Improvements in Mill Fill-Level Measurement via State-of-the-Art Digital Signal Processing (DSP) Technology

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Abstract

A novel approach to mill fill-level measurement is presented here that greatly deviates from traditional sound based measurement systems of the past. High resolution vibration sensors and modern digital signal processing (DSP) hardware are used to replace the archaic shot gun microphone and analog filter approach of the past. This all digitally based system will be shown to yield a more accurate and responsive fill-level measurement that also has a further benefit of being a more stable over time. This paper will discuss the components of the system, the theory of operation, the physical mounting topology and finally real data measurements obtained from the system in operation.

System Description

The MillScan DSP2000 system is comprised of three major components; high resolution vibration sensors (accelerometers), a remote DSP unit mounted directly to the mill shell and a base DSP that interfaces with the plant's control room. See Figure 1. for more details.

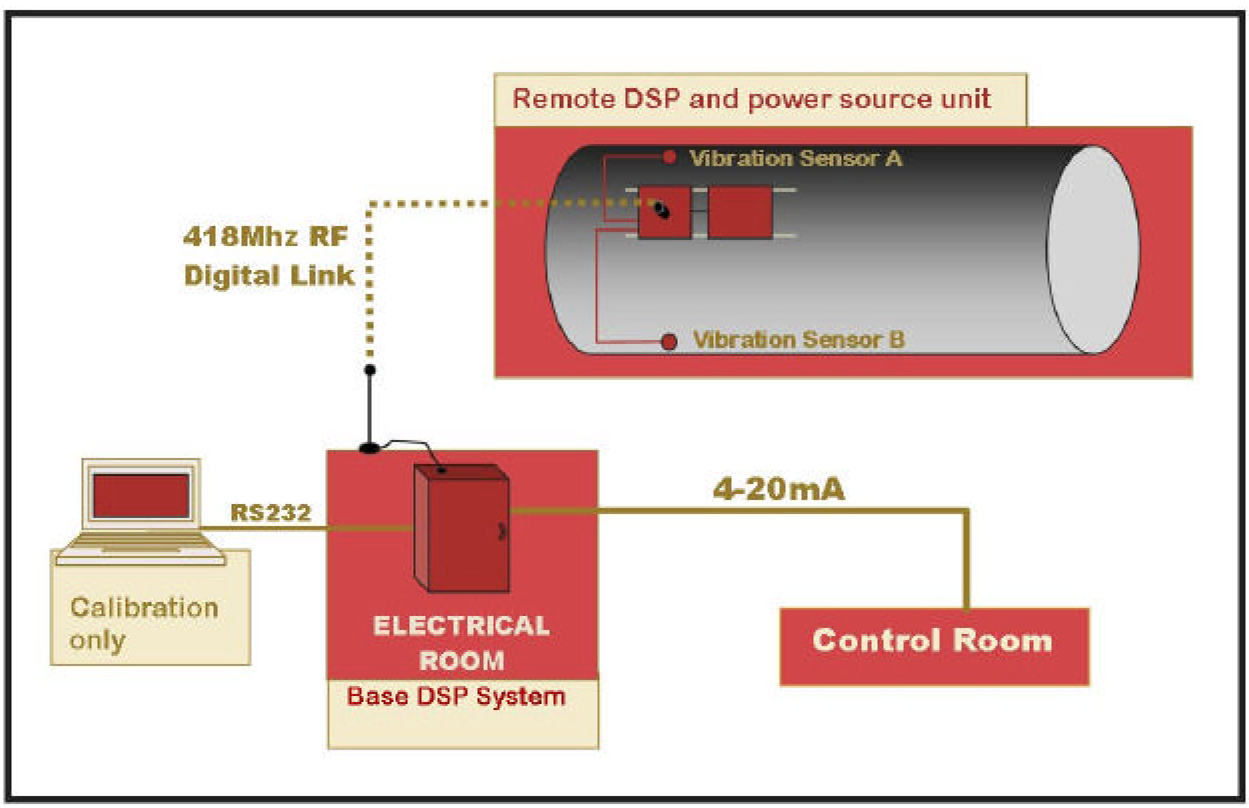

Figure 1. System Description Overview

Beginning with the accelerometers, mill vibration signals are directly collected off of the shell of the mill and passed to a 16 bit analog to digital converter (ADC) in the remote unit. The digital signal representation of the vibration data is then converted from the time domain to the frequency domain via FFT software in the high performance 32 bit floating point DSP also located in the remote unit. This yields a frequency signature for a fixed window of time. This process is repeated whereby hundreds of frequency signatures or windows of data are collected. The windows are then individually filtered and averaged to generate a clean stable spectral signal that corresponds to a real-time mill fill-level measurement. This data is then transmitted from the remote unit to the base unit via a 418 MHz RF link.

The base DSP then collects the remote's filtered spectral information for storage in a large local buffer. This data is then passed through a non-linear classifier such that a fill-level measurement is obtained and transmitted back to the control room via a two wire 4-20 mA link. Note: up to four remote units can be used simultaneously to monitor up to four mills with one base unit.

Theory of Operation

Two vibration sensors, 180 degrees apart, are used to collect signal information from mill so that the instantaneous readings can be averaged together. We found that when only one sensor was employed, the reading would oscillate according to whether the balls in the mill directly struck the wall of the mill near the sensor or on the opposite wall where there was no sensor. In other words, for a given fill level, we would get a strong reading if the balls hit near the sensor and a much weaker reading if the balls struck the wall a distance away from the sensor. The two sensors approach overcomes this problem and enables us to obtain an average instantaneous vibration measurement for the entire mill.

Once vibration data is collected from the sensors and converted to spectral digital data by the remote and finally passed to the base, it is fed into a dynamic neural network. The neural net acts as a non-linear classifier such that the current spectral signature along with other key parameters is used to output a fill-level measurement from 0 to 100 percent. See Figure 2.

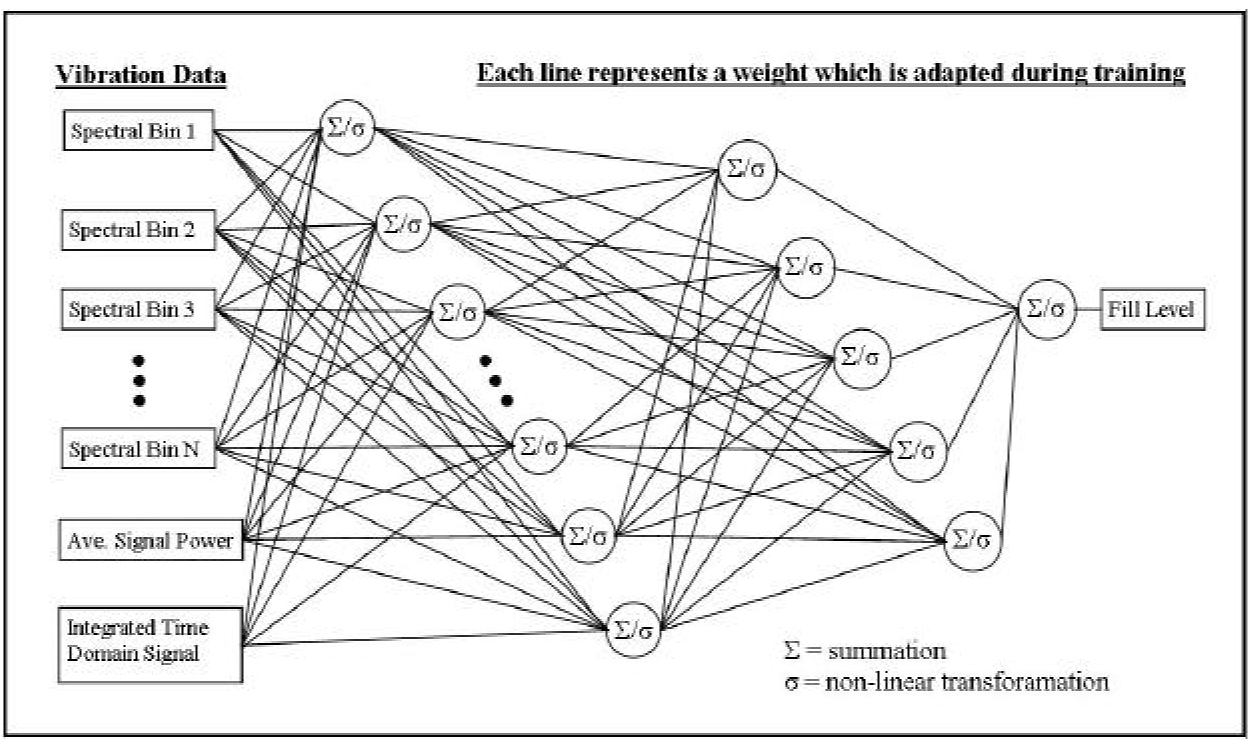

Figure 2. Dynamic Neural Net Topology for Mill Fill-Level Output Generation

While this algorithm is considered proprietary information, the following details can be released: the neural net basically converts a multi-dimensional input space down to a single element or metric. The net has two main modes of operation and these are known as training and feed forward. Training consists of presenting the net with numerous input patterns and a known output value and allowing the net to adapt its weight coefficients. Feed forward is the same as run mode in that the network is trained, the weights are fixed and an input pattern is presented to yield a single output value.

Neural net training is referred to as system calibration in the MillScan manual and thus will be termed this for the rest of this paper. This procedure consists of filling the mill to a level that is considered to be at least 10 percent above normal operating conditions. Once this is achieved and all return and feed signals in the control room are stable or flat, the system is set to acquire and save several vibration snap shots. This is called a "full mill acquisition" measurement. The mill is then emptied and once the return and feed signals are found to be near zero, vibration snap shots are again taken and this is deemed an "empty mill acquisition". These two sets of snap shots, full and empty measurements, are then used to calibrate the system (train the neural net).

The calibration process is performed by connecting a PC or laptop to the base unit via a RS232 serial port link. We then run the MillScan DSP2000 graphical software on the laptop and commence calibration. This is a relatively simple process where the operator just presses a single button to acquire full mill data and another button to later acquire empty mill data. See the buttons on the right hand side of Figure 3.

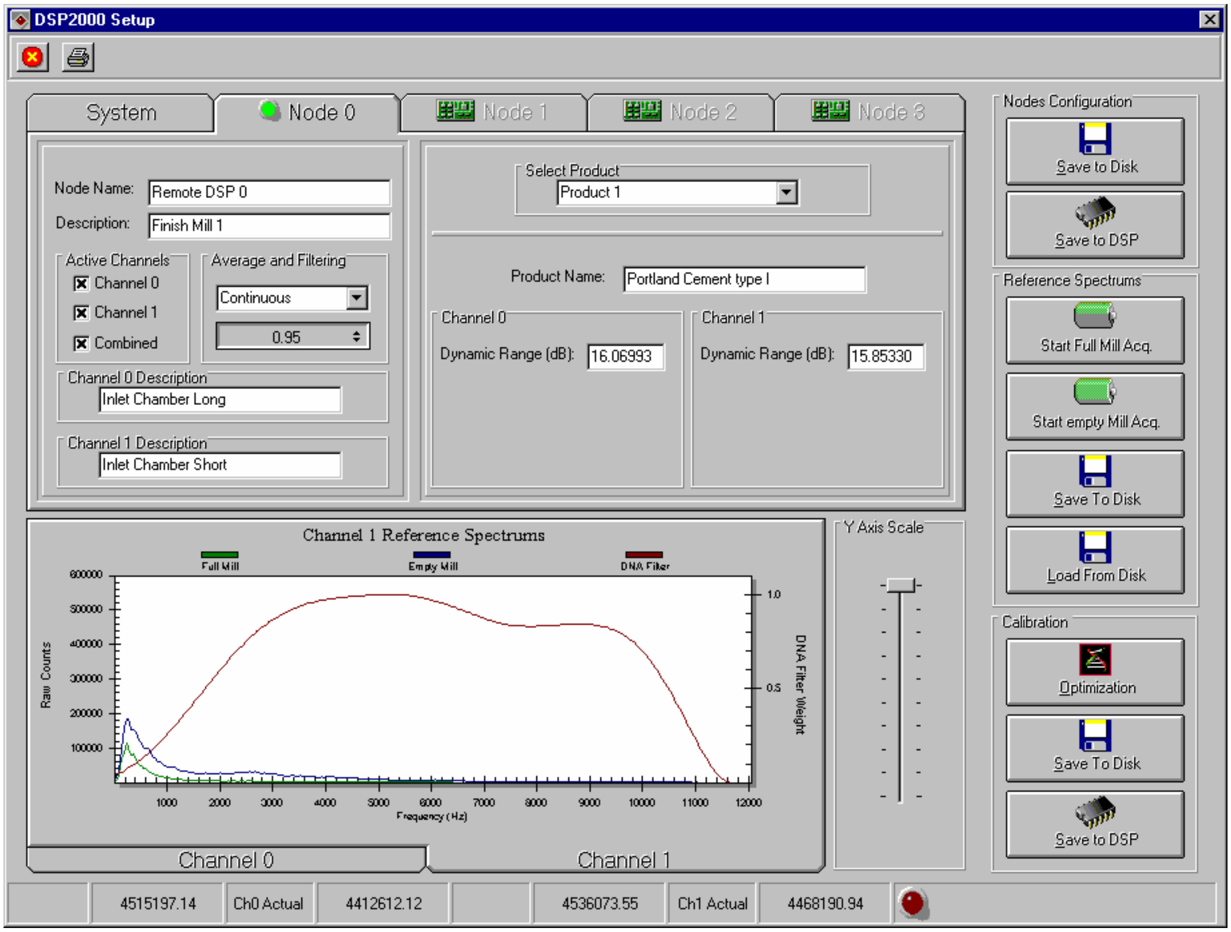

Figure 3. MillScan DSP2000 Calibration Window for Node 0

In Figure 3, the top two buttons on the right hand side are used to select one of four nodes (remotes) for calibration and final operation. The next four buttons below these are used for the full and empty calibration along with two more buttons that allow the user to save this calibration to computer disk and retrieve it at a later date if desired. Finally, the last three buttons near the bottom right are used to run the calibration, save the results to PC disk and also download the network weights to the base DSP. Figure 3 also illustrates that a user can assign a name for a particular node/remote and add a mill description.

The system also supports calibration for different types of cements, up to four. For example, when the same mill is employed to grind Type I and Type III cement, the mill vibration characteristics change due to the different blaine and fineness required for each product. Having an individual calibration for each product compensates this effect, therefore improving accuracy. See the *select product* field in Figure 3.

The two fields associated with *dynamic range (dB)* relate to the dynamic range found between the full and empty signal measurements. The higher the number in these fields, the greater the differences found in the full and empty measurements. There are two measurements, channel 0 and channel 1, which correspond to the full/empty data taken off of two vibration sensors. The software has several other features that can be employed by more advanced operators for experimentation. They, however, are not covered here due to time and space constraints.

Physical Mounting and Power

The base unit easily mounts on a wall near the mill or in the electrical room nearby. This unit is powered from 110-220V and has an antenna and cable that can be run through a wall to the mill area. The only requirement is that the base and remote antenna be roughly 150 meters or less apart from one another.

The remote unit (node) typically is mounted to a steel plate that is then bolted to the shell of the mill. The unit is powered from a motion power generator that uses the kinetic energy (spinning) of the mill to drive a gearbox and DC generator mechanism. The generator is then mounted on the steel plate next to the remote unit.

Results and Conclusions

Recent results from an installation in February are shown in Figure 4. This data was collected in a control room via the Foxboro system and then exported to Microsoft Excel for graphing. The mill was initially shut down and then restarted on February 21st, 23:30 hours. The MillScan (DSP) signal was left unfiltered for this first test while the others were filtered (single pole low pass filter with cut-off at T) per usual operation in the control room as follows: feed T = 0.25, returns T = 1.5, electronic ears T = 0.25 and MillScan DSP system = no filtering.

In the testing illustrated in Figure 4, the mill was relatively empty at start-up and then the returns were rapidly increased, decreased and then brought to a normal stable operating level. We found that *the response of the DSP system in tracking this change was almost immediate* and actually ahead of the return signal. The peak on the DSP signal on 02/22/02, 00:40 hours appears to be about 5 minutes earlier in the data than the peak found in the return signal. This is due to the return signal being delayed as it passes through the low pass filter in the control room and material transport delays through the mill system. This faster response allows us to detect an overload or under load condition much faster than with the material return or bucket elevator power signals.

We also noticed that the DSP signal has a *greater dynamic range* (peaks and valleys ranging higher and lower) than the electronic ear. This can be attributed to the fact that the electronic ear is heavily filtered in its system. This is probably required to overcome noise issues related to measuring sound from a microphone where crosstalk and sound reflection can degrade the measurement.

Another key area to observe in Figure 4 is on 02/22/02 at 17:40 hours where the feed has been drastically cut. The DSP tracks this change nearly instantaneously. Unfortunately, you cannot see the full dramatic effect of this because the graph had to be squashed horizontally to fit into this paper. However, it should be more apparent in the slide presentation at the conference when this is presented at normal width.

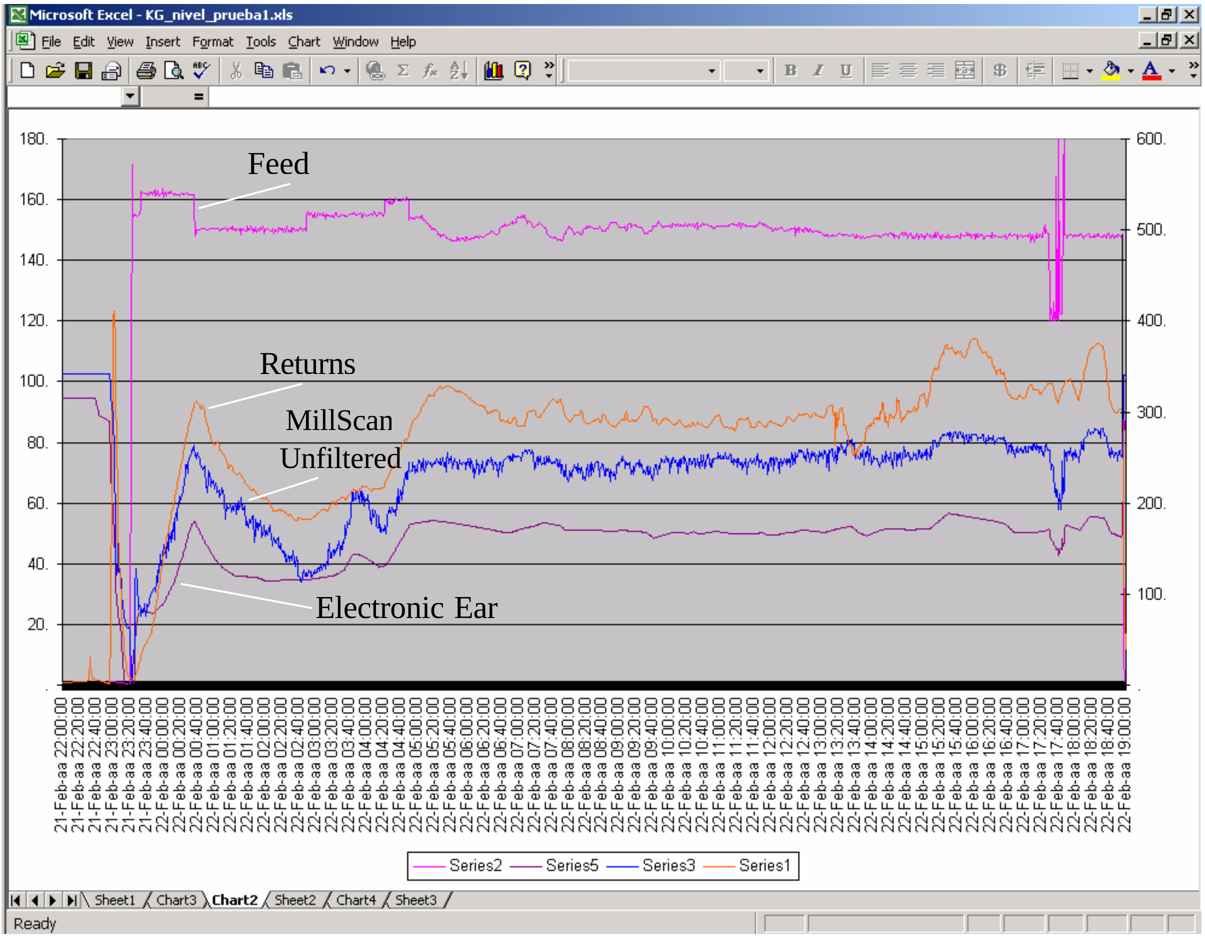

Figure 4. Inlet Chamber Dataset #1

One final note is that it can be seen that the DSP signal is not only more accurate during the entire duration mentioned but also more sensitive to slight changes in fill level during this period of time. For example, at 10:00 hours, the return signal can be seen to have a small peak while being increased. This small peak is actually two peaks accumulated material in the return path; however it shows up as one due to the heavy filtering on this signal. The unfiltered DSP signal shows this effect and the filtered DSP signal shows the effect nearly identical to that of the return signal. The slope of the two lines only being different to the increased feed mentioned earlier. During this time, the ear stays constant and does not reflect any change. *The extra sensitivity of the DSP instrument therefore, helps to maximize mill production by increasing the acceptable mill feed level by a small amount.* The control system can now track more accurately as a result of this increased resolution. In an ear based system, since the ear stays constant and does not pick up these subtle changes, we completely loose this new opportunity.

Figure 5 illustrates the data obtained on the next day of testing. All signals have the same filtering settings as earlier except that the MillScan DSP signal was duplicated and viewed as both filtered (white) and unfiltered (blue) in the control room. The filter cut-off for the white signal is T = 1.5. This is the same filter cut-off point used on the return signal and this was found to be both responsive and smooth enough for future implementation in the control loop.

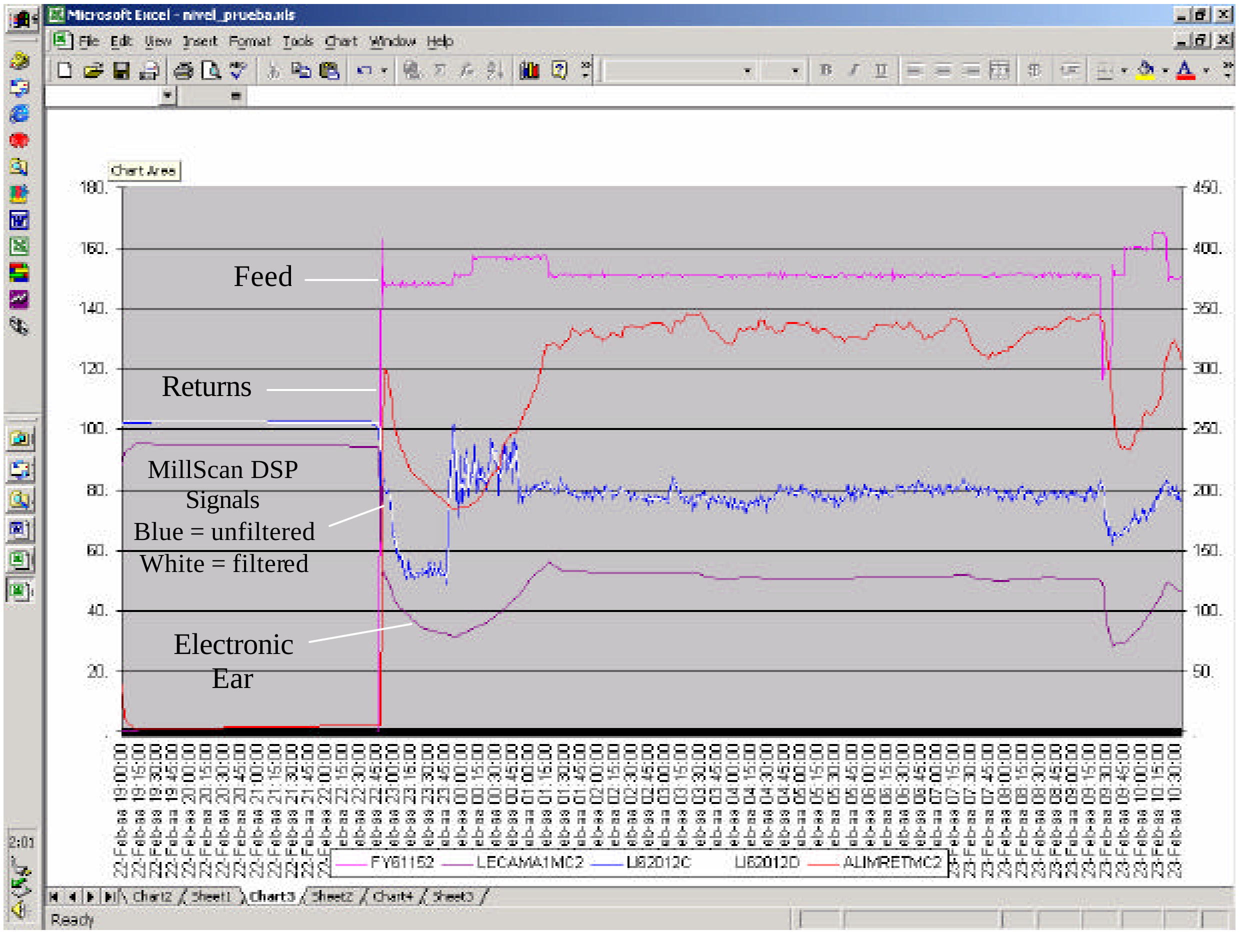

Figure 5. Inlet Chamber Dataset #2

For this test, the mill was started at a point in time where it was approximately 80 percent full. See 02/22/02 at 22:45 hours in Figure 5. Early on, it can be observed that there is a great discrepancy between the DSP's signal and that measured by the electronic ear. It turns out that there was an obstruction in the feed shaft such that the material did not drop evenly as planned. Thus material did not enter the mill at a regular rate and because the material being pulverized was of a type "fine", the material in the inlet chamber was quickly swept out to the outlet chamber. Hence we see a sharp drop at start-up in mill level. Then, at approximately 23:45 hours we observe a sharp increase in the fill level where it was determined that the material stuck in the feed chute broke free and fell into the chamber. The material accumulated in the feed path, due to the initial obstruction, poured into the chamber in large clumps over a 45 minute period and then finally stabilized around 00:45 hours.

Unfortunately, it was not determined what physically caused the obstruction, but it is theorized that it could be related to the heavy rains and resultant humidity that occurred during the night while the mill was shut down. This graph shows that the mill was down at least from 19:00 to

22:45 hours on 02/22/02. This is a considerable amount of time for the material to be held constant or in a fixed position in the feed path under high humidity conditions. What is important to note during this time is that the signal from the electronic ear shows none of this phenomena and instead simply follows the return signal. This is a key conclusion that the author observed many times when comparing data collected from the ear versus the vibration sensor-based system. *The ear tends to track the return signal and not the actual fill level of the mill due to both the feed and returns inputs.*

Another area of data in Figure 5 also supports this theory well. During the period from 09:30 to 10:30 hours on 02/23/02, it can be observed that the feed was briefly cut (8 minutes), the returns decreased and then the feed significantly increased. The electronic ear signal during this time dips farther below that of the DSP's measurements. The electronic ear is basically tracking the return signal, which has a deep dip during this period, to a greater extent then the actual fill level of the mill. The reason the DSP signal does not dip as significantly as the ear is that during this time the feed is greatly being increased. Observe the feed signal from 09:45 to 10:15. Hence the increased feed makes up for the cut in returns during this period and the overall fill level of the mill actually is not as low as indicated by the ear.

In conclusion, the on contact vibration sensor/DSP based system has been shown to be very responsive, sensitive and accurate in determining the mill's current fill level. By taking the measurement directly off of the mill shell, we eliminate traditional sound based measurement issues such as crosstalk between adjacent mills and reflection of sound generated from the mill.

Calibration of the system is a simple process of taking a few minutes of measurement when the mill is full and when the mill is empty. Because the system is completely digital after sensor data has been converted from analog signals, it is expected to be stable over time. There are no analog components in the design that can degrade or drift over time as in the traditional sound based systems. Finally, having a system that can track the true fill level of the mill will enable plants to detect possible problems and equipment failures earlier as well as increase the overall efficiency of their processes.

Short Bibliography

Dr. Karl Gugel is technical manager of Digital Control Lab which produces DSP based control systems for industrial grinding machines, MRI machine testing and industrial adaptive noise cancellation. In addition to this work, he is also a lecturer and researcher at the University of Florida in the electrical engineering department. His areas of interest include industrial signal processing & control using microprocessor, DSP and FPGA hardware.

Filiberto Morales is currently an Electrical Manger at ESSROC's Nazareth Plant with 12+ years experience in automation and process control in the cement industry. He holds two BSEE degrees from The State University of Nuevo Leon in Mexico.