Chapter 2: The Milling Circuit

Milling circuits are used to grind material to a fine product. The particle size that leaves this circuit is a measure of the quality of the product produced by the milling circuit. This quality is important, because it determines the ability of downstream processes to extract maximum possible benefit (for example gold recovery from the ore). A milling circuit will therefore operate in an optimised manner when it produces high quality product at the maximum possible rate and efficiency (Craig et al., 1992). The first and primary objective of a controller will therefore be to control the circuit in such a manner that the required setpoint for particle size is achieved. Another control objective will be to maximise the throughput of the milling circuit.

In order to design a controller, the dynamics of the process have to be investigated. A milling circuit is an interactive multivariable process (Craig & Hulbert, 1986, Metzner & Babarovich, 1991). This means that there are a number of input and output variables that affect each other. A simplified diagram of a typical milling circuit is shown in Figure 2-1. This specific circuit has six plant inputs ($u$) and five plant outputs ($y$).

![Diagram of Milling Circuit]

**Figure 2-1: Milling Circuit**

The feed to the mill is the fine material ($u_3$) and rocks ($u_4$), which are usually extracted from the mine, as well as water ($u_2$). The grinding process occurs in the mill and the turning speed
of the mill \((u_6)\) is an input variable that can be specified. The mill load \((y_2\), specified as a percentage of the maximum load\) is the mass of material in the mill (tonnes), which is an important output to control. The mill power \((y_3)\) is the power that is used to turn the mill (MW) and can be used as an indication of the throughput of the milling circuit (Bell, 1992). The throughput is the amount of product produced by the milling circuit per unit time \((t/h)\). The exact relationship between the power and the throughput will be discussed in more detail later.

A pulp flows out of the mill through an end-discharge grate into a sump. The level in the sump \((y_1)\) is an output variable that needs to be controlled to prevent it from overflowing or running dry. More dilution water \((u_1)\) is added to the sump and the diluted pulp is pumped to a hydrocyclone. The pulp density \((y_4)\) is an output variable while the flow rate of the pulp \((u_5)\), determined by the pump speed, is an input variable. The cyclone separates the small particles from the larger ones. The larger particles leave the cyclone at the bottom and are recycled to the mill for further grinding. The small particles leave the cyclone at the top as the product of the milling circuit. The size of these particles \((y_5)\) leaving the cyclone is a very important output variable and is measured using a particle size measurement (PSM) technique. The PSM is the percentage of the particles below 75 \(\mu m\) in diameter. The larger this value, the finer the product will be.

Often, no distinction is made between the feed of the fine material \((u_3)\) and the feed of the coarse material \((u_4)\). When these two inputs are combined, the plant will have only five inputs.

### 2.1 Circuit Dynamics

The approximate influence of each input variable on each output variable, when a positive step change is applied to each input variable individually, is shown in Figure 2-2 (Craig & Hulbert, 1987). The effect on the power output \((y_3)\) is not shown since it is a quadratic function of the mill load. An explanation of the nature of each input-output response will be given later.
Figure 2-2: Circuit Dynamics

These relationships can be approximated by transfer functions. Appendix D shows an example of a transfer function matrix for a milling circuit when the relationships were approximated with first order or second order transfer functions or with pure integrators with dead time.

The throughput of the milling circuit is not a linear function. When plotted against the load in the mill, a parabolic function is obtained with a maximum throughput near a load of 70% (Bell, 1992). When the power used by the mill is plotted against the mill load, a parabolic function with a maximum near a load of 70% is also obtained. The power used by the mill is therefore often used as an indication of the throughput of the mill (Craig et al., 1992). Figure 2-3 shows how the power changes as a function of the load.
The response of the power can therefore be approximated as a parabolic function of the load according to the following equation:

$$Power = Power_{\text{max}} - \alpha (Load_{\text{base}} - Load)^2$$ \hspace{1cm} (2.1)

The problem with this relationship is that it is not fixed. The power/load relationship is only on average a parabolic function. When looking at the points individually, they may deviate from the overall parabolic function. The setpoint of the load where the power reaches its optimum (Load_{\text{base}}) and the maximum power (Power_{\text{max}}) may also shift around over time. This is caused by disturbances such as changing feed-ore size and composition and other unmeasured dynamics. The power (and therefore also the throughput) can be controlled by using an optimiser controller that changes the setpoint of the load (which is controlled by the MPC controller) such that the power is kept at its optimum value. A block flow diagram for this kind of cascade control is given in Figure 2-4.

![Figure 2-4: Control of Mill Power](image)

The effects of each input variable on the outputs are now described in more detail.
2.1.1 Dilution Water ($u_1$)

When the flow of the dilution water is increased (positive step change), the level in the sump will rise steadily (pure integrator). This is because the flow out of the sump is held constant by the pump. The sump will eventually overflow if the level is not controlled. The increase in dilution water furthermore causes a decrease in the density of the flow to the cyclone ($y_3$). The decrease in density will cause a finer overflow (or an increase in the particle size measurement [PSM]: $y_5$) and a more dilute underflow from the cyclone. The more dilute underflow from the cyclone results in more water in the mill. The addition of more water to the mill causes the pulp to flow out more easily, causing the mill load to drop.

2.1.2 Feed Water ($u_2$)

Increasing the feed water to the mill will initially increase the mill load at the front end of the mill. This increases the pressure gradient in the mill, which leads to an increased outflow of the pulp. The added water furthermore also dilutes the pulp, which also increases the outflow. The mill load will therefore drop. The increased outflow of the mill will cause the level in the sump to rise steadily. The increased outflow from the mill will furthermore sharply increase the cyclone feed density, resulting in a coarser cyclone overflow (smaller PSM). After the initial disturbance the mill load quickly reaches equilibrium again and the PSM and the cyclone feed density jumps back to normal. The extra water added to the milling circuit will accumulate in the sump and the sump will eventually overflow if the level is not controlled.

2.1.3 Solids Feed ($u_3 + u_4$)

A positive step in the solids feed will cause a steady increase in the mill load (pure integrator). The mill will be overloaded if the load is not controlled. The increase in solids feed will increase the cyclone feed density, again resulting in a coarser cyclone overflow or lower PSM. The increase in solids feed however has no measurable effect on the sump level.
2.1.4 Cyclone Feed Flow \((u_5)\)

By increasing the cyclone feed flow, the level in the sump will immediately begin to decrease steadily. The sump will eventually run dry if the level is not controlled. The increased cyclone feed flow will furthermore cause a coarser cyclone overflow (lower PSM). The cyclone underflow density will decrease, causing an increase in the mill load. No measurable change in the cyclone feed density is detected.

2.1.5 Mill Speed \((u_6)\)

When the mill speed is increased, the outflow out of the mill will also increase, causing an initial drop in the mill load. After the initial drop in the mill load, it will again return to normal operating conditions due to an increased reflux stream from the cyclone. The increase in outflow from the mill will furthermore cause the sump level to rise to a new steady state value. The density out of the sump will also increase due to the increased outflow from the mill. The particle size of the product will initially increase (the PSM will decrease), but eventually it will return more or less to normal operating conditions.

2.2 Simulating the Milling Circuit

In order to develop a controller, it is very convenient to have a simulator to do it on. This will save a lot of time and money, since the controller development can be done without stopping or disrupting the real process. A prerequisite for this, however, is that the simulator should be an accurate representation of the real process. A program was therefore written that simulates a milling circuit. The simulator was written as follows (Hulbert, 2000): The milling circuit was divided in three parts, a plant input module, a plant state module and a plant output module. Figure 2-5 shows how these three modules fit together. A more detailed description of the computer algorithm for the simulator is given in Appendix C (Hulbert, 1999).
Each of these modules can be subdivided into different parts, each part contributing to make the simulator more realistic. Characteristics like random noise and disturbances, drifting of the variables, valve slack and hysteresis, nonlinearities and dead times are added to each appropriate module. The extent of the contribution of all these characteristics can easily be changed by changing a multiplier "knob". This "knob" is a value between 0 and 100 % and can be specified for each input, state or output variable. A "knob" value of zero would eliminate all the characteristics of the module and therefore represent an ideal process, while a value of 100 % would represent a process with all the characteristics set at their maximum values. The characteristics of each module will now be described in more detail.

### 2.2.1 Plant Input Module

Each plant input is controlled by a proportional-integral (PI) controller with an actuator as shown in Figure 2-6.

![Figure 2-6: Plant input module](image)

The measurement of the plant input can have added noise. The noise is generated by finding a random number between -1 and 1. This value is filtered to smooth the random number, since
real noise is not as erratic as a randomly generated number. A first order filter is used to produce a meandering noise signal:

\[ G_{\text{noise}} = \frac{k_{\text{noise}}}{1 + \tau_{\text{noise}}s} \] (2.2)

Figure 2-7 shows the difference between randomly generated noise and the same noise that has been filtered using a first order filter.

![Random noise and Filtered noise](image)

Figure 2-7: Random noise and Filtered noise

After filtering the noise, it is added to the measured value. This measurement of the plant input is made available for the PI-controller. The actual plant input can have (a different) added disturbance noise as well as an offset. This disturbance noise is also generated using a random number between −1 and 1 and filtering it with a first order filter.

The minimum and maximum values of all the input variables are specified. The minimum and maximum values of the inputs may change over time (for instance a pump that cannot deliver at its maximum capacity due to wear). These changing limits (called soft limits) will typically start at a certain value and then drift away over time (see Figure 2-8). The drift rates (a linear function of time) of the soft minimum and soft maximum values are therefore parameters that have to be specified. The soft minimum is restricted between the minimum and the soft maximum, while the soft maximum is restricted between the maximum and the soft minimum.
In order to add versatility to the simulator, the drift rate is multiplied with the *multiplier knob* described earlier. The value of this knob can be changed between 0 and 100 % to represent the extent of the non-ideal factors (0 = ideal, 100 = maximum non-ideal).

The base level (or steady state value) of the input is specified and can also be made to drift over time (linear function). This base level is furthermore restricted between the soft maximum and soft minimum values.

The actuator can have dead time, 1st-order response, slack and non-linearity as shown in Figure 2-9.

![Figure 2-9: Actuator](image)

The slack is a characteristic of the valve and will cause the actual input (for instance the flow rate) to be smaller than specified when the valve is opening or larger than specified when the valve is closing. When restricting the input variables between the soft minimum and soft maximum, the slack has to be added to the limits specified to the control valve to ensure that the actual values of the inputs are at the soft limits (see Figure 2-10).
Figure 2-10: Soft maximum and minimum with slack added

The non-linear factor is also a characteristic of the valve. The following function was used to describe the non-linearity of the valve:

\[ y = (1 + \alpha)x - \alpha x^2 \]  \hspace{1cm} (2.3)

where: \( x \) = the scaled input between 0 and 1 (scaled by subtracting the soft minimum and dividing with the difference between the soft minimum and soft maximum)

\( \alpha \) = the non-linear factor (between −1 and 1, \( \alpha = 0 \) for linear relationship)

\( y \) is then scaled back to the normal units by multiplying with the difference between the soft minimum and the soft maximum and adding the soft minimum again.

2.2.2 Plant State Module

Each input-output pair has an associated dead-time delay and a state that is updated incrementally (see Figure 2-11). The state can respond immediately to changes in an input. It can also (more usually) be influenced according to a first-order response or an integrator. The Laplace-transform form of the dynamic model is as follows:

\[ g(s) = \frac{\frac{a + b \tau s}{\tau}}{1 + \tau s} e^{-\mu s} \]  \hspace{1cm} (2.4)

or
\[ g(s) = \frac{a}{s} e^{-\tau_d s} \] (2.5)

\( a \) is the gain of the model, \( b \) is the immediate response coefficient, \( \tau \) is the time constant and \( \tau_d \) is the dead time. Noise, generated in the same manner as described for the input module, can also be added to each state variable.

![Diagram of Plant state module](image)

**Figure 2-11: Plant state module**

The state variables also have maxima and minima, as well as soft maxima and soft minima that can drift (the same as for the input module). The state variables additionally have a base level that can also drift. The base level is restricted between the soft minimum and the soft maximum. The drifting of the base level represents the non-ideal behaviour of the plant in that the steady state values of the plant may change over time. In calculating the drift of the base level, the drift rate is also multiplied with the *multiplier knob* to determine the extent of the non-ideal factor.

### 2.2.3 Plant Output Module

Each plant output can have an associated dead time. An output is obtained from the sum of its base level, the deviations of associated states from their base-levels, and measurement noise (see Figure 2-12). There can be a parabolic response to a state (with a maximum at the state's base level). Besides specifications of the minimum and maximum for a plant output, achievable *soft limits* can be specified and made to drift. The base level of a plant output can also be made to drift; the extent of which is specified by the *multiplier knob* (the same as for the state module).
2.3 Difficulties in Controlling a Milling Circuit

There are a number of reasons why it is difficult to control a milling circuit satisfactorily. By looking at the transfer function matrix for a milling circuit in Appendix D, it is clear why. The first reason is that there is a lot of interaction between the inputs and the outputs of the multivariable process.

Secondly, the process has widely differing time constants. The transfer function between the Dilution water and the Particle size leaving the cyclone has, for instance, a time constant of 83s. The effect of the Dilution water on the Mill load, on the other hand, has a time constant which is more than 20 times larger (1864s). This means that the response of a change in the Dilution water \((u_1)\) on the Mill Load \((y_2)\) will be much more sluggish than the response of the Particle size \((y_3)\).

Another problem is the large dead times for certain input-output pairs. The largest dead time is between the Solids feed and the Cyclone density, namely 480s. The larger the dead time, the slower the response of the controller will be. The system furthermore also contains a number of integrators (Sump level and Mill load). Integrators cause difficulty since they do not reach steady state after a step change has been applied; it continues to change at a steady rate.

The milling circuit is also a highly non-linear system. When the process deviates too far from the steady state values, the process may differ substantially from the model at steady state. It is also a process with a lot of unmodelled and unmeasured disturbances such as changes in
the density and composition of the feed ore. The process furthermore changes over time as the circuit ages. All these effects will eventually have a deteriorating effect on the performance of the controller.