Control of the amplitude in a surging balling drum circuit, a new approach to an old problem

Regular paper

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Abstract

In this paper we suggest a new method for controlling the balling drums used in the iron ore industry. We suggest that a cluster of drums are controlled collectively rather than individually. Further, we investigate the possibility of using an extended Kalman filter for estimating the amplitude and frequency of the oscillations in such drums. The filters thresholding point is identified, and the limit for when the filter is usable is given.

Five keywords: Balling drums, surging, estimation, extended Kalman filter, thresholding

1 Introduction

Use of balling drums has become common in many parts of the industry. In the iron ore industry, balling drums used in pellets production has a long tradition. The main problem areas associated with such drums are therefore well described and to some extent also analysed.

A problem the iron ore industry has been dealing with for as long as the balling drums has been used, is that they tend to give a surging output under some operational conditions. This surging is a problem for the balling drum circuit only if the amplitudes get too high. A process shutdown will then normally be the result, but danger for some equipment, such as the conveyor belt for recirculation of undersized pellets, is also evident. The major problem with surging lies however, in the subsequent process segment, which is the induration process, also denoted as the "warm process". If the input to the warm process is fluctuating, then the efficiency of this segment is reduced, accompanied by a considerably increase in energy consum and poor product quality. Unfortunately, the conditions which cause the drum to oscillate, coincidence with those required for good product quality (see e.g. [1], [5]). Several attempts has therefore been made to design an automatic control scheme for regulating the amplitude to zero. See e.g. [3].

So far the problem has only been considered for a single drum and tandem drums. In this paper we point out why such a strategy may not be optimal and suggest an alternative way to solve the problem.

2 Preliminary results

In this section we give some preliminary results and a brief overview of previous research within this area. Over the last four decades the problem with surging drums has been investigated from several points of view. A great deal of work has been carried out in developing mathematical models of the balling drum, and about thirty years ago, the first model was established. See e.g. [3] or [4]. This model has infinity dimension, and is as such not useful for control purposes. A lot of knowledge about the system is, however, gained from this model. Later, simplified models has been presented, see e.g. [1]. Simulations based on these models reveals that the moisture content in the pellets are the most important process parameter to be controlled if one wishes to stabilize and keep the process stable. The binder, which is added in order to obtain sufficient mechanical strength, tends to have an contrary effect. This suggests that a simple multivariable control could be applied to regulate the moisture content, mechanical strength and the amount of onsized pellets. Unfortunately, this turns out not to be possible. One of reasons for this is that some plant parameters are hard to measure on line, and consequently difficult to control. An other reason is that small changes in the operating conditions may cause large changes in the operating point, see [1]. Together with noisy measurements, this offers a big challenge to this approach. The moisture content in the pellets, which as already mentioned, is the most important parameter from a control point of view, has so far not been possible to measure on line with the desired accuracy. The best equipment available today offer a accuracy no better that ± 0.5 % in absolute value, ref. [7], and that is not sufficient for this purpose as a change less than this value may cause the drum to surge. A method avoiding some of this problems was presented in 1976 by P. E. Wellstead and N. Munro, ref [3]. This method, which is the first based on control theory analysis, concludes that the surging is a limit cycle caused by to high loop gain. Then the well known method of reducing the gain, which is exactly the same as reducing the amount of recycled undersized pellets, is applied to stabilize the drum. Results from simulations based on the model described in [1], shows that a reduction of the recycled pellets of about 10-12 % will be sufficient to stabilize the drum. When the drum is stabilized, a multivariable control system for controlling the amount of onsize pellets and the moisture content in the pellets, can be designed. This method offer the opportunity to regulate the water and binder content in the pellets to the desired level, and represent therefore a great achievement compared to the previous method.

3 Stabilizing and controlling the drums

3.1 Method 1

The simplest method suggested to stabilize the drum circuit is to add moisture in the recycle circuit when the surging occur.. If a proper amount of moisture is added then the surging will decrease and finally stop. This method has been implemented on a real drum (ref.[7]), but some serious problems were revealed. First of all, a method for detecting that surging really was present was not sufficiently developed. Secondly, as the surging disappear, the system will no longer be observable in the sense that all information needed to decide the amount of moisture to be added in order to keep the process stable without overcompensating, is lost. For this reasons the method was rejected, ref [7]. Another problem with this method is that it is very suboptimal from a energy point of view due to the fact that the moisture content can not be regulated. This will normally result in too high water content in the onsize pellets, which, in addition to increased energy consum, will result in poor quality and reduced drum throughput. In other words, the product quality and productivity are not considered in this control scheme.

3.2 Method 2

A second method is to reduce the amount of recycled pellets, as described in section 2. When the drum is stabilized a multivariable feedback controller can be designed for controlling the output and moisture content independently. Since the moisture content is an important quality parameter, this means that the quality is regulated in some sense. From an economical or a productivity point of view, this method is not optimal. This is due to the reduced amount of recycled undersized pellets. A mass balance will show that if the recycled mass is reduced by taking some fraction out of the system, then the amount of onsize pellets will be reduced accordingly. The physical upper limit on the production rate to the system is reached when the bed depth in the drum reaches the level where the pellets start sliding instead of rolling. No growth can then take place. Measure in bed depth, this limit will be independent of the amount recycled pellets as long as the moisture content is constant. This method of stabilizing the drum will therefore lower the maximum output of onsized pellets.

As mentioned in the previous section, one of the problems with the first method was that the observability is lost at the same moment as surging disappears. A similar problem appears also in this method. If we assume that the amount of undersized pellets which is removed from the system should be as small as possible, then we should remove just enough to get the system stabilized. If the conditions are changed in such a direction that the system becomes more stable, i.e. the moisture content is increased, then it is impossible to discover that less material should be removed. The problem with unobservable system is therefore still present.

3.3 Method 3, a new approach

The surging does no harm to the pellets quality. The quality is, in fact, good when the drum is oscillating. From a quality point of view there should therefore not be any problem to let the surging be present. The remaining problem then is to make sure that the amount of green pellets transferred to the warm part is constant. In order to obtain this goal, a cluster of drums is controlled collectively, rather than controlling each drum individually. The control scheme may be described in the following way:

1. All drums are operated with surging output, and the amplitude is kept on a desirable value by controlling the water and binder content in the fines.
2. The drum with largest amplitude is chosen as reference, which means that the RPM is fixed.
3. By adjusting the drums RPM their phase angel, relative to the reference drum, is controlled in such a way that the amplitude in the total output from all drums is kept at its minimum.

Controlling the amplitude to the desired value will in this setting means that the quality parameters (the content of moisture and binder) will decide the level of the amplitude. As the amplitudes in practice are not equal, the drum with largest amplitude should preferably be chosen as reference, as this allow us to more easily derive criteria for when the total amplitude is zero. Further more, as this drum normally will have the lowest signal to noise ratio (SNR), it is likely to have the best estimate of amplitude and phase.

The advantages of this method can be summarize as follows:

1. The process parameters can be kept at a level which gives higher product quality
2. The total pelletizing process will consume considerable less energy compared to the situation where the moisture content is kept at a higher lever to avoid surging
3. The total capacity (throughput) of the drum is not reduced
4. There is no need for an advanced process model as the drums are treated as oscillators with controllable amplitude and frequency

   A prerequisite for this method is that the following assumptions hold:

- it is possible to detect the oscillation and estimate its amplitude and frequency
- the amplitude is controllable in some range
- the frequency is controllable in some range

The two latter items are well documented in the literature, see e.g. [1], so we will therefore concentrate on the first item in the following section.

4 Estimation of amplitude and frequency

4.1 Description of the filter

An extended Kalman filter (EKF) is used for estimation of the frequency, amplitude and phase of the oscillations. The signal model used by the EKF is

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ x_3(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(x) \\ x_3(k) \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} w_1(k) \\ w_2(x) \end{bmatrix} \tag{1}$$

$$y(k) = x_3(k) \sin x_2(k) + v(k) \tag{2}$$

where x_1 is the phase increment (or frequency), x_2 is the phase and x_3 is the amplitude of the oscillation. $w = [w_1 \ \ w_2]^T$ and v are white, zero mean processes with covariance matrices $Q = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix}$ and R. Locally the state is uniquely determined by the output y, but owing to the factor $\sin(x_2)$ in output equation this does not hold globally. In fact, a simultaneous change of sign in x_1 and x_2, or a shift of x_2 by any number of periods, does not change the output. However, with a reasonable initialization of the EKF this mild nonuniqueness does in general not cause any problems. The choice of the matrix Q is a compromise between accuracy in steady state and capability to track a changing amplitude or frequency. R is set equal to the covariance of assumed measurement noise of the true, measured output.

4.2 Estimation of the amplitude

In this work we assume that control of the first harmonic component of the oscillations will give sufficient accuracy for this application. Figure 1 shows a typical situation from a physical plant in LKAB's works in Kiruna, Sweden. The measurement is done with a sampling period of 1 second. As we see, the signal has considerable noise components. The variance is calculated to be approximately 135 $\left[\frac{kg}{h}\right]^2$.

The dark solid-drawn line is the estimate from the Kalman filter, and the light solid-drawn line is its estimate of the amplitude. The filter model is based on a sinusoid, which in this application corresponds to the first harmonic of

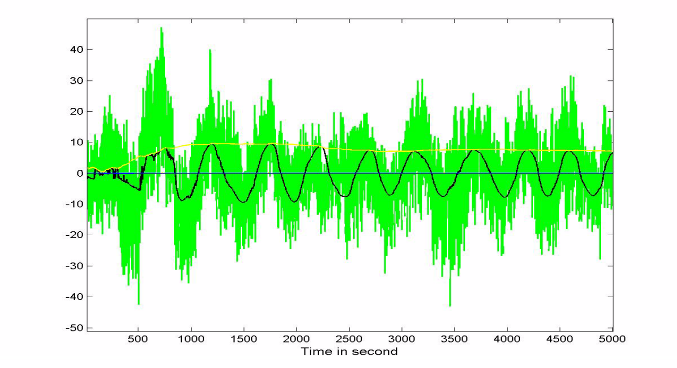

Figure 1: Estimate of amplitude

the oscillation. The solid-drawn line is the filters estimate of the amplitude. A question of crucial importance at this stage is as follows: *what is the lowest possible amplitude the filter is capable of detecting, given a specified level of noise.* If we permit the amplitude to get below this limit we will no longer be able to control the phase angel to the desired value. It is therefore important to establish this limit.

The signal to noise ratio is given by the following equation

$$R_{s-n} = 10 \log \left(\frac{A^2}{2Var(v)} \right)$$

where A is the amplitude of the oscillation and v is the signal noise, which is assumed to be white. In figure 2 the filters signal to noise ratio curve with respect to amplitude error is shown.

The thresholding phenomena, which is when a relative small change in the signal to noise ratio results in a big change in the performance, occurs for $R_{s-n} < -10\ dB$. The thresholding point will then be for $R_{s-n} = -10\ dB$. This corresponds to a variance $R = 500 \left[\frac{10^3 kg}{h}\right]^2$ at an amplitude $A = 10\ \frac{10^3 kg}{h}$. In the interval $-5 < R_{s-n} < -3$ the error starts to increase. The corresponding variance interval is $500 \left[\frac{10^3 kg}{h}\right]^2 < R < 100 \left[\frac{10^3 kg}{h}\right]^2$. The process variance is normally in the interval $50 \left[\frac{10^3 kg}{h}\right]^2 < R < 150 \left[\frac{10^3 kg}{h}\right]^2$, which corresponds to $-4,75\ dB < R_{s-n} < 0\ dB$, when the amplitude is $A = 10\ \frac{10^3 kg}{h}$. The lowest possible amplitude we can allow with this filter and a variance $R = 135$ $\left[\frac{10^3 kg}{h}\right]^2$, will be approximately $5,2\ \frac{10^3 kg}{h}$. In the real plant this is a low value which normally not cause any problems at all.

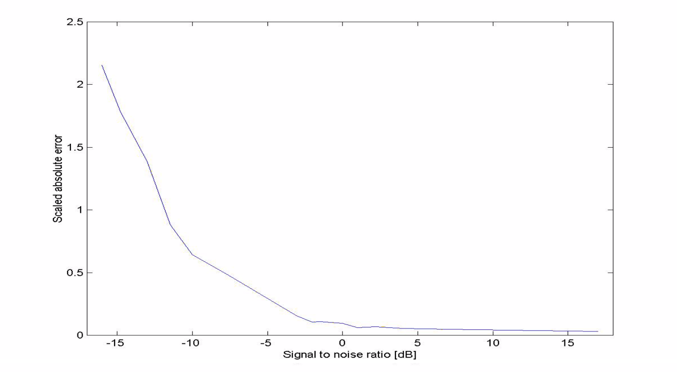

Figure 2: Signal to noise ratio curve

Repeatedly simulations shows that the filter in fact does work in this situation. We should however, not expect the filter to have good performance close to the thresholding point. In figure 3 a representative result is shown.

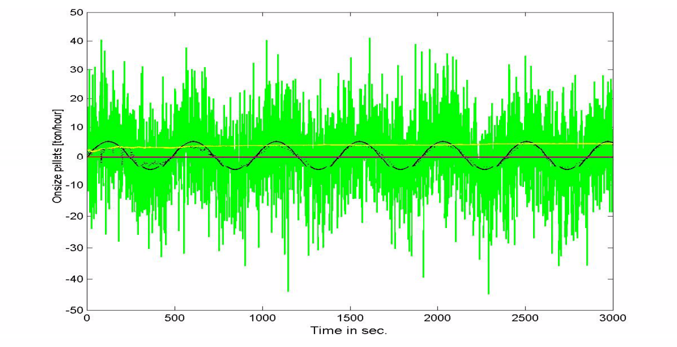

Figure 3: Simulation with A $= 5,2\ \frac{10^3 kg}{h}$

4.3 Estimation of the phase

In figure 4 the filters signal to noise ratio curve with respect to phase error is shown. As we, see the thresholding phenomena is not so explicit as it was in the case of amplitude error. The limiting part will therefore be the filters capability to estimate the amplitude rather than the phase.

Figure 5 and 6 are showing the filters estimate of amplitude and phase with a variance of 135 $\left[\frac{10^3 kg}{h}\right]^2$ and 250 $\left[\frac{10^3 kg}{h}\right]^2$ respectively.

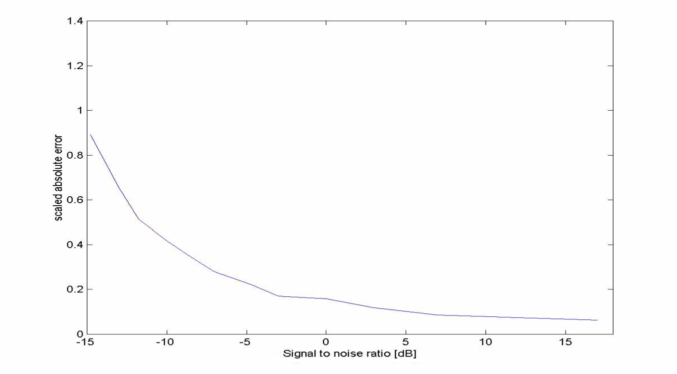

Figure 4: Signal to noise ratio curve

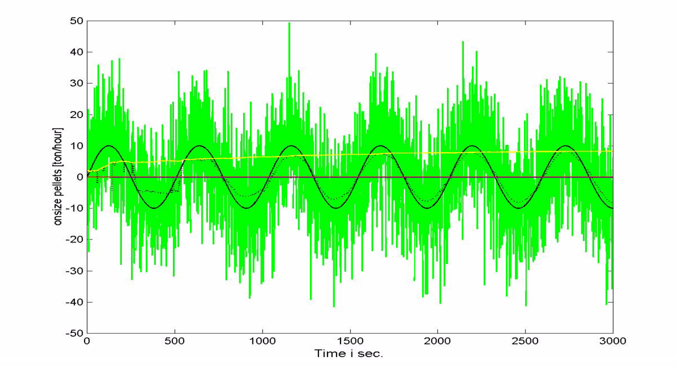

Figure 5: Result from simulation with R = 135 $\left[\frac{10^3 kg}{h}\right]^2$

In the figures the clean sinusoid is the signal to be estimated (without any noise). The dashed line is the filters estimate of the real signal, and the light solid-drawn line is the filters estimate of the amplitude. As we see, the filter works quite well in both situations. However, it is clear from the figures that the amplitude estimate is more incorrect in the last example. This is consistent with our earlier findings.

5 Concluding remarks

In this paper we have suggested a new approach to the old problem of controlling the balling drums used for pelletizing iron ore. As a prerequisite for this method is that is has to be possible to estimate the oscillations amplitude and

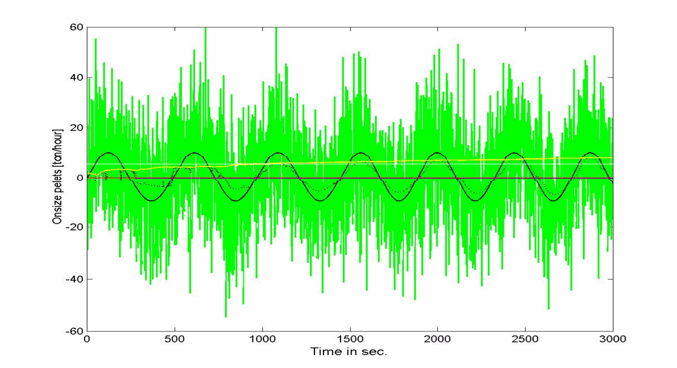

Figure 6: Result from simulation with R $= 250 \left[\frac{10^3 kg}{h}\right]^2$

frequency, we have investigated the possibility for using an extended Kalman filter for this purpose. In section 4 we show that this is indeed possible. We have established the lower limit for the amplitude for a given signal noise variance. The oscillations in a real plant of the size we consider, will normally have an amplitude in the interval $10 \left[\frac{tons}{h}\right] \leq A \leq 50 \left[\frac{tons}{h}\right]$, which corresponds to a signal to noise ratio $-4,3\ dB \leq R_{s-n} \leq 9,6$. The signal to noise ratio will therefore be in an interval well above the thresholding point.

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