Chapter 10

Control Design: Intuition or Analysis?

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10.1 Introduction

In previous chapters, we discussed some of the many different types of control methods available and typically used in the pulp and paper industry (simple feedback, cascade, ratio, feedforward, etc.). It is not uncommon, in practice, to use any one of these control methods for a given application.

The blending and mixing of two process streams is a typical application important to all industries. In pulp and paper, it is common to blend dilution water with a pulp slurry to do consistency control. This is a process that can be modeled by a material balance.

We can also blend a hot process stream with a cold process stream to do temperature control. This is a process that can be modeled by both a material and an energy balance.

Although these two processes have different controlled variables, they are both analogous to blending and, therefore, are very similar from a process control standpoint. Furthermore, it is possible to control consistency or temperature using any one of the feedback, cascade, ratio, or feedforward algorithms. This raises several questions. Which control method is best? How do we evaluate each method? Which method is the most cost effective? How do we determine which method to use for a specific application?

This chapter answers all of these questions by looking at two very different approaches to control system design and analysis. First, we will design by intuition, an approach used by many engineers that draws from their experience and training. Next, we will design by analysis. This is a systems approach using material and energy balance equations to determine the best control strategy. Finally, a comparison of these two design methods will be done by outlining the advantages and disadvantages of each for several specific applications.

The reader should understand that there are many other analogous blending and mixing processes in the pulp and paper industry to which the control theory in this chapter applies. In addition, the general systems approach discussed here is directly applicable to other processes. The same methodology can be used to analyze non-blending processes to determine appropriate control
methods. All material in this chapter, including the control theory, is practical and has been used and proven in the pulp and paper industry.

10.2 The Blend System Process Design

One of the first steps in doing a control project is to complete the design of a new process, or to evaluate the design of an existing process. The process used to blend white water with pulp consists of a pulp storage tank, a stock pump, a dilution pump, and the blend piping. The design of this process is critical to the final control performance. It is essential to design a process for good control and not design the control system to compensate for problems in the process design. This will help ensure the best control possible.

The blending process can be designed in any number of ways, three of which are shown in Fig. 10.1. Most engineers would agree that Fig. 10.1A shows a good blend process design because the pump can be used as a mixer. In practice, today's highly efficient pumps do not provide good mixing. Instead, the mixing is done by turbulence as the pulp flows in the pipe between the dilution line and the consistency transmitter.

Good mixing requires sufficient turbulence as well as adequate mixing time. However, too much turbulence can result in a noisy and erroneous consistency measurement. Likewise, too much mixing time will result in excessive deadtime which will degrade process control. The solution to this dilemma is in the design of the transport piping. We must design a highly turbulent section of pipe for mixing immediately downstream of the pump. This must be followed by a settling or stilling section to achieve near laminar flow just upstream of the consistency transmitter. The total deadtime for both regions should always be less than ten seconds. Experience has shown that both mixing and settling zones can be designed with a total of two to four seconds of deadtime to provide outstanding control.

For critical control loops it can be advantageous to recycle some furnish back into the storage tank (Fig. 10.1B). This will ensure adequate flows when the furnish demand is significantly reduced. For example, nominal furnish flows to the paper machine (design loads) will result in good mixing, small deadtimes, and excellent control. However, in the same process, very small flows to the machine may result in poor control even at optimum tuning unless a recycle line is used.

The process in Fig. 10.1A is considered a good design because it de-couples the interaction between dilution water flow and furnish flow. This interaction is a problem with the process in Fig. 10.1C. Manipulating the dilution flow rate at the stock pump discharge will affect the total furnish flow rate. Likewise, stroking the furnish flow valve will disturb the dilution flow which, in turn, will affect consistency. Moreover, the process design of Fig. 10.1C will not only result in a flow/consistency interaction, but dilution and furnish line pressures will interact as well. The result is unstable control.
In contrast, the pulp storage tank in Fig.10.2.1A ensures a constant head at the pump suction. It is this static head that de-couples the interactions described above. Consequently, blending should typically be done immediately downstream from a storage tank at the pump suction.

![Diagram of pulp and water flow](image)

Fig. 10.1. Design blend process for good control

The next step in process design is to ensure that all instrumentation, piping, and associated pumps are properly sized and installed. It is necessary to follow all manufacturers' recommendations for straight pipe runs upstream and downstream of each instrument. Many consistency transmitters require adequately sized piping to ensure the stock velocity does not exceed 3–4 ft./sec. These and other design and installation criteria are presented in Chapters 3 and 4.

We have used a very simple example of how to design a process for good control. The important point is to spend adequate time to complete this task before the final process design is approved. The result will always yield a better process with less control variability. This often leads to improved product quality, lower manufacturing costs, and increased productivity.
10.3 Control Design by Intuition

The final control design should be done concurrently with the process design for reasons discussed above. Control and process engineers must work together. The intuitive approach to control design usually draws from an engineer's basic training and industrial experience. All too often, it involves pairing control variables (primary control elements) with manipulated variables (final control elements) and inserting PID controllers. For example, to develop a consistency control method for the process in Fig. 10.1A, the conventional and obvious approach is to use simple feedback as shown in Fig. 10.2. It is estimated that more than 95% of all consistency loops in the pulp and paper industry use this control method.

![DILUTION FURNISH FLOW](image)

**Fig. 10.2. Typical feedback control loop**

It is easy to identify potential disturbances in this loop and to add controls to compensate for these disturbances. For example, if the dilution pump supplies water to several different areas in the mill, the header pressure may vary as the total water demand varies. Consequently, this disturbance will affect the dilution water flow (Fig. 10.2) which in turn will upset the consistency loop. Intuitively, we can solve this problem by adding a cascaded flow loop as shown in Fig. 10.3. In this case, the flow loop very quickly compensates for header pressure upsets to maintain the dilution flow at setpoint. This helps avoid consistency variations.

Another disturbance to the loop in Fig. 10.2 can be caused by a change in pulp demand. For example, an increase in furnish flow will cause an increase in furnish consistency requiring the feedback loop to raise the dilution flow. However, with feedback control alone, considerable time may lapse before consistency is back on setpoint. Intuitively, we may regulate this load change much faster with feedforward control as shown in Fig. 10.4. With this configuration, a change in furnish flow will cause an immediate change in dilution flow that will compensate to keep the consistency at setpoint. This, of course, assumes the feedforward loop is properly tuned.
Finally, by combining the cascade and feedforward controls of Figs. 10.3 and 10.4, we would appear to have an excellent control method (Fig. 10.5) capable of handling all disturbances. However, this is not the case. The intuitive approach has led us astray. There are many problems with the method of Fig. 10.5.

First, if the feedback loop is precisely tuned for high performance at 1,000 GPM load, it will become highly unstable at 500 GPM and very slow responding at 2,000 GPM. The reasons for this problem will be discussed later in this chapter. In addition, the dilution flow loop may not achieve its intended function of stable control. Dilution header pressure variations can not be corrected simply by adding a flowmeter and closing the loop. This can make the problem even worse because each new flow
loop in the header becomes coupled with other flow loops elsewhere in the mill feeding from the same pump. The result can be severe control loop interaction and unstable performance. Finally, the feedforward control will not perform properly at any operating conditions other than those for which it was tuned. For example, changes in the internal storage tank consistency, and even changes in consistency setpoint will affect feedforward tuning. In addition, if a dilution flow loop is not used (e.g., Fig. 10.4), changes in pressure drop across the dilution valve will impact feedforward tuning. Moreover, if the installed flow characteristic of the valve is nonlinear, then changes in valve position will also affect feedforward tuning.

Using intuition, we have added the cascaded flow loop in Fig. 10.5. This is a clear case of using unnecessary controls to try to compensate for problems in the process design. Large pressure variations in the dilution header is a result of an undersized pump. Pumps which service more than one important control loop should be sized to operate on or near the flat part of the total head pump curve. This eliminates most of the pressure swings and avoids the control loop interaction discussed above.

Clearly, the intuitive approach has failed us. How, then, do we design for good control?

10.4 Control Design by Analysis

The material and energy balance equations for any process provide insight into how that process should be controlled. To illustrate the systems approach to control system design, we will discuss two analogous processes: consistency (the blending of pulp and water) and temperature (the blending of a hot and a cold process stream).
10.4.1 Consistency

The first step in our analysis is to write the material balance equations for the consistency process in Fig. 10.1A. These consist of an overall flow balance and a fiber balance:

\[
F_I + F_D = F_F
\]  (1)

\[
F_I N_I + F_D N_D = F_F N_F
\]  (2)

Where:

- \(F_I, N_I\) = Inventory flow and consistency (before dilution)
- \(F_D, N_D\) = Dilution flow and consistency
- \(F_F, N_F\) = Furnish flow and consistency (after dilution).

The next step is to rearrange and combine these equations in a very special way that will reveal much about the process in terms of its control. We must solve these equations for the controlled variable \(N_F\) as a function of variables we can manipulate and variables we can measure or calculate from field instrument data. A good starting point is to brainstorm a list of these independent variables so we know which ones are desirable in the final equation. For our simple blend process, the list may include \(F_D, F_F,\) and \(N_I\). We selected \(F_D\) and \(F_F\) since they both can be measured directly using field instrumentation. We also selected \(N_I\) since it can be indirectly determined using a material balance equation and data from field devices.

The process of combining and rearranging equations can be time consuming. There are many variations of the equations, but only one most clearly defines the control needs. The process of finding this equation should not be rushed. It can take considerable effort, especially when the process is complex with many material and energy balance equations. However, for our simple blend process, Eqs. 1 and 2 yield the following:

\[
N_F = \frac{F_D}{F_F} (N_D - N_I) + N_I
\]  (3)

If we substitute \(R\) for the ratio \(F_D/F_F\) and assume the dilution water consistency \((N_D)\) is 0.0, the equation simplifies:

\[
N_F = -RN_I + N_I
\]  (4)
We now have a relationship equating the process variable that we wish to control (dependent variable) to several independent variables. The next step is to select one of the independent variables to use as the manipulated variable in the control loop. The ratio of dilution flow to furnish flow, R, is the obvious choice for our blend process (Eq. 4). Typically, we cannot manipulate N1, the only other independent variable in the equation.

In summary, the material balance indicates that we should manipulate the setpoint of a ratio controller in order to properly regulate consistency (Fig. 10.6). When a control system is designed from the process material and energy balance equations, it is said to be consistent with the process and usually provides good control over a broad range of operation. It is interesting that this method of control was omitted during our design by intuition. Unfortunately, this has been the case for consistency control in the pulp and paper industry for many years.

Fig. 10.6. Typical ratio control loop in a mixing process

There are several reasons why Fig. 10.6 is a better method of control than the methods discussed earlier. First, the ratio loop has an element of feedforward control that does not require tuning. As the furnish flow changes by a given amount, the dilution flow will also change by the same percentage (e.g., doubling the furnish flow will feedforward to immediately double the dilution flow). This will keep furnish consistency constant regardless of changes in furnish flow. Therefore, we have eliminated all interaction over the entire range of furnish flow. Recall that the feedforward strategy in Fig. 10.4 requires tuning that only performs well over a very narrow range of operation. This control method was developed by intuition and therefore is not consistent with the process material balance equations. Another advantage of the controls in Fig. 10.6 is they maintain a constant process gain, even over a wide range of process load. We have defined the steady-state process gain as the rate of change in controlled variable per change in manipulated variable ($\Delta$ process output/$\Delta$ process input). This is easily determined by differentiating the material balance (Eq. 4):
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\[ \frac{\partial N_F}{\partial R} = -N_I \quad (5) \]

The process gain, therefore, is only a function of the consistency inside the storage tank, and for many pulp and paper processes this is reasonably constant. It is important to maintain constant gains in the control loop. This helps keep the amount of maintenance for controller tuning to a minimum and preserves loop stability at all process loads (e.g., process gain does not vary with \( F_F \)).

In contrast, all of the control methods designed by intuition (Fig. 10.2 through 10.5) directly manipulate dilution flow \( (F_D) \). In these cases, we differentiate Eq. 3 with respect to \( F_D \) to obtain the process gain:

\[ \frac{\partial N_F}{\partial F_D} = -\frac{N_I}{F_F} \quad (6) \]

Here, we find the process gain is inversely proportional to furnish flow. This means the controller gain must be retuned each time a significant change is made to \( F_F \). For example, if the consistency loop is well tuned for a 1,000 GPM load, the controller gain must be reduced by 50% when the load is changed to 500 GPM to maintain the same level of stability. If this change in controller gain is not made, the loop will go unstable. Likewise, if the load is increased from 1,000 GPM to 2,000 GPM, the controller will become sluggish and slow responding. In this case, the controller gain must be doubled to maintain the same degree of stability.

In summary, the control method of Fig. 10.6 is consistent with the process. By designing this system from material balance equations, we have compensated for most of the control loop disturbances, solved the problem of process gain changes with furnish flow, and resolved the problem of interaction between furnish flow and consistency.

10.4.2 Energy

It is not obvious that the consistency (mass) process described above is analogous to a temperature (energy) process. On the surface, consistency and temperature control appear to be entirely different. However, when we realize that both processes fall into the general category of blending, the analogy becomes more clear. One process blends dilution water with pulp, while the other blends a hot process stream and a cold process stream. When we do the material and energy balance for the temperature process (Fig. 10.7), the analogy to the consistency process is obvious.
\[
F_H + F_C = F_W
\]  
(7)

\[
F_H T_H + F_C T_C = F_W T_W
\]  
(8)

Where:
- \(F_H, T_H\) = Hot process stream flow and temperature
- \(F_C, T_C\) = Cold process stream flow and temperature
- \(F_W, T_W\) = Mixed process stream flow and temperature.

These equations are directly analogous to Eqs. 1 and 2. Temperature in the energy process is analogous to consistency in the mass process. We can now rearrange and combine these equations as was done for the mass process:

\[
T_W = \frac{F_C}{F_W} (T_C - T_H) + T_H
\]  
(9)

Next, we can substitute \(R\) for the ratio \(F_C/F_W\) and \(\Delta T\) for \(T_H - T_C\):

\[
T_W = -R \Delta T + T_H
\]  
(10)
Notice we are not able to make the simplifying assumption $T_c = 0.0$ as we did with the analogous variable of the mass process (i.e., $N_p = 0.0$). Finally, if we again select $R$ as the manipulated variable for temperature control, we can obtain the process gain by differentiating Eq. 10:

$$\frac{\partial T_w}{\partial p} = -\Delta T \quad (11)$$

Consequently, the process gain is only a function of $\Delta T$ and not $F_w$. Therefore, load changes will not affect controller tuning, however, large changes in $\Delta T$ will, just as changes in $N_i$ will affect tuning of the consistency loop.

There are many analogous blend processes in the pulp and paper industry. Although each may have a different controlled variable, they are all very similar from a control perspective. Regardless of the application, the systems approach to control design using mass and/or energy balance equations should always be used to confirm intuitive designs.

**10.5 Applications**

We can now answer the questions posed in the introduction of this chapter. Which control method for blending is best? Which is the most cost effective? How do we determine which method to use for a specific application? The best way to answer these questions is to first eliminate all the control strategies that have no significant value in blending.

We will start with the feedforward method of Fig. 10.4. This approach of summing a feedforward signal to the control output of a feedback loop is commonly used in all industries. Unfortunately, this control method is not consistent with any real process in pulp and paper or any other industry (i.e., it does not conform to the mass and energy balance of any process). Consequently, the controls in Fig. 10.4 have no place in blending and should be limited to processes where all else fails. Other problems with this configuration have already been discussed in this chapter.

Next, we can rule out using the controls in Fig. 10.5 (cascaded feedforward) for all the same reasons. In addition, the instrumentation required in Fig. 10.5 is identical to that used for ratio control (Fig. 10.6). Since there is no cost incentive, the ratio configuration is preferred over cascaded feedforward because it provides much better control.

This leaves us with a choice between the control methods of Figs. 10.2, 10.3, and 10.6. Simple feedback is the most cost effective and most commonly used method (Fig. 10.2). It can be applied to applications where tight blend control is not important. It is also the best choice for processes that run at constant load. For example, controlling machine chest consistency with a constant flow to the...
stuff box is best done using simple feedback control. In this case, there is no load change and putting a flow or ratio loop on the dilution line will not improve control. The additional loop, however, can cause unnecessary flow oscillations which will directly translate into basis weight variations on the paper machine. It is also important to use a dedicated dilution pump for stuff box consistency control to eliminate header pressure disturbances.

Next, the cascade control method in Fig. 10.3 may have a few limited applications in processes where one of the blend streams experience large deviations in header pressure. This is usually the result of manual load changes on a pump that is undersized. In this case, care should be taken to avoid control loop interaction between multiple flow loops on the same header. Also note that the instrumentation required for cascade control is only one flowmeter short of that required for the much better ratio control in Fig. 10.6.

Finally, the additional cost for instrumentation needed in Fig. 10.6 (ratio method) can only be justified for critical applications requiring very tight blend control. Consistency controls for paper machine dry stock blending (Dumdie, 1988) and for the pulp mill pressure screen feed (Dumdie, 1991) are two examples. In addition, the ratio method may be necessary in applications with large load changes to ensure loop stability and fast response at all loads.

References
