Just the opposite happens when we decrease the voltage on the pump.

We can see the process is unstable. Fig. 6.23 represents a scheme of the mentioned unstable hydraulic process.

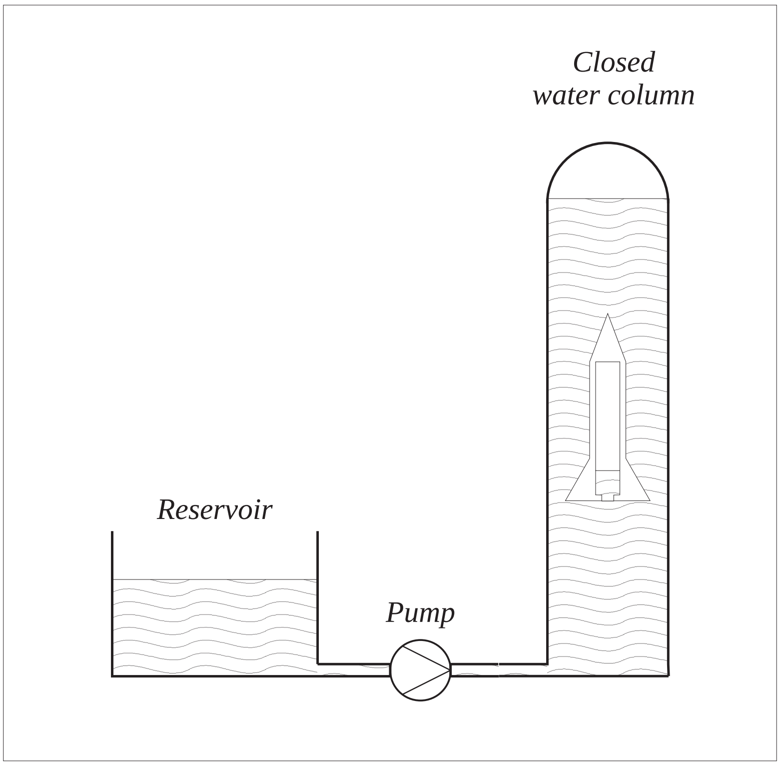


*Fig. 6.23. A scheme of unstable hydraulic process*

We chose the following controller parameters

$$K = -2,\ \ T_i = 7,\ T_d = 1.5s,\ T_f = 0.1s \tag{6.23}$$

and limits:

$$U_{\max} = 5.5V,\ \ U_{\min} = 3V \tag{6.24}$$

The reference was 1.2V (20 cm) from 0 to 50s and from 100 to 150s and 2.4V (36cm) from 50s to 100s and from 150s to the end of experiment.

As a controller we used program module CONTROL in PASCAL developed in our department [Vrančić, 1993]. Sampling time was 20 ms. Note the signal $\Delta u$=1.2V was added to the controller output during the time when the reference was 2.4V to diminish the overshoot when reference changes.

Figures 6.24 and 6.25 show the results of experiment.

Results show that the most useful response appears when using conditioning technique. Incremental algorithm has again very sluggish response and appears as a method which was not capable to handle with such limited process. When no protection against windup is used, we can also see that some problems appear.

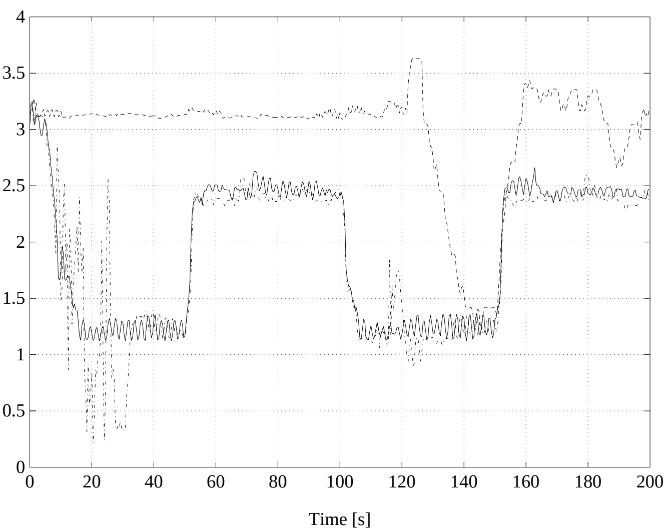


*Fig. 6.24. Process output (y); __ Conditioning technique, -- Incremental algorithm, -.- Without AW protection*

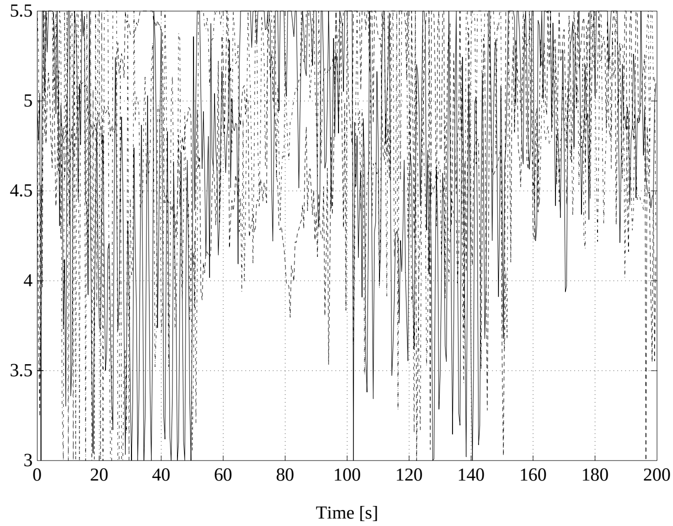


*Fig. 6.25. Process input ($u^r$); __ Conditioning technique,*
*-- Incremental algorithm, -.- Without AW protection*