The Blend Station

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Abstract The paper treats the problem of ratio control. Previous solutions based on simple Ratio stations perform poorly during transients caused by setpoint changes. A new solution, the Blend station, that improves control during transients is proposed. Both a constant-gain and an adaptive version are presented.

Keywords Ratio control, ratio station, blending, mixing.

1. Introduction

Process control problems are traditionally solved using PID controllers that are connected through well-known couplings such as cascade control, feedforward control, ratio control, split-range control, etc. See Seborg *et al.* (1989), Åström and Hägglund (1995), and Dumdie (1996). Logic, selectors and sequence functions are also used to obtain the desired overall control function. This distributed approach was previously accomplished using single-station controllers, function modules, relays etc. Nowadays, most functions are incorporated in DCS systems.

The use of the basic PID controller has been improved since the introduction of computers in process control. Facilities such as automatic tuning, adaptation, gain scheduling, anti-windup, back-calculation, alarms and supervisory functions, are examples of such improvements. See Åström and Hägglund (1995).

However, very little research and development has been devoted to the basic couplings. These are often performed in the same way as before the computer implementations, i.e. when function modules and hard wiring had to be used. In modern DCS systems, there is a potential for improvement also of these functions.

This paper treats ratio control. Ratio control is applied when the control objective is to keep the ratio between two variables, often flows, at

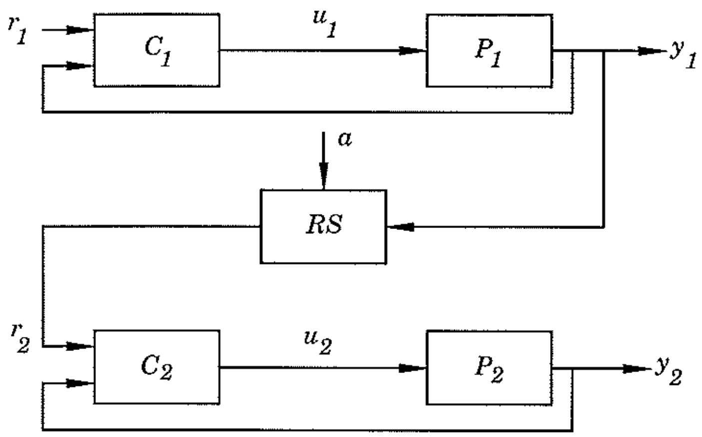

Figure 1 Ratio control using a Ratio station *(RS)* applied to main flow y_1

a certain ratio a. In combustion, e.g., it is desired to control the fuel to air supply ratio, in order for the combustion to be as efficient as possible. Blending of chemicals is another example where it is desired to keep the ratio between different flows constant. In in-line blending systems, when there is no downstream mixing tanks, this is of special importance. If the composition is not maintained, quality problems may occur.

Ratio control is traditionally obtained using simple Ratio stations. See Shinskey (1981), Shinskey (1988), and Seborg *et al.* (1989). These are explained in the next section. Using Ratio stations, the desired ratio may be kept during steady-state operation. However, during transients the Ratio station fails to retain the desired ratio a. This is a serious problem, since ratio control normally is applied to problems where the flows are supposed to vary and where steady-state conditions are uncommon.

This paper suggests an improved control strategy for ratio control. The simple Ratio station is replaced by a Blend station. The Blend station keeps the two flows closer to the desired ratio a during transients. The paper suggests both a constant-gain Blend station and an adaptive Blend station where no parameter tuning is required from the user.

2. Ratio control

Ratio control is normally solved in the way shown in Figure 1. There are two control loops. The main loop consists of process P_1 and controller C_1. Output y_1 is the main flow and the external setpoint r_1 is the desired main flow. In the second loop, consisting of process P_2 and controller C_2, it is attempted to control the flow y_2 so that the ratio y_2/y_1 is equal to the desired ratio a. In Figure 1 this is obtained using a Ratio station where setpoint r_2 is determined by

$$r_2(t) = ay_1(t) \tag{1}$$

i.e. simply by multiplying the main flow y_1 with the desired ratio a.

In Equation (1), parameters a is assumed to be constant. This is not necessary. The desired ratio a is often time-varying. In combustion, e.g., the ratio a is often adjusted based on O_2 measurements in the exhaust.

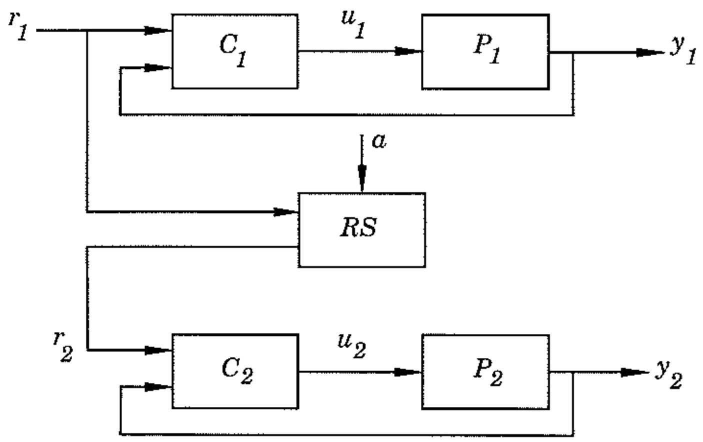

Figure 2 Ratio control using a Ratio station *(RS)* applied to setpoint r_1

Provided the controllers have integral action, the solution given in Figure 1 will work in steady-state, i.e. $y_1 = r_1$ and $y_2 = ay_1$. However, using the simple Ratio station to form the secondary setpoint r_2 according to Equation (1) is not efficient during transients. The second flow y_2 will always be delayed compared to the desired flow ay_1. The length of this delay is determined by the dynamics in the second loop.

When setpoint r_1 is increasing, the delay causes an under-supply of the media corresponding to flow y_2, and conversely when r_1 is decreasing there is an excess of the media corresponding to flow y_2.

There are cases when it is important never to get any under-supply of one of the two media. In the combustion case, one gets an under-supply of air during the transient part when the external set point increases, but an excess of air when the set point decreases. To prevent the fuel not being fully burnt by an under-supply of air, the solution in Figure 1 has to be complemented with some logic using MAX/MIN selectors. See Åström and Hägglund (1995).

A suggested approach to overcome the transient problems is to apply the Ratio station to setpoint r_1 instead of measurement signal y_1, see Figure 2. In this solution, setpoint r_2 is determined by

$$r_2(t) = ar_1(t) \tag{2}$$

Now, the second flow is not necessarily delayed compared to the main flow as in the previous approach. The transient behaviour is determined by the dynamics in both loops. By tuning the controllers so that the loops get the same closed-loop dynamics, the ratio y_2/y_1 may be kept equal to a even during the transients at setpoint changes.

There are, however, some severe drawbacks with the solution proposed in Figure 2. The procedure is a kind of open-loop approach. If the dynamics in one of the loops change, so may the ratio y_2/y_1. Process dynamics often change in process control, mostly due to nonlinearities.

To obtain the same closed-loop dynamics in the two loops, one of the loops in Figure 2 has to be detuned. Normally, the secondary loop is the fastest, and consequently the one that has to be detuned. A consequence of the detuning is that the loop will give unnecessarily slow responses to load disturbances.

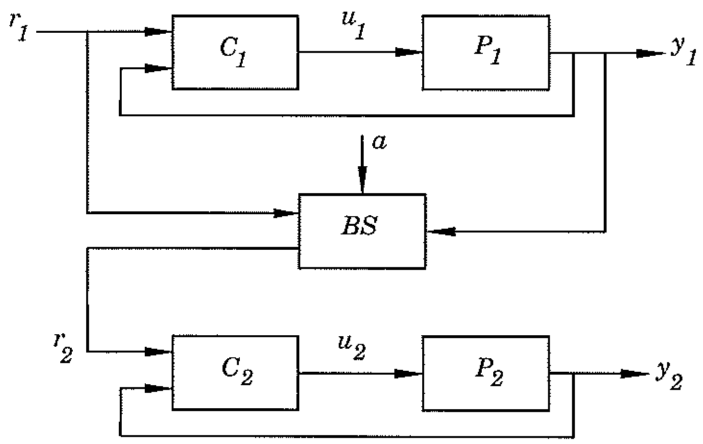

Figure 3 Ratio control using the Blend station *(BS)*

An advantage with the solution in Figure 1, where the true main flow y_1 is used to form the setpoint, is that the ratio will be kept even if the main flow cannot be kept close to the setpoint r_1. If e.g. a load disturbance causes the primary flow y_1 to deviate from set-point r_1, the secondary loop will try to keep the ratio y_2/y_1 close to a even during the load transient. There are situation when this feature is important also from a security point of view.

So, even if the approach given in Figure 2 has some desirable features at setpoint changes, the approach given in Figure 1 is normally preferred and has become industrial practice.

3. The Blend station

The main drawback with the simple Ratio station approach shown in Figure 1 is that the secondary flow y_2 is delayed compared to the desired flow ay_1. This problem can be solved if not only y_1 is used to form the secondary setpoint, but also the main setpoint r_1. The structure, called the Blend station, is shown in Figure 3.

In the Blend station, the secondary setpoint is determined according to

$$r_2(t) = a\,(\gamma r_1(t) + (1-\gamma)y_1(y)) \tag{3}$$

Gain γ is a weighting factor that determines the relation between setpoint r_1 and main flow y_1 when forming secondary setpoint r_2. Choosing $\gamma = 0$ means that the standard Ratio station given in Figure 1 is obtained. Choosing $\gamma = 1$ means that the structure given in Figure 2 is obtained. The Blend station provides the possibility to combine the two approaches.

The following example illustrates the benefits of using the Blend station instead of the simple Ratio station.

EXAMPLE 1—THE BLEND STATION
Consider two processes, P_1 and P_2, both with structures given by the transfer function

$$\frac{1}{(1+sT)^2} \tag{4}$$

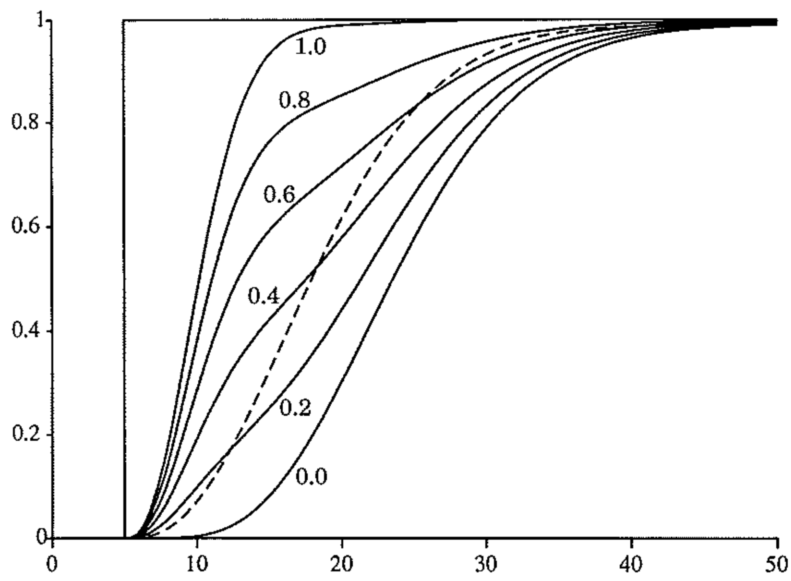

Figure 4. Setpoint responses for different choices of γ. Flow y_1 is shown in dashed line. Flow y_2 is shown for $\gamma = 0, 0.2, 0.4, 0.6, 0.8$, and 1.0

The main process, P_1, has the time constants $T = 10$, and the secondary process, P_2, has the time constants $T = 2$. The processes are controlled using the Blend station configuration in Figure 3. The controllers C_1 and C_2 are both PI controllers with settings:

$$\begin{aligned} K_1 &= 1 \qquad T_{i1} = 7.0 \\ K_2 &= 1 \qquad T_{i2} = 2.8 \end{aligned} \tag{5}$$

For simplicity, desired ratio a is chosen to $a = 1$, which means that it is desired to keep the two flows equal, $y_1 = y_2$.

Figure 4 shows responses using different values of γ. The case $\gamma = 0$ corresponds to the standard use of the Ratio station given in Figure 1. The delay of the second flow y_2 during transients causes a significant deviation from the desired ratio a.

The case $\gamma = 1$ corresponds to use of the Ratio station given in Figure 2, but without detuning the second loop to obtain the same closed-loop dynamics.

The optimum choice of γ seems to be somewhere around $\gamma = 0.4$. The choice of γ is treated in the next subsection. Even better results would have been obtained by "shaping" the setpoint r_2. This is of less importance when setpoint r_1 is changing smoothly instead of stepwise. This is demonstrated in the next section. □

Choice of γ

Assume that the two *closed* loops can be approximated by first-order systems with time constants T_1 and T_2, respectively. This means that

$$\begin{aligned} Y_1(s) &= \frac{1}{1+sT_1} R_1(s) \\ Y_2(s) &= \frac{1}{1+sT_2} R_2(s) \end{aligned} \tag{6}$$

From Equation (3), the second setpoint is given by

$$
\begin{aligned}
R_2(s) &= a\left(\gamma R_1(s) + (1-\gamma)Y_1(s)\right) \\
&= a\left(\gamma + (1-\gamma)\frac{1}{1+sT_1}\right)R_1(s) \\
&= a\frac{1+s\gamma T_1}{1+sT_1}R_1(s)
\end{aligned}
\tag{7}
$$

This means that the relation between the main setpoint r_1 and the second flow y_2 can be approximated by

$$
\begin{aligned}
Y_2(s) &= \frac{1}{1+sT_2}a\frac{1+s\gamma T_1}{1+sT_1}R_1(s) \\
&\approx \frac{1}{1+sT_2}a\frac{1}{1+s(1-\gamma)T_1}R_1(s) \\
&\approx a\frac{1}{1+s\left((1-\gamma)T_1+T_2\right)}R_1(s)
\end{aligned}
\tag{8}
$$

This first approximation is that the zero in $-\gamma T_1$ is replaced by a pole in γT_1. The second approximation is that the two poles are replaced by one single pole with time constant equal to the sum of the two time constants.

Since it is desired to obtain the same time constant in the transfer function from r_1 to y_2 as from r_1 to y_1, the following relation is desired

$$(1-\gamma)T_1 + T_2 = T_1 \tag{9}$$

Hence, the optimal value of γ is close to

$$\gamma = \frac{T_2}{T_1} \tag{10}$$

Equation (10) is obviously true for the case $T_1 = T_2$. In this case, when both loops have the same dynamics, the external setpoint r_1 should be applied on both loops simultaneously in order to keep the ratio equal to a. This is accomplished using $\gamma = 1$. Equation (10) is also true when $T_2 = 0$, i.e. when the second loop lacks dynamics. Since no delay is present, the ratio is kept equal to a using the standard Ratio station, i.e. by using $\gamma = 0$. Note that when $T_1 < T_2$, that is when the main flow dynamics is faster than the dynamics in the second loop, Equation (10) suggests that the gain should be chosen such that $\gamma > 1$.

The two closed-loop time constants T_1 and T_2 are normally not known. If the controllers are properly tuned, it is, however, often possible to approximate the relation between T_1 and T_2 with the relation between the integral times of the two controllers, i.e.

$$\gamma = \frac{T_{i2}}{T_{i1}} \tag{11}$$

The ratio between the two integral times used in Example 1 give the gain

$$\gamma = \frac{2.8}{7.0} = 0.4 \tag{12}$$

This gain is shown to be close to optimal in Figure 4.

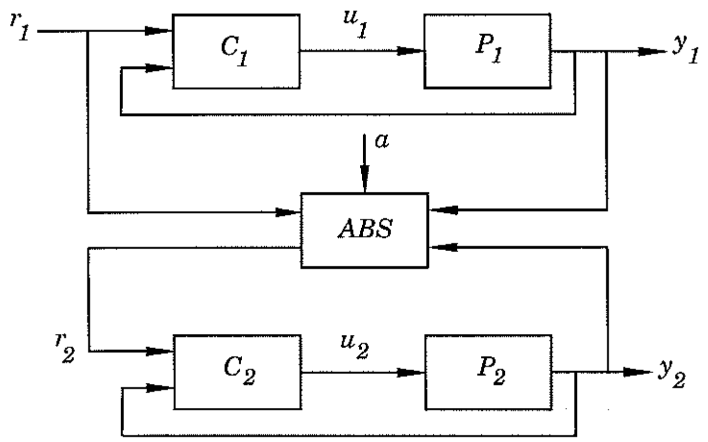

Figure 5 Ratio control using the adaptive Blend station *(ABS)*

4. The adaptive Blend station

The previous section demonstrated the advantages of using the Blend station to solve ratio control problems. Guidelines for choosing the gain γ were also given. However, in process control it is highly desirable not to introduce further parameters to be tuned by the users. Furthermore, since the processes often are time varying and nonlinear, optimal choices of parameters vary over time. Therefore, an adaptive procedure to automatically obtain gain γ is proposed in this section. The structure of the adaptive Blend station is given in Figure 5.

In the adaptive Blend station, gain γ is adjusted on line based on the actual values of the two flows y_1 and y_2. The following adaptation mechanism is suggested:

$$\frac{d\gamma}{dt} = \frac{S}{T_i}(ay_1 - y_2) \tag{13}$$

In Equation (13), gain γ is adjusted based on the integral of the difference between the two flows, properly scaled with the desired ratio a. Equilibrium occurs when $ay_1 = y_2$ or $S = 0$.

Integral time T_i determines the adaptation rate. It is reasonable to determine it automatically as a factor times the longest integral time of the two loops. In the simulation examples shown later in this paper, the value $T_i = 70$ is chosen, corresponding to a value that is 10 times longer than the longest integral time of the two controllers C_1 and C_2.

The sign parameter S takes the values $+1$, -1, or 0. When the main setpoint r_1 increases, gain γ should increase if $ay_1 > y_2$, and decrease if $ay_1 < y_2$. However, when r_1 decreases the opposite is true. When r_1 decreases, gain γ should decrease if $ay_1 > y_2$, and increase if $ay_1 < y_2$. The sign parameter S takes care of this in the following way

```
S=IF r1>MAX(y1,y2/a)+eps then 1
  ELSE IF r1<MIN(y1,y2/a)-eps then -1
  ELSE 0
```

A hysteresis, eps, is introduced to avoid adaptation when the signals are close to the setpoints. The main reason is to avoid adaptation when

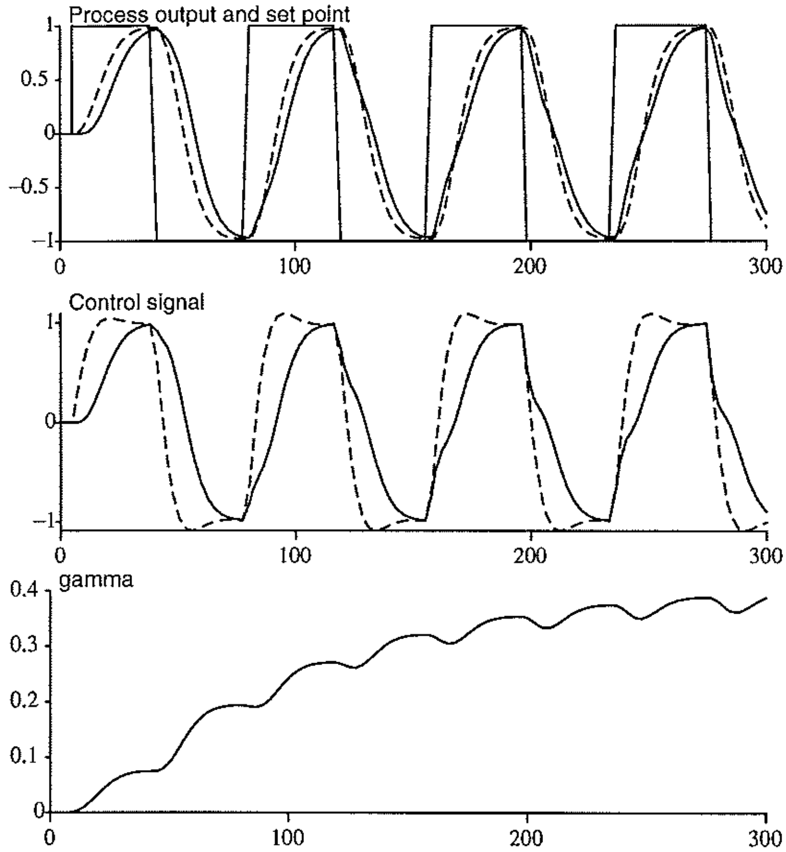

Figure 6 Control using the adaptive Blend station. The upper diagram shows setpoint r_1, main flow y_1 (dashed line), and secondary flow y_2. The middle diagram shows corresponding control signals u_1 and u_2. The lower diagram shows gain γ

the signal to noise ratio is small. The hysteresis eps can be fixed once and for all, or it may be determined from the noise levels in the signal. The hysteresis is chosen equal to 0.01 in the simulations presented in this paper.

EXAMPLE 2—THE ADAPTIVE BLEND STATION
In this example, the same processes and controllers as used in the previous example are considered. The gain γ is adjusted according to Equation (13), with integral time $T_i = 70$, i.e. ten times the longest integral time of the two controllers C_1 and C_2.

Figure 6 illustrates control using the adaptive Blend station, when the external setpoint r_1 varies in form of a square wave. The adaptive Blend station is initialized with $\gamma = 0$. This means that the first setpoint change shows control using the standard Ratio station. There is a significant deviation between the two flows during this transient.

The gain converges to a value close to $\gamma = 0.4$, which is the ratio suggested by Equation (11), i.e. the ratio between the integral times of the two controllers C_1 and C_2.

Figure 6 clearly demonstrates how the variations in the ratio y_2/y_1 decreases significantly when γ is increased from 0 to 0.4.

In Figure 7, the same experiment is performed, but now the external setpoint r_1 is varied in form of a sinusoid instead of a square wave. Again,

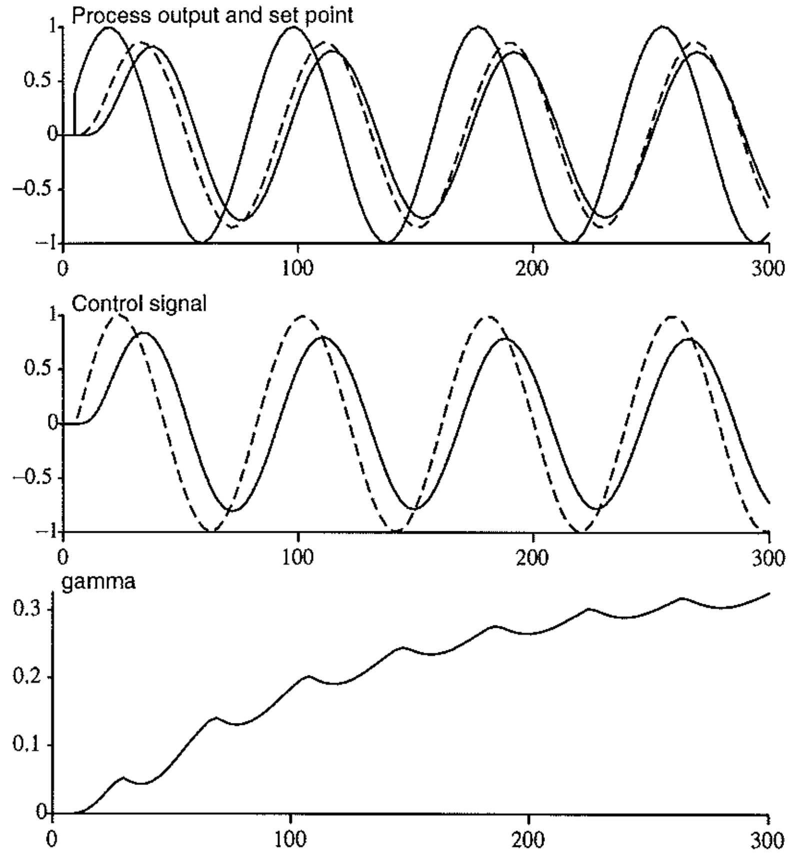

Figure 7 Control using the adaptive Blend station. The upper diagram shows setpoint r_1, main flow y_1 (dashed line), and secondary flow y_2. The middle diagram shows corresponding control signals u_1 and u_2. The lower diagram shows gain γ

the Blend station manages to keep the two flows closer to each other. The figure also demonstrates that smooth setpoint changes result in smaller deviations in the ratio y_2/y_1. □

5. Industrial field test

The Blend station has been field tested in a paper mill. This section shows results from a process section where pulp is bleached by adding Hydrosulphite to the pulp flow. The goal is to keep the ratio between the pulp flow and the Hydrosulphite flow constant.

Originally, a Ratio station configured according to Figure 1 was used. The pulp flow controller, C_1, was a PI controller with setting $K_1 = 0.2$ and $T_{i1} = 4s$. The Hydrosulphite controller C_2, was also a PI controller with setting $K_2 = 0.078$ and $T_{i2} = 1.07s$.

The results obtained using the original Ratio station are shown in Figure 8. The figure shows responses to two setpoint changes in the pulp flow. The Hydrosulphite flow is scaled with the desired ratio and translated, so that the desired flow rates become identical. The figure clearly demonstrates the deviation between the two flows during the transients. The Hydrosulphite flow is delayed compared to the pulp flow.

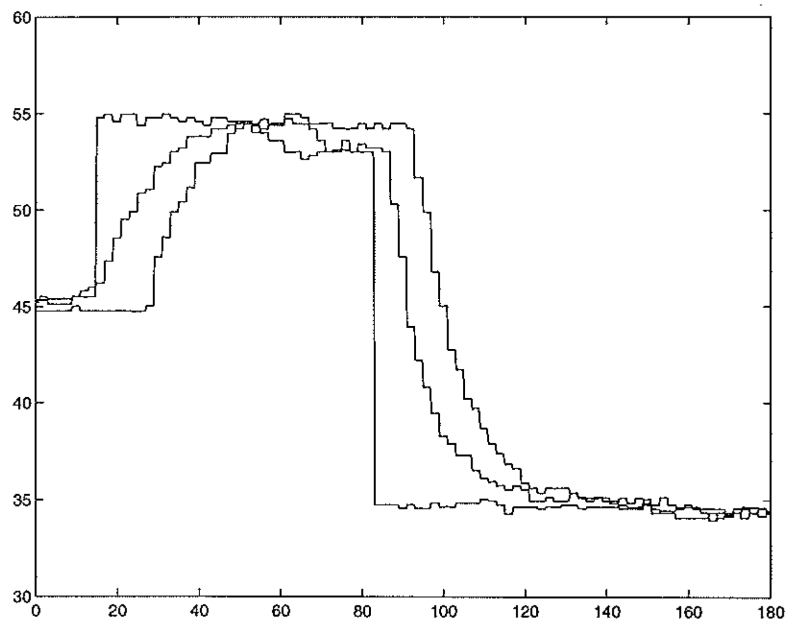

Figure 8 Ratio control of a pulp bleaching process using the original Ratio station. The figure shows two changes in the pulp setpoint, the pulp flow (fastest response) and the Hydrosulphite flow (slowest response)

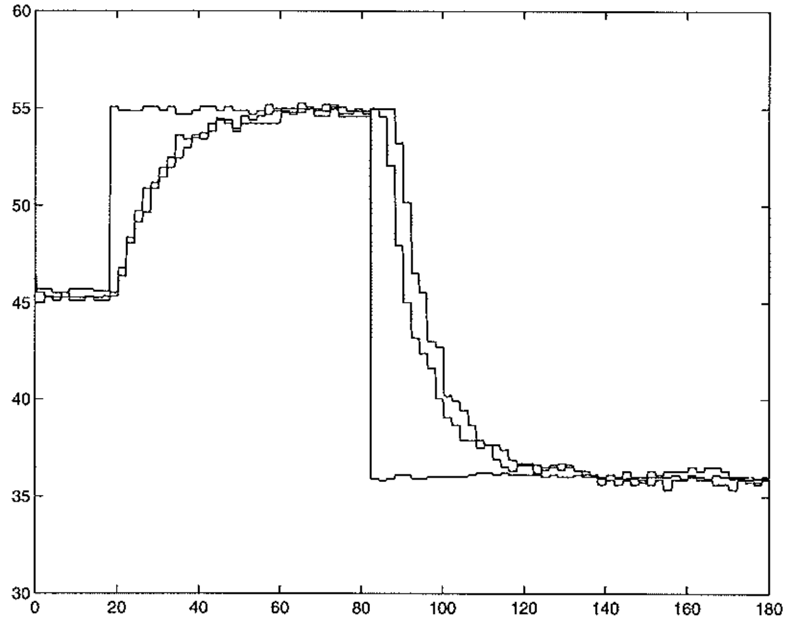

Figure 9 Ratio control of a pulp bleaching process using the Blend station with gain $\gamma = 0.5$. The figure shows two changes in the pulp setpoint, the pulp flow (fastest response) and the Hydrosulphite flow (slowest response)

Figure 9 shows the results obtained when a Blend station was applied on the process. Here, gain factor γ was chosen to $\gamma = 0.5$. Comparing Figures 8 and 9 reveals that the Blend station reduces the flow differences during transients significantly. However, there is still a delay in the Hydrosulphite flow. Therefore, gain factor γ was increased further.

Figure 10 shows the results obtained using gain factor $\gamma = 0.75$. Here,

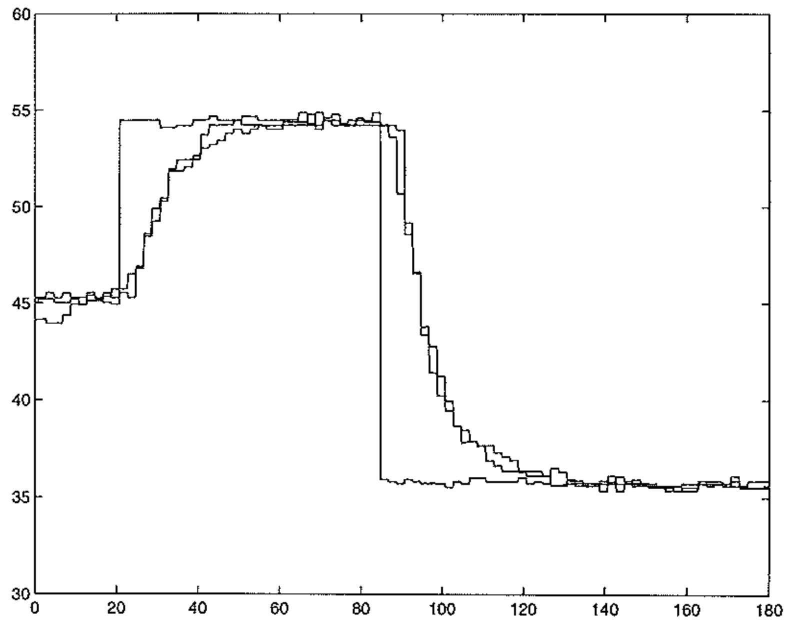

Figure 10 Ratio control of a pulp bleaching process using the Blend station with gain $\gamma = 0.75$. The figure shows two changes in the pulp setpoint, and the pulp and Hydrosulphite flows

the difference between the two flows is almost eliminated.

This field test confirms the advantages of using the Blend station instead of a Ratio station during ratio control. The simple rule of thump for choosing gain factor γ as the ratio between the integral times of the two loops does not hold in this case. Equation (11) suggests a value $\gamma \approx 0.27$, while the experiments show that the optimal value is close to $\gamma = 0.75$.

Therefore, this field test indirectly also shows the advantages of using the adaptive Blend station, so that an optimal value of γ can be obtained without user interaction.

6. Conclusions

This paper treats the problem of ratio control. The industrial standard for solving ratio control problems is to use a simple Ratio station. This solution works in steady state, but during transients the Ratio station fails to keep the ratio between the two flows.

The suggested Blend station improves ratio control during transients. Both a constant-gain and an adaptive version of the Blend station is presented. The benefits of replacing Ratio stations with Blend stations are demonstrated through simulations as well as industrial field tests.

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The Blend station is patent pending.

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