The Application of Control Theory to the Management of Sound Emitted from Open-Cut Mining

Tim Procter (1), Deanna Tomerini (2) and A.L. Brown (3)

(1) Griffith School of Environment, Griffith University, Brisbane, Australia

ABSTRACT

This paper shows how the management of sound emissions from the constantly changing environs of a large open-cut mine can be modelled as a closed-loop control system and how using this approach has already been shown to decrease the noise immision levels from an open cut mine. In traditionally control theory, a closed-loop control system (also called a feedback control system) uses a 'set point' as a reference value, to characterise the desired output response of a process. The actual measured 'output response', is compared to the set point and the difference between the two, the error, becomes the input signal to the 'control device'. The measured difference between the set point and the output response of the process can be due to a change in the set point or due to a disturbance to the system. A well-tuned control system is characterised by its stability, its ability to respond to external disturbances and its reliable and repeatable performance.

For an open-cut mine the desired output response is to not exceed a specific noise limit while maximising production and minimising any periods of shutdown. To achieve this, the disturbances to the system must be managed. Disturbances to the system include changes to the mine plan, changes in equipment location and changes in the weather. The current control strategy for open cut mines can be insensitive to the error signal and the response to disturbances can be too slow resulting in difficulty bringing the system back under control without enforcing shutdown measures. In this paper it is shown how the management of sound immissions from an open-cut mine can be represented as a closed-loop control system. This has enabled the elements of the control system to be examined using traditional control theory and facilitated the development of a new management tool that is being implemented in a case study in the Hunter Valley.

1 INTRODUCTION

Control systems are used to achieve and/or maintain desired outcomes from a process. This is achieved by comparing the *actual* outcome with the *desired* outcome and using the difference to drive a change in the system being controlled.

A simple example of an effective control system is an air-conditioning unit. The desired outcome is the maintenance of the internal temperature of a room at a specific temperature on a hot summer's day. The sensor on the room's air conditioning unit measures the air temperature in the room and compares this with the desired temperature on the unit's control panel. If the measured temperature is different from the desired temperature, the temperature or volume of the cold air blown into the room changes to close the gap between the two measurements. The differences can be the result of two factors; a change in the desired room temperature (i.e. the setpoint on the air conditioner unit) or due to a change in the thermal load on the room (e.g. somebody opened a window). The aim of the air conditioning unit (the room temperature control device) is to: 1. attain an outcome that matches the desired setting on the control panel, including when the desired setting is changed; and 2. maintain the desire outcome despite any disturbances to the system.

The above example demonstrates the use of a traditional control system, or feedback control system, that uses a 'set point' and a measured 'output response' to determine the input signal to a 'c`ontrol device'. The elements of the feedback control system are shown in the block diagram in Figure 1. For the above example, the control device is the air conditioning unit and the process is the mixing of the cold air from the unit with the air in the room. A feedback loop enables the transient response of a system to be controlled following a change to the set point or to a disturbance to the process (Dorf & Bishop 2011).
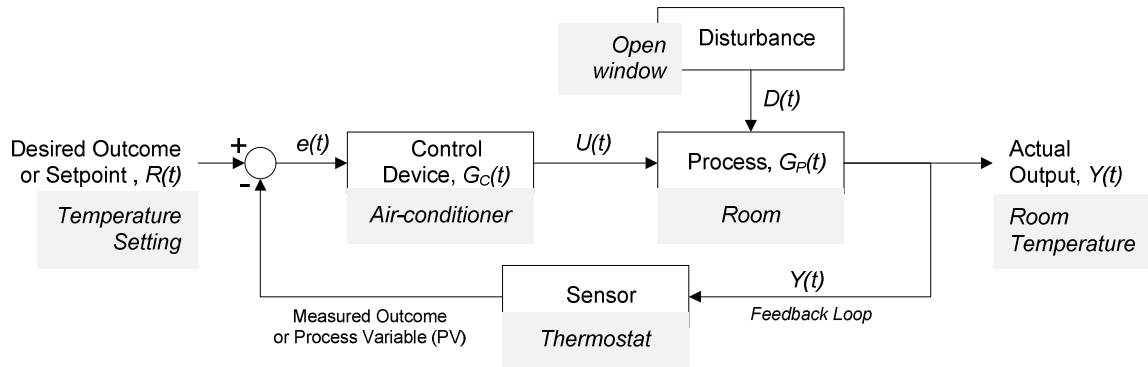
Figure 1: Block diagram of a simple feedback control system
Based on simple feedback control loop presented by Coughanowr & LeBlanc (2009),
Dorf and Bishop (2011), Urbas (2012) and De Dona (undated)

The difference between the desired outcome (the set point) $R(t)$ and the measured outcome (or process variable) PV, of the actual output $Y(t)$ is referred to as the error $e(t)$. The response of the control device $U(t)$ is dependent on the magnitude and sign of the error $e(t)$ and the control device transfer function $G_C(t)$. The transfer function is the differential equation that converts the input signal to the control device to an output response to the process.

In a traditional feedback control system the control device handles the error using a combined proportional-integral-derivative function described as:

$$U(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{1}$$

where K_p, K_i and K_d are the respective proportional, integral and derivative control constants (or gain).

Traditional control theory describes many possible controller types, three of which are; the proportional (P) controller, the proportional-integral (PI) controller and the combined proportional-integral-derivative (PID) controller. The response of the three different controller types (P, PI and PID) to a disturbance in the system being controlled is demonstrated in Figure 2. The output response for three control types is compared to the increase in the output variable $Y(t)$ if the effect of the disturbance went uncontrolled.
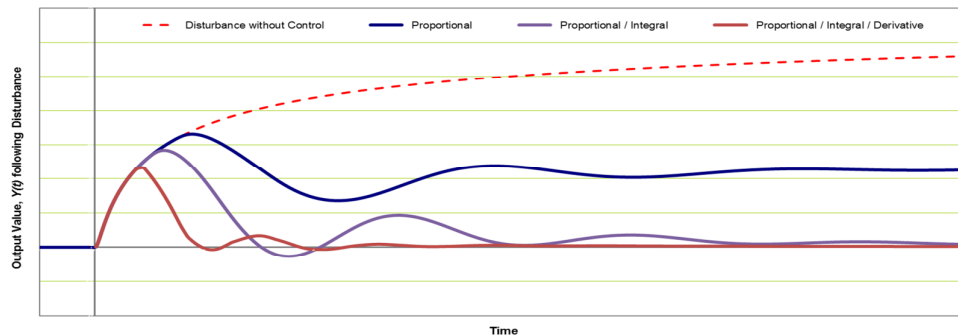

Figure 2 – Control action response for three modes of control

A key attribute of the proportional control function $K_p e(t)$ is the compromise required in setting the proportional controller gain K_p. If K_p is small the proportional controller is slow to respond and will result in a discrepancy or offset between the set point $R(t)$ and the output $Y(t)$. This is because $U(t)$ approaches zero as e(t) approaches zero.

The size of the resultant offset for a system using a proportional controller can be reduced by increasing K_p However, if K_p is too large, a control system configured with only a proportional control function can become unstable (Coughanowr & LeBlanc, 2009). This is because the system over reacts to the error $e(t)$ causing the control device $G_C(t)$ to swing between a positive and negative response. This results in the system output $Y(t)$ oscillating around an output that is offset from the desired set point $R(t)$ (Coughanowr & LeBlanc 2009). This can be clearly seen in Figure 2, where the proportionally (P) controlled system does not return to the original set-point.

Combining the integral control function $K_i \int_0^t e(t)dt$ with the proportional control function to create a proportional-integral controller eliminates the offset between $R(t)$ and the output $Y(t)$ at the expense of the system stability (Altmann 2005, Coughanowr & LeBlanc 2009). As can be seen in Figure 2, after the introduction of the disturbance the proportional-integral control system continues to oscillate when both the proportional and proportional-integral-derivative control systems have settled. The addition of the derivative control function $K_d \, de(t)/dt$ enables the proportional-integral-derivative controller to respond to the rate of change in the error $e(t)$. The faster the error $e(t)$ changes the greater the derivative control function's contribution to the control device response $U(t)$. Adding the derivative control function also allows the controller gain K_p to be increased without causing the control system to become unstable as observed with just the proportional control function (Coughanowr & LeBlanc 2009). Coughanowr and LeBlanc (2009) describe the derivative action as pre-emptive as it is anticipating a change in output based on the rate of change in the error over time.

Another important attribute that increases the instability of the control system represented by Figure 1 is the time lag in the response of the system. This is referred to as dead-time and can be due to a slow response of the process $G_P(t)$ to a change in $U(t)$, transport lag (the time it takes for the change to propagate through to the sensor), a time lag in the measurement device, a time lag in the reporting of $Y(t)$, and/or a lag in the control device $G_C(t)$. The longer the delay in the system responding to a change in the set point $R(t)$ or to the influence of a disturbance $D(t)$ the greater the initial difference between $Y(t)$ and $R(t)$ before the system is brought back under control. Altmann (2005) describes dead-time as the worst enemy of good control as it can lead to instabilities that can be difficult to bring back under control.

2   Control Theory and the Control of Noise Immissions

The control of noise immissions from a large industrial operation such as an open cut coal mine can be represented as a feedback control system based on the block diagram shown in Figure 1. In the case of an open cut mine the control device $G_C(t)$ could be better described as a control strategy as it is actualised by humans based on their awareness of what is happening in and around the mine. The process $G_P(t)$ is a complex amalgam of discrete events involving machines performing a range of cyclic or one-off activities in an area covering hundreds of hectares of land. The sensor may consist of one or more continuous noise monitors reporting in isolation or as part of a network. $Y(t)$ is the noise immission of the mine at the sensor location and $R(t)$ is the noise immission limit for the mine at the sensor location.

Dorf and Bishop (2011) note that to understand how a system will respond to a change in operating conditions it is first necessary to understand the system and the relationship between the system variables. Coughanowr and LeBlanc (2009) argue that "being able to determine or predict the dynamic behavior of a process is crucial to being able to design a control system for it". Dorf and Bishop (2011) breakdown the control system design process into seven main building blocks.

It is proposed the seven step design process can be applied to the control of the noise immissions from an open cut mining operation as follows:

- Establish the control goals - The desired noise immissions output from the mining operation can be represented as $Y(t) \leq R(t)$, where $Y(t)$ is sound pressure level from the mine, the source of interest, at a specific receiver location and $R(t)$ is the noise immission limit of the source of interest at that location. The noise immission limits are imposed by statutory authorities as environmental license conditions or development approval consent requirements. A second objective would be to minimise the disruption to the mining operation through the implementation of unnecessary control strategies when $Y(t) < R(t)$.

- Identify the variables to be controlled – The controllable variables include: the sound power level of the mining and processing equipment; the location of the mining and processing equipment in relation to a specific receiver location; and the transmission path of the sound signal from the source(s) to the receiver.

- Write the specifications – The performance specification provides information on: how the system will regulate against disturbances; how the system will respond to commands; what are realistic commands; the sensitivity of the system; and robustness of the system (Dorf & Bishop 2011).

- Establish the system configuration and identify the major system elements – A closed loop feedback control system that could be used to represent the control of noise immissions from an open cut coal mine is shown in Figure 3.
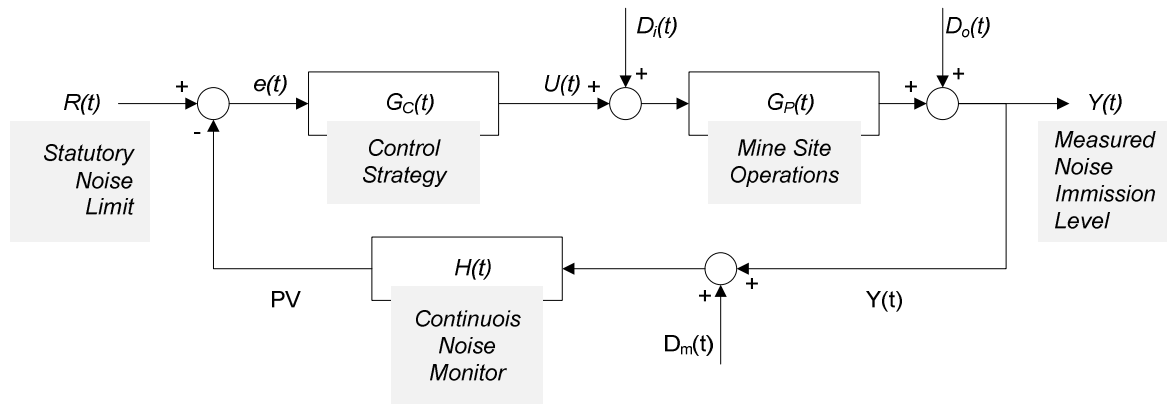

Figure 3 – Block diagram of feedback control system with input, output and measurement disturbance used to represent the control of the noise immissions from an open cut mining operation

The major elements in Figure 3 include: the control device $G_C(t)$ which can be described as being predominantly human controlled; the process $G_P(t)$ which incorporates emission of sound by the mining processes and the propagation of the sound to the sensor location; the sensor $H(t)$ incorporating one or more continuous noise monitors (Wolfenden 2015); and disturbances that influence the control of the noise immissions from the open cut coal mine. These disturbances include: input disturbances to the process $D_i(t)$ that modify the response of the process to the signal from the control device; output disturbances $D_o(t)$ that modify the output signal $Y(t)$; and measurement disturbances $D_m(t)$ that hinder the source sound signal identification.

The propagation of sound incorporated into the process element $G_P(t)$ could be described as the noise emission output from the mining operation assuming isothermal conditions with hemispherical propagation and known barrier attenuation and ground effects. The change in meteorological conditions would be one of the input disturbances to the process $D_i(t)$ that modify the response of the process to the signal from the control device. The spatial differences in meteorological conditions that enhance or retard the propagation of the sound signal from the source to the receiver location would be considered a disturbance $D_o(t)$ to the output $Y(t)$.

- Obtain a model of the process, the actuator, and the sensor – Coughanowr and LeBlanc (2009) note that the model of the process is extremely valuable as it facilitates the design of control systems, devices or strategies that enable the control of the process variables at their desired settings.

- Describe a controller and select key parameters to be adjusted – In practice, the control device $G_C(t)$ for controlling the noise immission of a large open cut coal mine is a control strategy rather than a tuneable device. The control strategy incorporates a hierarchy of controls that could be implemented by the mine

management, specifically the Open Cut Examiner (OCE), when $Y(t) > R(t)$. The hierarchy of the controls will vary over the life of the mine to accommodate the mine plan design, production requirements, mining methods, machine selection and the proximity to sensitive noise receivers (Procter et.al. 2016).

- Optimize the parameters and analyse the performance - Having access to a representative model of a process enables the interactive analysis of the system response to disturbances and possible control options.

3   APPLIED NOISE CONTROL

The following section investigates the application of the control theory discussed above to the management of the noise immissions attributed to an open cut coal mine located in the Hunter Valley coalfields of New South Wales. The mine has a network of six continuous noise monitors located to the East and South of the site. The noise monitors measure and report on the acoustic environment using metrics such as: $L_{Aeq,15minute}$; $L_{A90,15minute}$; and $L_{eq,15minute}$ at 1/3 octave intervals. Four of the noise monitors are also capable of determining the direction of the dominant noise sources contributing to the acoustic environment at the monitoring location. In addition to the network of continuous noise monitors, the mine has a network of weather stations measuring and reporting on the local meteorological conditions.

The original mine plan included a major re-orientation of the open cut pit in 2015/2016. It was predicted the sound pressure level attributed to the mine in the region to the South-east of the re-orientated open cut pit would increase by 4 to 5 dB. The change in the acoustic environment due to the re-orientation of the open cut pit was measured by a continuous noise monitor located 2.3 km to the South-east of the site.

The results from the noise monitor are shown in Figure 4 as the variation in the frequency distribution from 2015 to 2016. The results are for the winter evening/night time noise immission level attributed to the mine at the monitoring location 2.3 km to the South-east of the mine.
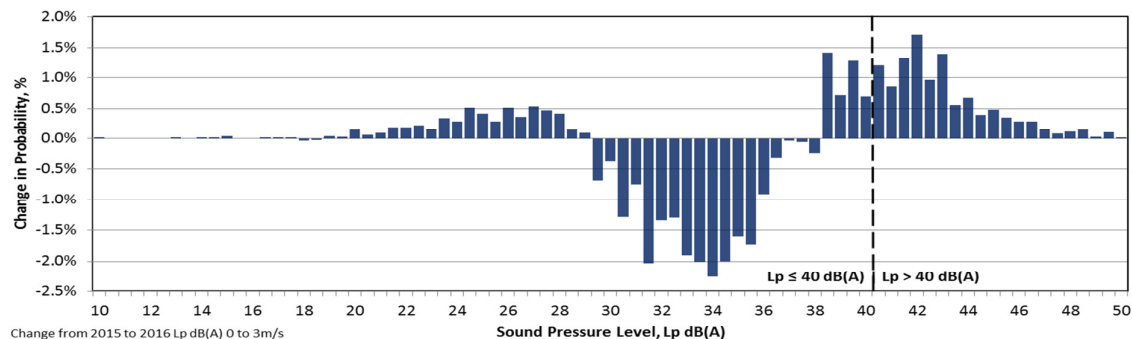

Figure 4 – Variation in the frequency distribution from 2015 to 2016 of the measured winter evening/night time noise immission level attributed to the mine before the new control system (described below) was implemented.

Figure 4 shows an increase in the frequency of occurrence of noise immission levels greater than 38 dB(A). These noise immission levels are attributed to the mine by the directional noise meter. There is a corresponding decrease in the frequency of occurrence of noise immission levels in the 30 to 38 dB(A) range (the desired range). The shift in the frequency distribution from the 30 to 38 dB(A) range to greater than 38 dB(A) can be linked to an increase in the number of machines operating in exposed locations within the mine. Figure 5 also shows an increase in the frequency of occurrence of noise immission levels less than 30 dB(A). This can be linked to an increase in the number and duration of machines being shut down as a noise control measure.

The increase in the average measured sound pressure level from winter 2015 to winter 2016 attributable to the re-orientation of the open cut pit was approximately 3 dB. The increase in the measured noise immission level at the monitoring location was accompanied by an 85% increase in the noise immission levels above 40dB(A) at that location and a 16% increase in the number of complaints.

During 2017 it was anticipated there could be a further 2 dB increase in the noise immission level at the monitoring locations as the mine transitioned through the re-orientation of the open cut pit. As a result, in 2017 a prototype of a new reporting system was developed to help improve the control of noise emanating from the mine. The initial objective of the prototype was to integrate the existing monitoring systems with 'smart' technology. The ideas behind the prototype included aspects of situation awareness, information visualisation and the use of control theory to help identify weaknesses in the existing control strategy.

Figure 5 shows a 210 minute sample of the reported sound pressure level L_P attributed to a mine located approximately 2.3 km from the noise monitor. The change in the sound pressure level L_P in Figure 6 is attributed to a change in meteorological conditions that enhance the propagation of the sound emitted by the machines operating in the mine towards the noise monitor location. The trace of the reported sound pressure level L_P resembles a process reaction response curve with the control system off-line. In this instance the control system is not off-line but it's action is delayed because it is only initiated following a system alarm at 19:10.
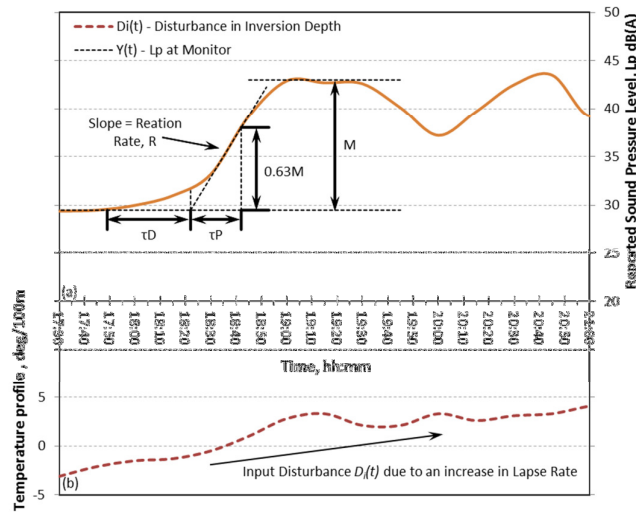

Figure 5 – Analysis of sound pressure level L_P response curve showing the dead-time τ_D of the process reaction, the system time constant τ_P and reaction rate R of L_P following an input disturbance $D_i(t)$ before the implementation of the 'smart' technology

When a control device is off-line the reaction of the process to a disturbance can be used to determine the system dead-time τ_D, the system time constant τ_P and the reaction rate R. In Figure 5(a) the dead-time τ_D = 33 minutes, the system time constant τ_P = 20 minutes and the reaction rate R = 0.44 dB/minute.

It is noted that the input disturbance $D_i(t)$ shown in Figure 5(b) is not represented by a step change in the air column temperature profile (lapse rate) but represents the gradual development of an inversion and an increase in the stability of the meteorological conditions. Long term observations of the temperature profile monitoring data indicate that the shift from a negative lapse rate associated with unstable conditions to a positive lapse rate associated with stable conditions occurs over a period of time. The rate of change of the input disturbance is affected by the speed and direction of the prevailing wind, the air and ground temperature, and the humidity. The input disturbance $D_i(t)$ shown in Figure 5(a) is typical of the rate of change of the input disturbance following sunset on a winter evening if the wind is from the North-west quadrant at 0.5 to 2.5 m/s.

The second attribute worth noting is that the reported sound pressure level L_P is not the process variable PV that is sent to the control device $G_C(t)$. The PV is a system alarm that is triggered if $L_P > 38dB(A)$ for a number of predefined time increments. Figure 6 shows the relationship between L_P, PV and associated system dead-time τ_D, the system time constant τ_P and the reaction rate R.
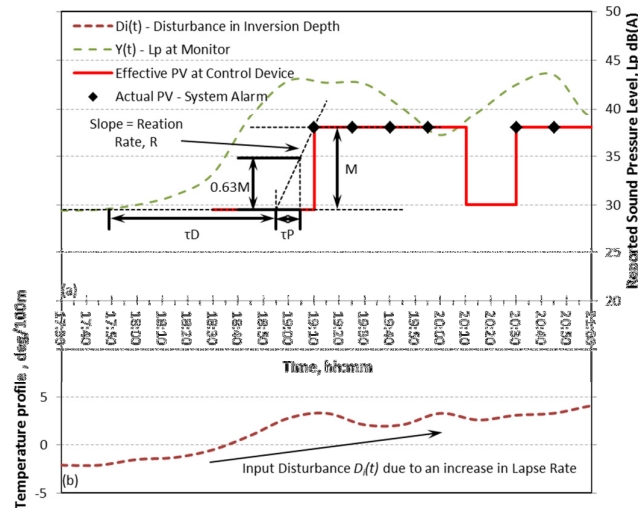
Figure 6 – Analysis of PV response curve showing the dead-time τ_D of the process reaction, the system time constant τ_P and reaction rate R of the reported PV following an input disturbance $D_i(t)$

In Figure 6(a) the dead-time τ_D = 66 minutes, the system time constant τ_P = 9.5 minutes and the estimated re-action rate R = 0.57 dB/minute. The PV dead-time is the summation of the L_P response curve dead-time τ_D of 33 minute plus the PV sensor lag of an additional 33 minutes. The L_P response curve in Figure 6 shows that the PV sensor lag has had a detrimental impact on the control of the system.

The analysis of the PV response curve in Figure 6(a) using a tradition control theory analysis technique shows there is an inherent weakness in the control strategy used by the mine in question. This is independent of any analysis of the control device/strategy $G_C(t)$, the process $G_P(t)$ or the sensor $H(t)$. To remove the PV sensor lag the system alarm was replaced by a new sensor reporting system using 'smart' technology. With the 'smart' technology the PV response curve shown in Figure 6 would be replaced with the PV response curve shown in Figure 7.
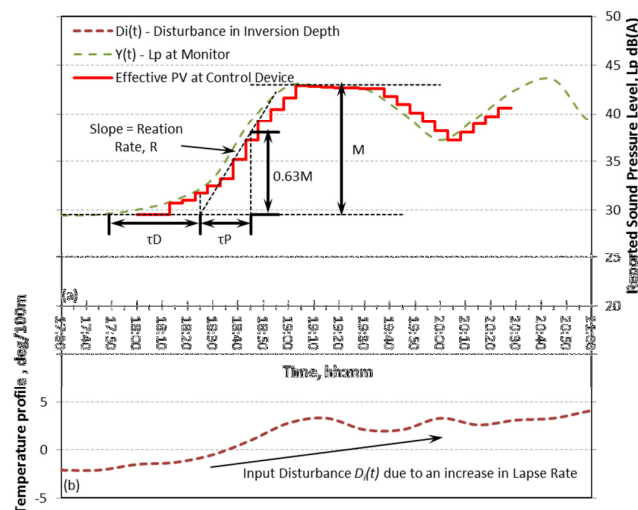

Figure 7 – Analysis of new PV response curve showing the dead-time τ_D of the process reaction, the system time constant τ_P and reaction rate R of the reported PV following an input disturbance $D_i(t)$ showing the updated PV using the 'smart' technology sensor reporting system

In Figure 7(a) the dead-time τ_D has been reduced to 36 minutes, the system time constant τ_P = 20 minutes consistent with the L_P response curve and the estimated reaction rate R = 0.43 dB/minute, which is also consistent with the L_P response curve.

The prototype of the 'smart' technology sensor reporting system developed for the mine in 2017 was able to reduce the PV sensor lag from 33 minutes to 3 minutes. Figure 8 shows the effect of reducing the PV sensor lag on the L_P response curve and PV response curve. The control objective is: $Y(t) \le R(t)$ where $R(t) = 40dB(A)$.
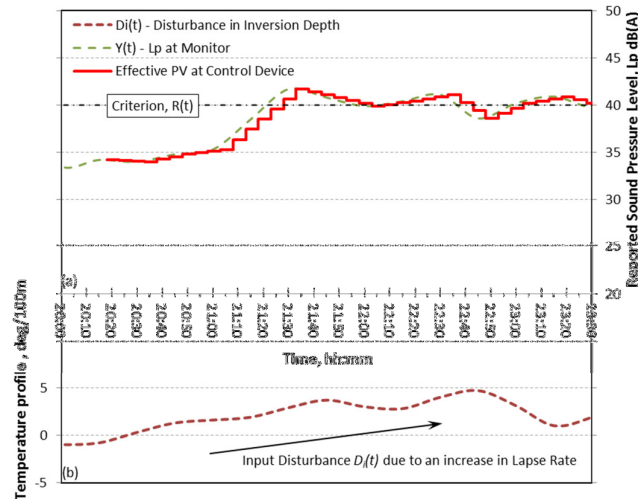

Figure 8 – L_P and PV response curves following the implementation of the
'smart' technology sensor reporting system

Figure 8(a) shows a reduction in the overshoot of the L_P response curve for $R(t) = 40dB(A)$ plus improved control in comparison to the L_P response curves in Figure 6. The improvement in the L_P response curve can be attributed to the reduction in the PV sensor lag and an increase in the PV sensor updates from 15 minutes to 5 minutes.

Figure 9 shows the reduction in the measured winter evening/night time noise immission levels attributed to the mine following the implementation of the 'smart' technology sensor reporting system. The variation in the frequency distribution are for winter evening/night time from 2016 to 2017 at the continuous noise monitor location 2.3 km to the South-east of the mine during the second year of the re-orientation of the open cut pit.
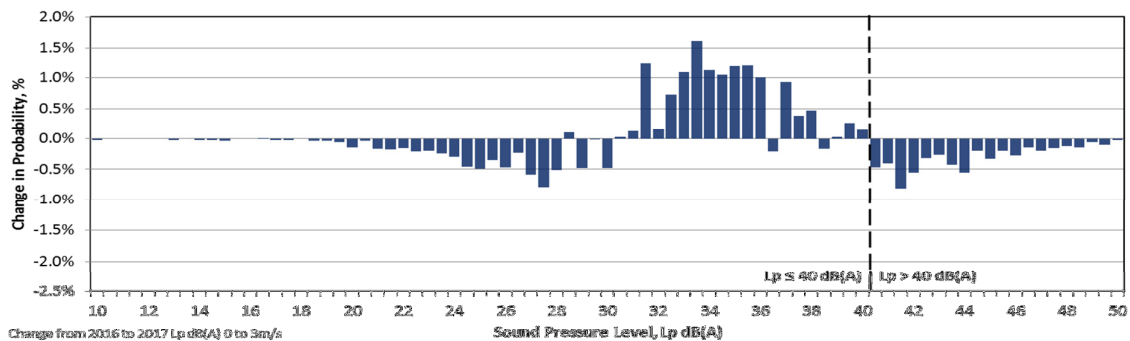

Figure 9 – Variation in the frequency distribution from 2016 to 2017 of the measured winter evening/night
time noise immission level at the monitoring location 2.3 km to the South-east of the mine system
following implementation of the 'smart' technology sensor reporting system

Figure 9 shows a decrease in the frequency of occurrence of noise emission levels over 40 dB(A) and a corresponding increase in the frequency of occurrence of noise emission levels in the 31 to 40 dB(A) range. This shift in the frequency distribution from above 40 dB(A) to below 40 dB(A) is consistent with the established goal for the control system, that $Y(t) \leq R(t)$ where $R(t) = 40 \, dB(A)$.

Figure 9 also shows a decrease in the frequency of noise levels less than 31 dB(A). This is consistent with the second objective of the control system: to minimise the disruption to the mining operation through the implementation of unnecessary control strategies when $Y(t) < R(t)$. This has been achieved through the implementation of noise control strategies that were designed to reduce the sound output from machines in exposed locations without shutting the machines down.

The decrease in the average measured sound pressure level from winter 2016 to winter 2017 attributable to the prototype of the 'smart' technology sensor reporting system equated to a gross decrease in the average sound pressure level at the monitoring location of 3 dB. This was accompanied by a 25% decrease in the noise immision levels above 40 dB(A) and a 25% decrease in the number of complaints. In addition to this, the preemptive management of the mining equipment resulted in a reduction in the number and duration of machine shutdowns. The net result was a decrease in the noise impacts and a corresponding increase in the mine's production.

4 DISCUSSION

In the above example, the analysis of the control of noise emitted from an open-cut coal mine as a feedback control loop enabled the dead-time of the control system to be reduced by approximately 50%. However, the example above only investigated one aspect of the feedback control loop. Traditional control theory presents a number of techniques that could be used to further tune the control system.

Arbogast et al. (2004) recommend that to achieve satisfactory control using a simple feedback controller the system dead time τ_D should be less than the system time constant τ_P. The question is: how to further reduce the system dead time τ_D.

Coughanowr & LeBlanc (2009) propose that for systems with dead time a controller incorporating a derivative component is required to prevent large overshoot and long settling times. The derivative control function $K_d \, de(t)/dt$ responds to the rate of change in the error $e(t)$. An example of the rate of change in the error $e(t)$ is shown in Figure 6 where it is used to calculate the system reaction rate R.

The feedback control loop could be modified to incorporate a feedforward system that provides information on pending changes in machine location or future meteorological conditions. The objective would be to develop a control system that combines information on the error $e(t)$ with feedforward information on changes in machine location and feedforward information on meteorological conditions. The feedforward predictions $F(t)$ would be generated by an operational noise model of the mine. The resulting predictions from the feedforward component of the system would contribute to the situation awareness of the OCE. Success of such a system would be reliant on the integration of all the data sources and the inferences of pending issues and predictions of possible actions and the resulting outcomes. This, in turn, would be reliant on the timeliness of the information and how the information is presented.

The final element to investigate is the measuring element $H(t)$ and effect of disturbances to the measurement $D_m(t)$ on the process variable PV. Coughanowr and LeBlanc (2009) investigate the effect of measurement lag on control systems and report that, as a general rule, the measuring element needs to respond as quickly as possible in order to achieve satisfactory control. In addition to this, a high noise level in the signal-to-noise ratio of the process variable PV can result in the control system responding to the noise and not the signal. If the signal-to-noise ratio is low, to reduce the influence of the measurement disturbance $D_m(t)$ on the system, responsiveness of the control action is often sluggish in order to minimise the overreaction of the system. Clearly, there is a need to have confidence in the process variable PV by maximising the signal-to-noise ratio of the measuring element.

5   CONCLUSION

This paper demonstrates that investigating the control of noise emitted from an open-cut coal mine using traditional control theory can highlight inherent weakness in existing control strategies. The example provided presents the noise management process as elements of a feedback control loop. This enables the noise monitoring results from an operational mine to be analysed using traditionally control theory. In the example presented, the analysis of the noise monitoring data identified a lag in the reporting of the process variable (PV sensor lag) to the control device of up to 66 minutes. The subsequent implementation of a 'smart' technology sensor reporting system reduced the PV sensor lag by approximately 50%. This improvement in the control system response resulted in a quantifiable decrease in the noise immision levels attributed to the mine and the number of noise complaints, and a reported increase in production due to an increase in machine availability.

It is speculated that by examining each element of a mine's noise control strategy as part of a feedback control loop further improvements in the control of the noise emitted from an open cut coal mine could be realised.

6   ACKNOWLEDGMENT

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