SMARTBit:

IN-SITU BIT/ROCK INTERFACE MONITORING DEVICE

by

Benjamin Hopkins Miller
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Golden, Colorado
Date ____________

Signed: __________________________
Benjamin Hopkins Miller

Approved: _________________________
Dr. John P. H. Steele
Thesis Advisor

Golden, Colorado
Date ____________

__________________________
Dr. Joan Gosink
Division Head, Professor
Division of Engineering
ABSTRACT

As mining operations progress toward tele-mining and autonomous procedures, the need for machine performance monitoring increases. Presently, through a combination of vision, sound, and other subjective observations, an operator attempts to optimize the mechanical excavator’s operation. As the operator is moved away from the face in the case of tele-mining or completely removed for autonomous operation, the qualitative sensory input is lost. This lost information must be replaced with quantifiable sensory input, such as chip formation detection. SmartBit sensors have been developed to provide sensory output from all cutting implements on a mechanical mining machine using either radial or conical bits. The piezoelectric film sensor, used in the SmartBit, performs in a fashion similar to a dynamic strain gauge allowing monitoring of the loading state of an individual bit. Along with external circuitry, the sensor outputs a measurement of the force impulses experienced by the bit during the cutting and fracture of the rock. Chip formation can be predicted with high confidence (>80%) through the analysis of the load waveforms associated with bit/rock interface monitoring provided by SmartBit sensors.
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CHAPTER 1
INTRODUCTION

Mining’s technological progression, while being impressive in some aspects, is stagnant in many others. The scale of mining remains the primary focus of technological improvements; for example as surface haul truck capacities approach 400-ton, the need for higher technologies has been met. But the major changes to operations, such as mechanized mining and even the invention of the air-powered drill, have been slow. Mining automation is another major change that the industry will see in the coming years. Manufacturing and mineral processing industries have profited from the benefits provided by automation, and the technological opportunities for mining automation have begun to appear. The motivation for automation lies not only in a mine’s bottom line, but the safety and health of its work force. (RAND 2001)

The economic benefits of automation fall into three categories: higher equipment utilization by avoiding shift changes, breaks, and worker fatigue, reduced need for human support systems, and reduced wear and tear on equipment. Higher utilization perhaps would be the most significant improvement. Presently, utilization rates rarely are above 50%. (Ozdemir 2000) Even an increase of a few percent in utilization could mean millions of dollars to a mining operation. Also by reducing support systems costs, such as ventilation and over excavation large savings can be achieved. In addition, large savings could be derived from a reduction in the wear and tear on equipment due to operator error.
The other major motivator for mine automation, as well as tele-operation, is worker safety and health. By removing the miners from the face, risk of injury as well as exposure to unhealthy environments (e.g. noise and dust) are substantially reduced. (Bergstrom 2000, MAP 2000) However, by removing the operator from the face, a great deal of sensory information is lost. This information can be described as a mind-machine link. A skilled operator is able to “feel” the machine. This information comes from all of the senses of the operator. Some of these senses can be relayed through present technologies such as video and audio signals, but some of the information is still lost. When speaking with operators they describe a “seat of the pants” type control. By feeling the vibrations of the machine, vital machine performance information is collected. To replace the lost information in the move to tele-operation and automation, new quantitative sensory information is necessary.

SmartBit sensors, the focus of this thesis, will provide tele-operators, as well as automated control systems, with some of this quantitative information by monitoring the cutting behavior of the individual bits of a mechanical miner. Bit/Rock interaction monitoring has been performed before, but only in laboratory settings. In the work presented here, prototypes for conical as well as radial bits have been developed (Chapter 5), and an algorithm to predict chip formation from sensor data has been developed (Chapter 3) and tested (Chapter 4). Through the use of SmartBit sensors and other sensors such as the Stolar Horizon sensor (Stolarczyk 1996), the mind/machine link, which was lost by removing the operator from the working face, can be returned and possibly improved.
CHAPTER 2
THE PRIOR ART OF IN-SITU BIT/ROCK INTERACTION

2.1 Prior Art Search

In the process of investigating prior art of bit-rock interaction monitoring, little has been found on in-situ operating equipment. The search spanned the traditional sources, such as journals, proceedings, magazines, and books; government publications, such as USBM’s Information Circulars and RI’s; issued patents from the last 30 years; and electronic sources. The search did reveal two laboratories focused on the topic. The US Bureau of Mine’s (USBM) Twin Cities Coal Cutting Facilities were in operation until 1987 when the USBM was dissolved. The other facility, the Earth Mechanics Institute (EMI) is on the Colorado School of Mines (CSM) campus. Most information collected in this search had very little relevance to the topic of in-situ real-time machine performance, but one in-situ device was found. In addition, some cross-discipline sources of machine performance monitoring related to cutting are included. The descriptions of prior art will be divided into five sections: Bit/Rock interaction monitoring nomenclature, USBM facility and equipment, EMI facility and equipment, the USBM in-situ device, and cross-discipline topics.

2.2 Bit/Rock Interaction Monitoring Nomenclature

The equipment briefly described in the following sections can be discussed using the same nomenclature. Their operation is also very similar. The operation and nomenclature of the Linear Cutting Machine (LCM) at Earth Mechanics Institute (EMI) will be described thoroughly, and the other machines are simple variations of the LCM.
2.2.1 LCM Experiments at EMI

The LCM tests measure full-scale cutting forces acting on a cutter while cutting actual rock. Full-scale testing eliminates the uncertainties of scaling and any unusual rock cutting behavior not reflected by its physical properties. The actual force requirements on the cutter are recorded during the linear cutting tests. This data may be used as input for selection and design of an excavator, selection of a cutter, and to define optimum cutting geometry and performance prediction. The drag force recorded during LCM testing is directly related to the torque requirement of an excavator, and the specific energy requirement is calculated based on the drag forces related to volume of material cut. Using the Specific Energy (hp-hr/yd³), achievable production rates are calculated for a machine with a known horsepower available to the cutterhead. Lower specific energy means that a given machine will produce more material, or that a smaller / less expensive machine may be used to produce the required amount of material. The normal forces recorded by the LCM are used to calculate the necessary effective mass and thrust required of the excavator. This is important to ensure that the excavator is able to provide the necessary thrust. Muck (rock cuttings) size distribution measurements can be performed on the cuttings from LCM testing. This provides valuable data for designing material handling, dust control systems, and gradation control. Matching the machines productivity with the product gradation provides for the economic optimization of the cutterhead design for the specified continuous miner. (Asbury 2002)

2.2.2 Linear Cutting Test Equipment and Procedures

The Linear Cutting Machine (LCM) features a large stiff reaction frame on which the cutter is mounted. A tri-axial load cell, located between the cutter and the frame, monitors forces and a linear variable displacement transducer (LVDT) monitors travel of the rock sample. The rock sample is cast in concrete within a heavy steel box to provide the necessary confinement during testing. (Fig. 2.1 and 2.2) A servo controlled hydraulic actuator forces the sample through the cutter at a preset depth of penetration, width of
spacing and constant velocity. During the cut, the tri-axial load cell measures the normal, drag, and side forces acting on the cutter. (Fig. 2.3) After each cut the rock box is moved sideways by a preset spacing to duplicate the action of the multiple cutters on a mechanical excavator.

In field excavation, the individual cutters on the machine always operate on a rock surface damaged from the previous cutting action. This scenario is duplicated in the laboratory by thoroughly conditioning the rock surface before testing begins. This is accomplished by making several passes before data is collected. (Asbury 2002)

Figure 2.1 A picture of the LCM testing set-up. (Asbury 2002)
Figure 2.2 A schematic drawing of the LCM testing set-up. (Asbury 2002)

Figure 2.3 Schematic drawing of forces acting on a conical pick cutter. (Asbury 2002)
2.2.3 Linear Cutting Test Parameters

The LCM test consists of three major variables: line spacing between cuts, penetration of cuts, and angle of attack. The dependent (measured and calculated) variables are average cutter forces (normal, drag and side), specific energy and muck (rock cuttings) size distribution. The constant variables are cutting sequence (single scroll pattern), cutting speed (10 in./sec., 254 mm/s), skew angle (0°) and tilt angle (0°).

The primary considerations for the selection of the bit type, optimum cutting geometry and type of excavator are the production rates and the size gradation of the mined material. Cutting efficiency can be initially evaluated as a function of specific energy. Specific energy is defined as the amount of energy required to excavate a unit volume of rock. It is a function of drag force and cut profile area. (Asbury 2002)
2.3 Bureau of Mines Facilities

Initially the USBM’s coal cutting facilities were developed for coal dust studies. However, it was soon realized that very little data existed for mechanical excavation. The USBM developed their Coal Cutting Technology Facilities (Roepke 1983) to provide a new body of data for mechanical excavation. The facilities also began development of some of the initial automated underground excavators shortly before the USBM was dissolved. While these references deal with bit/rock interaction (excluding the autonomous miner) they all fail at accomplishing the goal of in-situ real-time bit/rock interaction monitoring. All the equipment in this section are laboratory based.

2.3.1 Bureau of Mines Test Bed for Autonomous Mining

In the late 1980’s and early 1990’s, the Bureau of Mines developed a semi-autonomous mechanical mining machine. (Schiffbauer 1988) Based on a Joy 16 Continuous Miner (CM), it incorporated computer control of the CM. The motivation was to make mining more efficient and, therefore, more profitable. Their efficiency claims included increased productivity as well as improved worker safety. The purpose of the experiments was to determine the feasibility and techniques of mining automation. Machine control began with dead reckoning control, but progressed to closed loop control. The CM’s sensing was limited to the primary appendages. Once the closed loop control was implemented, scripting produced the machine’s automation. This meant the machine’s tasks were defined and then fixed routines represented these functions. These functions included: setup, tram to face, find start, first cut, produce, fill shuttle, back out, move new, and shut down. While these functions completely encompass a CM’s job, the effect of fixed scripting is an inability to react to changing conditions.
2.3.2 Vertical Cutter

The Bureau of Mines developed a test machine for extend use tests. The vertical cutting linear tester is a modified vertical slotter. The measurements are taken not on the bit holder, but the sample bed. Extend wear tests are completed by stepping across the sample. The sample is then stepped forward for the next pass and cuts progress back across the sample. This is fully automated allowing for bit wear tests. The equipment also can be equipped with dust collection/sampling hardware. Force is only monitored in the normal direction for simplicity.
2.3.3 Rotary Drum

The rotary drum test apparatus is a short section of continuous miner cutting drum. Cutting depth, speed, and position can be varied. Cutting force is measured from a differential pressure transducer connected across the hydraulic motors of the head. The pressure drop is related to the torque at the cutting head. A magnetic gear tooth sensor monitors angular velocity. The system can be set to traverse through the sample automatically. This allows for wear and failure tests to be performed.

Figure 2.7 Rotary Drum. (Roepke 1983)

2.3.4 Large Linear Cutting System

The large linear cutting system is a modified planer mill. The quill head and motor from the overhead rail have been removed and replaced with a rigid mount for the bit dynamometer. Again the bit is mounted and the sample is passed beneath the bit. Data is taken on a three-axis dynamometer. The large linear cutter is also outfitted with a
dust collection/sampling system. The bit force dynamometer is a commercially built system from Kistler. It utilizes six pairs of piezoelectric force transducers.

![Large Linear Cutting System](image)

Figure 2.8 Large Linear Cutting System. (Roepke 1983)

### 2.3.5 Microminer Multiple-Bit Linear Cutter

The microminer is a specially built mining machine designed by the Bureau of Mines. It was further modified to allow for full-scale bit tests. One of the bit mounts is instrumented to measure the orthogonal forces of the interaction. The instrumentation consists of three strain gauged clevis pins used to attach the bit block to the arm. During operation, the machine is anchored using roof jacks.
2.3.6 Small Linear Cutting System

The Small Linear Cutting System is a modified, horizontal, simplex, class C mill. Its maximum sample size is 33 cm wide by 25 cm long by 20 cm deep. Bit traverse rate can be fixed between 0.04 to 1.7 cm/s with maximum depth of cut of 3.8 cm. Its acceptable peak forces are 4000 lbs. Measurements are taken with a three-axis plate dynamometer. The tests are taken by fixing the bit to the dynamometer and traversing the sample. The apparatus includes a dust collection/sampling.
2.4 Earth Mechanics Institute

The Excavation Engineering and Earth Mechanics Institute (EMI) was established at Colorado School of Mines in 1974 to enhance education and research in the field of excavation technology both for mining and civil underground construction. Over the twenty-five years of its existence, EMI has developed a suite of physical property tests, cutter and cutter head evaluation procedures for performance prediction, project costing, and design of mechanical rock excavation tools for all types of mechanical excavators in mining, civil underground construction, and microtunneling. The developed test procedures and the performance/cost prediction models have been validated with extensive field data from excavation and drilling projects around the world. (Ozdemir 2001) Again all of the equipment fails to satisfy the main goal of SmartBit, in-situ real-time bit/rock interaction monitoring.

2.4.1 Drill Test Fixture

The Drill Test Fixture (DTF) is used for performance evaluation of drill bits and cutterheads less than 4 feet (1.2 m) in diameter. (Ozdemir 2001) The DTF has the ability to bore axially with the drill string, as well as slew, or cutting perpendicular to the drill string. The DTF is instrumented to measure all operational parameters, as well as vibrations generated by the cutting action. These measurements are digitally recorded with a computer based data acquisition system. The testing of a full-scale cutterhead provides an accurate measure of qualifying the dynamic effects of cutting and an economic proving ground for new bits and cutterheads.
2.4.2 Laboratory Tunnel Boring Machine (LTBM)

The LTBM is used to test the performance of full-scale cutterheads up to 7 feet (2 m) in diameter. It is mounted on a swivel frame so that any orientation can be tested, from straight up to straight down, and in wet or dry conditions. The LTBM data acquisition system is computer-based for high resolution and accuracy. Individual cutters can be instrumented to measure actual cutter forces during boring. (Ozdemir 2001)
2.4.3 Single Cutter Rotary Machine

A 5-foot diameter, single-cutter rotary machine tests full-scale cutter bits (disc, pick, etc.) for performance and wear evaluations over long periods of time. Water jets may also be incorporated into the system to perform jet-assisted mechanical cutting tests. (Ozdemir 2001)

2.5 In-Seam Tester

The USBM developed the in-seam tester as a portable underground device for testing the cutting forces experienced by a bit. (Church 1985) The device also can be equipped with dust collection/sampling equipment. Bit forces are measured with strain gauges mounted behind the bit block. Its purpose was to enable designers to select pick types, spacing, lacing, depth of cut, and rotary speed for specific coal types and seam conditions to improve cutting performance. This device does satisfy some of the goals of SmartBit. Full-scale bits can be completed in-situ, but they are far from real-time. For real-time monitoring the sensor must be able to fit onto an active machine.
2.6 Other Machine Monitoring for Cutting Applications

While the focus of this survey is mechanical excavation cuttability measurements, it is worth noting some of the other applications of similar technologies.

2.6.1 Measurement While Drilling (MWD)

Measurement while Drilling (MWD) is the application of sensor technology for drill rigs. Predominately, MWD is used in surface mine blast hole drills (Segui 2001) and petroleum wells. MWD is able to sense the rock formation as the bit travels through varying layers. This technology provides valuable geological data for mining engineers, and ongoing research hopes to use MWD to optimize blasting patterns as well as hole
charging. While MWD measures the cutting of rock, it differs greatly in its application of sensors from SmartBit technologies. MWD measures the torque, thrust, and drill string vibrations at the top of the drill string, unlike SmartBit sensors, which are located near the bit/rock interface.

2.6.2 Metal Cutting Manufacturing Automation

In closed loop machining control systems, sensors are used to measure the performance of the cutting tools. (Altintas 2000) Vibration sensors are used to monitor the cutting behavior. Due to metal’s uniform nature, cutting processes produce constant frequency vibrations within the system. This vibration monitoring can be used to measure the chipping and cutting of the tool. The SmartBit approach to cutting measurement is very similar in that it measures the vibrations caused by the chipping of the material. However, due to rock’s inhomogeneous nature, vibrations are not produced at constant frequency. This difference forces a frequency independent monitoring technique.
3.1 The Bit/Rock Interface

The bit/rock interactions can be described by the forces applied to the tip of the rock-cutting bit. The orthogonal directions are labeled as the normal, drag, and side forces. (Fig. 2.3) The normal force is normal to the rock surface with positive force being out of the rock surface. The drag force is the direction of travel with positive being opposite the travel direction. The side force is orthogonal to the other two components with positive being given by the right hand rule of the normal and drag force.

The waveform seen in Figure 3.1 is typical of the waveforms collected by the LCM at EMI for the sandstone sample used in this work. The normal and drag forces are displayed. The normal force is the larger amplitude waveform, while the drag is the much smaller amplitude waveform in Figure 3.1. Initially, the bit is cutting in the concrete, which is used to secure the sample. Much lower loads can be seen in this region. Five inches into the cut, the bit begins cutting the sandstone sample. Through observation, it can be seen that the normal and drag forces are well correlated. Their load curves have similar pulse shapes. To simplify the data analysis, only the normal and drag forces were processed.
From visual inspection, distinct pulses can be seen in the waveforms. These pulses are believed to be representative of stick-slip interaction of the bit and rock. As the bit moves through the sample, the load increases until it reaches a limit where a nearly complete unload occurs. This load-unload cycle is believed to be related largely to the formation of chips. The magnitude of the load also may be related to the size of the chip produced, with the larger load cycles representing larger chips.

### 3.2 Load Waveform Analysis

The waveform in Figure 3.1 shows load increasing as the bit enters the sample, and then fluctuating as it passes through the sample. The load waveform is normally studied by finding the mean and maximum load values, and then determining the expected loads a given bit will experience in a rock type. This is useful for determining statistical behavior of a machine, such as: the bit life due to wear, the optimal spacing for
the cutters, and the thrust required from the machine. For a real-time performance monitoring system, this approach will not work due to the necessary processing.

Initial observations of the load waveform lead to the belief that Fourier frequency analysis could determine the rate of chip formation. This technique is used in machine performance monitoring on metal lathes and mills. (Altintas 2000) In this technique a pulse is observed when a metal chip breaks free. The results of the Fourier analysis (Fig. 3.2) are the transform of the load waveform into the frequency domain as seen in Figure 3.1. No distinct frequency peaks can be seen in the plot, and therefore no frequencies can be related to the chips produced in the cut. The failure of the Fourier analysis is not surprising, however, due to the inhomogeneous nature of rock.

![Frequency plot of load waveform](image)

**Figure 3.2.** Frequency plot of load waveform; some low frequency signal shows above the white noise, but no dominant peaks are visible.
While frequency analysis using the Fourier transform method proved unsuccessful, it was still believed that the pulses in the waveform were representative of the formation of chips. This build up of load can be seen as the bit is traversing the sample. The bit begins sticking in the rock and popping small chips off. As this continues, the overall load increases until a critical limit is reached. Once this limit is surpassed a massive release can be seen. The first massive release occurs at ~6 inches into the sample (Fig. 3.1). It is also believed that the magnitude of the build-up is related to the size of the chip formed. From this description of the bit/rock interaction a time independent algorithm was written to sense these pulses.

3.3 Development of the Pulse Count Algorithm (PCA)

The Pulse Count Algorithm was developed in order to find the average pulse frequency from the LCM data. As mentioned above, the Fourier analysis was ineffective. As expected, the pulse frequencies were in the low frequency (<200 Hz) range, but there were no dominant frequencies. This is due to the irregular nature of the rock failure. An average frequency of chips vs. time or chips vs. distance can be found. Ultimately, the interest is in the number of chips vs. distance. To count the pulses, one must first define a pulse. A pulse is defined as a load (lbs, N or mV of strain gauge), which begins below an "unloaded" threshold (reset threshold) and has a maximum greater than a defined limit (pulse threshold). The defined limit can be imagined as the boundary between the bit catching and popping chips from the surface and simply scratching the surface.

Thresholds are used to control the effect of a noisy signal as well. The pulse threshold is the limit, which defines a pulse strong enough to be counted. The reset threshold helps to control noise about the pulse threshold. Without the reset threshold a noisy signal near the pulse threshold would produce incorrect pulse counts.
Figure 3.3 shows the algorithm developed for pulse counting. The algorithm looks at each data point in the data set until it passes the pulse threshold. After the threshold is passed the number of pulses increases by one, and the algorithm again traverses the data until the lower limit or reset threshold is passed. The pulse count is incremented and then this cycle is repeated. (Figure 3.3) This continues until the data set has been fully processed. After completion of the routine the pulse count is halved. This result is the number of peaks, which achieve a maximum above the pulse threshold and return below the reset threshold. This method is being used on a stored data set, but can be easily modified to run real-time on data received from an active sensor. The code used to implement this algorithm is given in Figure 3.4

![Figure 3.3 Pulse Count Algorithm flow chart.](image)
i=1;
pulseCount=0;
EndOfList=Length[data];
While[i != EndOfList,
   While[(data[[i]]<pulseThrhld && i!= EndOfList),
      i++;
      pulseCount++;
   
   While[(data[[i]]>resetThrhld && i!= EndOfList),
      i++;
      pulseCount++;
   ]
   Count = pulseCount/2
]

Figure 3.4 Pulse Count Algorithm implementation using Mathematica Code.

3.4 Threshold Values
The thresholds are used determine the effectiveness of the algorithm. In this preliminary description of the PCA, the thresholds were selected by examining the data set and qualitatively picking their values. For this example, thresholds of 9600 lbs (42.7 kN) for the pulse threshold and 2200 lbs (9.8 kN) for the reset threshold will be used. A more rigorous method using optimization for the selection of the thresholds will be discussed later.

3.5 Application of the PCA to a Load Waveform
The PCA will be applied to the first waveform (Fig. 3.5) with the threshold values discussed above. The horizontal lines are the threshold values. The upper value of 9600 lbs (42.7 kN) is the pulse threshold, and the lower value of 2200 lbs (9.8 kN) is the reset threshold. The PCA moves through the data set and as a pulse is detected, the pulse
count is incremented. The vertical lines denote the location of the beginning and end of a detected load-unload cycle, which represents a chip being formed. The value of eight chips the PCA produces can then be compared to sieve analysis performed on the cut. All chips collected in the sieves with screen spacing of greater than .5” (12.7mm) are defined as the sieve chip count. The motivation for this size is a focus on large chip production. The sieve chip count from this example is eight >.5” (12.7mm) chips. By comparing the two chip counts it can be seen that the threshold choice was acceptable as the count values were equal.

Figure 3.5 Load waveform with PCA applied; horizontal lines are thresholds; vertical lines are triggers on the thresholds; Pulse threshold = 9600 lbs (42.7 kN), Reset threshold = 2200 lbs (9.8 kN); PCA result: 8.

3.6 The Effect of Thresholds on Chip Count

By adjusting the thresholds, the PCA chip count can be varied. In Figure 3.6, the load waveform from before has the PCA applied to it again with thresholds of 13000 lbs
(57.8 kN) and 1100 lbs (4.9 kN). These thresholds span a greater space and therefore represent a larger necessary load to unload cycle. The chip count should be less using these thresholds, and is with the PCA arriving at a count of four. In the graph below, the PCA is applied with the range of the thresholds reduced to 8500 lbs (37.8 kN) and 3300 lbs (14.7 kN) [Figure 6]. As expected, this produces a larger pulse count of ten. Therefore, by varying the thresholds, the PCA’s chip count will match the sieve chip count.

![Graph](https://via.placeholder.com/150)

Figure 3.6 Load waveform with PCA applied with wider range for thresholds; Pulse threshold = 13000 lbs (57.8 kN), Reset threshold = 1100 lbs (4.9 kN); PCA result: 4.
3.7 Optimization of the PCA Thresholds

For all individual cuts, thresholds could be chosen to perfectly correlate the PCA and actual chip counts. Obviously, these values would not work universally on all cuts even in the same rock type. To determine the thresholds, which would produce the most accurate chip counts, an optimization routine was developed. The optimization was completed using a brute force technique of discretizing the range for each of the thresholds and applying the PCA for each threshold pair. The range for the pulse threshold spanned the mean to maximum of all cuts included in the data set. The range of the reset threshold spanned zero to the same mean. The PCA was then run on the cut data sets for all pairs of thresholds. Each of these runs produced an integer chip count, which was then compared to the chip count found by the sieve analysis. The comparison was done using a least squares approach. The difference between the chip counts was squared and displayed in a contour plot. An example contour plot and 3D surface plot can be seen in Figure 3.8 and 3.9. The contour plot represents the 3D error surface.
where the low values are expressed in darker tones. By searching for a valley in the surface, a minimal error can be found. This minimized error location corresponds to the optimal thresholds as expressed in two dimensional ordered pair, \( \{x,y\} \), associated with that point, where \( x \) is the reset threshold, and \( y \) is the pulse threshold. In other words, the valley seen in the plot represents the optimal threshold values. It can also be seen that the threshold does not need to be an exact number. A small range of thresholds will produce an optimal chip count difference. The known errors in our data processing allow us to determine a confidence rating of our chip production sensing. This confidence is described as the total chips in a sieve data set less the error and divided by the total chips.

Figure 3.8. Contour plot of error surface; darker values represent lower error.
Figure 3.9 Surface plot of error surface.
4.1 Introduction

The Pulse Count Algorithm (PCA) and optimization routines described in Chapter 3 were applied to load waveforms from the LCM. While these waveforms will differ from the piezo waveforms, they did provide data sets for testing and analyzing the performance of the PCA. The tests were performed on a sandstone sample using a radial bit. Although this bit would be a poor choice due to rapid wear, the sample did provide very dynamic load waveforms during cutting. This dynamic behavior provided large distinct chips for counting purposes, as well as waveforms that were easy to process. Data collected from the LCM will be processed in three formats: single-set, single-pass multi-set, and multi-pass optimization, where a pass refers to a complete horizontal layer being removed while a set is a single cut through the sample.

4.2 Single-Set Optimization

The PCA was applied to a single set of data from the LCM. The selected set was SB01.021 (all data sets are available on the Appendix CD). The data set was selected due to a significant chip count from sieve analysis. Using the same optimization routine from Chapter 3, one hundred pairs of thresholds were used, where the pulse threshold spanned the load maximum to mean, and the reset threshold spanned the load mean to minimum. These thresholds were applied through the PCA. Plots of the complete process can be found on the Appendix CD. The format of the plots can be seen below in Figure 4.1.
The plots contained in the appendix are similar, and differ only in the values used for the threshold lines and the chip count. The optimal threshold for the data set is then selected from the minima of the error surface (Fig 4.2 and 4.3) By inspection, the surface has a valley with similar error values. This allows some flexibility in the optimal threshold. In the following sections the optimal thresholds become more distinct. An approximate optimal threshold pair for set SB01.021 is (2500 lbs, 7500 lbs).

Figure 4.1 LCM load waveform with PCA applied: Yellow lines are thresholds; Horizontal lines are threshold triggers; green lines are force mean and maximum.
Figure 4.2 Contour plot of error surface for single set optimization

Figure 4.3 3-D surface plot of error surface for single set optimization
4.3 Single-Pass Multi-Set Optimization

The process of single-set optimization was applied across an entire pass. A pass includes approximately twenty-four sets. The threshold span was similar to a single set, but instead of using a single set’s minimum, mean, and maximum, the complete pass’s minima, mean, and maximum were used. The error surfaces from all sets contained in the pass were summed. This summation forms a new surface. (Fig. 4.4 and 4.5) Like the individual surfaces, the minima represent the optimal threshold pair. With summation, a more localized minimum can be developed than in Figures 4.2 and 4.3. This error surface is for the SB02 pass. Similar results can be seen for other passes on the Appendix CD. An approximate optimal threshold pair for pass SB02 is (2100 lbs, 7200 lbs). Again, this process does not further the calibration goals of the SmartBit project, but it does verify operation of the optimization algorithm.

Confidence predictions are also included in the optimization routine. The confidence is defined as the square root of the height minima of the error surface divided by sum of all chips produced during the pass. In other words, the root square sum of the least error divided by the ground truth. The confidence for pass SB02 was 81.3%.

\[
\text{Confidence} = \sqrt{\frac{\text{Minimum of Error Surface}}{\text{Physical Chip Count}}} \quad \text{[Eq 4.1]}
\]
Figure 4.4 Contour plot of error surface for single pass optimization

Figure 4.5 3-D surface plot of error surface for single pass optimization
4.4 Multi-Pass Optimization

As in Section 4.3, the PCA and optimization routine were applied to data sets. All sets from the three passes were processed using the same threshold pairs. The threshold spans were based on the mean, minimum, and maximum load values from all sets contained in the three passes. The error surface was calculated in the same root square summation as in Section 4.3 but included all sets from the three passes. The error surface can be seen below with the approximate optimized threshold pair (1350 lbs, 4500 lbs). (Fig 5.6 and 5.7) The confidence associated with the pair is 88.2%.

Figure 4.6 Contour plot of error surface for multi-pass optimization
4.5 Chapter Summary

While threshold pairs and other calculations of the LCM waveforms did not provide direct calibration for the SmartBit sensors, it did test and prove the operation of the calibration routine using the PCA and optimization algorithms. Once the physical implementation of the SmartBit sensor is completed, the same process will be repeated on the data collected from the SmartBit sensor.
CHAPTER 5
DESIGN AND PHYSICAL IMPLEMENTATION
OF THE SMARTBIT SENSOR

5.1 Introduction

The original project goal was the design and implementation of a sensor that could detect the individual health of mechanical excavation cutting implements, as well as being capable of directly monitoring the cutting process. During discussions with industrial sponsors, it became clear that optimization of machine performance is the most important objective for them. The sensor system developed in this research is intended to address all of these issues. The development of the sensor system can be subdivided into two parts: (1) the development of the physical transducer system, and (2) the development of the algorithms and software to interpret the signals received from the transducer. This chapter discusses the three activities involved in the development of the physical sensor: finite element analysis (FEA), radial bit sensor development, and conical bit sensor development. The algorithm, which has been developed for the processing of sensor data, was discussed in the previous chapter.

5.2 Finite Element Analysis (FEA) of Sensor Type and Configuration

As a first step in the design of the sensor system, a finite element analysis (FEA) was conducted to develop an understanding of the sensitivity of the physical structure to the loads being experienced. A model was developed to simulate the bit, block and mounting plate system of a bore miner. The model began as a three dimensional solid CAD model for each of the parts. A finite element mesh was then applied to transform
the model into a representation appropriate for analysis using FEA code. The following figures are the models in their various stages of development. The initial model includes the shank on the bit, which was intended to fit into a slot in the bit block. This proved to greatly complicate the model due to complicated meshing between complex surfaces such as the bit shank and bit block slot and, therefore, was modified. The shank and slot were removed from the model and the bit was attached to the now smooth top of the bit block. While this is a great reduction in the model’s complexity, the effect on the model’s results is negligible due to the location of model measurements.

Figure 5.1 Stages of bit FEA model: a) Solid model, b) Surface mesh.
The locations of possible sensor placement included the legs of the bit block and the bolts of the mounting plate. These areas were selected for the possible stress concentrations and their protection from damage during operation. The stresses/strains derived from the model were an order of magnitude less than the sensitivity of the commercially available strain gauges that were intended for implementation. The
displacement values in the bit block legs were $\sim 10^8$ mm, while a fairly sensitive strain gauge is able to measure in the $10^6$ mm range, using conventional data acquisition electronics. The results of the FEA analyses demonstrated two important results: (1) the location of the sensor would have to be close to the action (i.e., on or near the bit) and (2) the level of strains that are incurred during operation are small and thus the use of strain gauges would present significant challenges. Thus other types of sensors had to be investigated.

Figure 5.4 Bit/Bit Block displacement model.

5.3 Sensor Selection

With strain gauges eliminated from the sensor selection, other sensors types were researched. These included: piezoelectric film, capacitive, accelerometers (Doscher 1995), eddy current, and Hall effect. Piezoelectric film was selected as the most attractive solution. The selection was based primarily on cost and the lack of any required external circuitry. In the case of piezoelectric film, the current cost is very low, $\sim 1$-$4$ per sensor. Also piezoelectric film requires very limited external circuitry. Based upon these qualities, piezoelectric electric film was selected for physical testing and implementation, and ultimately as the final sensor type used in this research.
5.4 Piezoelectric Film Properties

Originally discovered over 100 years ago by the Curie brothers, piezoelectricity is the phenomena of electric charge generation due to deformation of a crystal. This effect was first discovered by mechanically deforming a quartz crystal. The effect also works in reverse; if a quartz crystal is subject to an electric field its dimensions will change.

SmartBit sensors use the piezoelectric film in a strain gauge format. The film behaves as a dynamic strain gauge, which requires no external power source. The sensitivity of these sensors is also much greater than standard strain gauges. However, piezo film’s major limitation is its poor behavior in low frequency applications. This can be overcome with external circuitry, but in the case of SmartBit sensors this is unnecessary due to the algorithm developed for data processing. (Measurement 1999)

5.5 Piezoelectric Film Electric Circuit Model

The piezoelectric film can be modeled as a load dependant voltage source in series with capacitance. (Fig 5.5) When a load such as a measurement device is applied, the circuit forms a divider circuit with high-pass filter characteristics, where the time constant \( \tau \), (in seconds) is equal to the product of resistance \( R \) (in Ohms) and capacitance (in Farads), i.e., \( RC \). The cutoff frequency of the RC high-pass filter is given by the following equation:

\[
\frac{1}{2\pi RC}
\]  

[Eq 5.1]

where, \( R \) is the measurement devices input resistance and \( C \) is the capacitance of the piezo film which is given by the equation,

\[
C = \frac{A}{t}
\]  

[Eq 5.2]
where \( \varepsilon \) is the permittivity of the film, \( A \) is the area of the film’s electrodes, and \( t \) is the film’s thickness. This value can also be verified by direct measurement. Operation below the cutoff frequency will cause the circuit to behave as a differentiator.

A differentiator can be described by the following equations. The voltage across \( C \) is designated as \( V_s - V \) where \( V_s \) is the voltage source and \( V \) is the voltage across the input impedance of the measurement device, therefore,

\[
I = C \frac{d}{dt} (V_s - V) - \frac{V}{R}
\]  

[Eq 5.3]

and if \( dV/dt \ll dV_s/dt \), then

\[
C \frac{dV_s}{dt} - \frac{V}{R}
\]  

[Eq 5.4]

and by solving for \( V \),

\[
V = \frac{V_s}{RC} \frac{d}{dt} \frac{dV_s}{dt}
\]  

[Eq 5.5]

For \( dV/dt \ll dV_s/dt \), the time constant \( \tau = RC \) must be sufficiently small. However, if the load \( R \) is too small it will act as a “short” and ground the signal. In the case of piezo film, it is this issue that is central to many of the implementation difficulties. Therefore, the output (voltage across \( R \)) is proportional to the rate of change of \( V_s \) (piezo film voltage source). This effect can be seen in Figure 5.6. A square wave is input into the circuit and the resulting waveform of \( V \) can be seen. The small spikes are generated by the transitions in the square wave. The loading which the mechanical excavation bit is expected to experience will be similar to a saw-tooth waveform. The effect of a differentiator circuit on a square wave input can be seen in Figure 5.6 and on a
saw tooth wave input in Figure 5.7. Instead of being an infinitely narrow impulse as in the case of a square wave, a wider pulse is output. (Horowitz 1989)

Figure 5.5 Electrical equivalent of piezoelectric film.

Figure 5.6 Square wave input (red) with differentiator output (blue).
5.6 Experimental Verification of Piezoelectric Film Operation

The initial test of the piezoelectric film was completed using a Tinius Olson hydraulic loading machine. The tests were motivated by a need for a controlled experiment to verify the operation of the piezo film. A cyclic loading algorithm was developed in LabView for the tests. The sensor mounting was prepared in different sample forms, with both successful and unsuccessful outcomes, as discussed below. The forms differed only in the mounting of a standardized sensor. The data collected from the tests were subjected to limited processing. The results provided qualitative proof of sensor operation. Primarily, these tests, through trial-and-error, developed the mounting procedures used for SmartBit sensors.

Figure 5.7 Saw tooth wave input (red) with differentiator output (blue).
The algorithm developed by Bryan Walter in LabView controls a proportional hydraulic servo-valve. Using the feedback of a pressure transducer, the pressure in the load cylinder is rapidly cycled between the two set points of the program. These set point pairs need only lie within the linear range of the mechanical components. The loading rate can also be controlled, which is important due to the dynamic loading needs of the piezo-film and measurement circuit pair. This is due to the differentiator behavior inherent in the circuitry.

The data collected from the load tests was processed in a very limited manner using Mathematica routines. The routines cleaned the signals slightly and produced plots of the signal. The data sets of the tests are provided in the appendix CD, but were inspected only for verification of film operation. Qualitatively, the measured response of the piezo film sensors tracked that of the known input from the driver program. Because
the frequency at which the system was driven was below the cutoff frequency of the RC network, the output of the sensor demonstrates the differentiator behavior mentioned previously.

Initially the film was loosely placed between two thin aluminum plates, but the piezo film critically failed before data was collected. This was due to a slight roughness in the aluminum surface. To remedy this flaw, half-inch steel plate was prepared to accept the piezo-film samples. The surfaces of the plate were milled to square each block. The surfaces where the piezo-film was mounted were further prepared using a surface grinder. The piezo-film was glued to the surface as further protection. This proved to be a successful mounting procedure and has been used for full scale bit testing.

Figure 5.9 Piezo film mount.
5.7 **SmartSaddle**

Mounting of the piezo-film in radial bit block hardware was initially viewed as a fairly simple task. However, this assumption was rapidly proven wrong. The preliminary plan was to machine a slot into the bit block. This slot would change the shank hole of the block from a rectangular opening to a T-shaped slot as seen in Figure 5.10. A sandwich of two steel plates and the piezo-film would then be interference fit into this slot. This plan could still be used if full radial cutter head implementation of the sensor occurs. The t-slot sensor-mounting layout is unacceptable for limited laboratory tests due to costs, which arise from the difficulty of modifications of the hardware. This problem was circumvented through the development of a custom LCM saddle. The saddle includes mounting hardware for the piezo-film as well as a rigid shank hole to act as a bit block.

![Figure 5.10 Proposed bit block modification](image)
The saddle is designed as an I-beam welded to a saddle plate. (Fig 5.11) The saddle plate is 1.5” thick plate with mounting holes for the LCM. During operation, the plate transmits the mounting hardware’s load to the LCM’s load cell. The I-beam was built using 6” x 1” steel plate. A slot was milled into the end of the I-beam to act as a shank hole in a bit block. The slot was made larger than a standard shank to accommodate the piezo-film hardware in the form of two steel plates encasing a piezo film sensor. A recess is milled in the I-beam for wiring. Two sections of the 6”x1” plate are used to complete the shank hole. These caps required spacers to increase the slot width to that of a manufactured bit block.

The piezo film, which is sandwiched between two quarter-inch thick plates, is mounted in the front side (nearest side to direction of travel). The film is loaded by a rocking action of the bit, which occurs due to the loose running fit of the bit shank and bit block. While this does not load the film normal to its surface, the interaction provides enough compressive stress on the film for sensor operation.
Figure 5.11 SmartSaddle solid model.

5.8 SmartSleeve

The SmartSleeve mounting hardware uses piezo-film as a thin load washer. The initial concept mock-up can be seen in Figure 5.12. Four thin aluminum plates protect the piezo-film. The center two plates have notches for the leads of the piezo-film. These plates sandwich the film and are glued together. The outer two plates are wear plates for protection. The sensor was tested for operational success with a Tinius Olson machines.
A much more hardened sensor was necessary and was developed late in the writing of this thesis. The concept is similar to the aluminum plate model. A wear sleeve was turned on a lathe to remove a portion of its shoulder. Piezo film was custom fit to the surface and affixed. A custom washer was machined to complete the sensor sandwich. The leads from the sensor are routed through a hole in this washer. The washer is also affixed to the sensor and wear sleeve. Preliminary tests are currently being conducted on this sensor.

5.9 Electronics package
The piezo-film requires ancillary electronics to stabilize the sensor and condition the sensor output. The film’s electrical output is in a measurable voltage range, but the current produced by the film is so low that it causes difficulties in manipulation and input of the signal to data acquisition systems. In addition, the piezo-film tends to build up charge during operation. Both of these problems required a solution before initial tests could begin. The preliminary fix for charge build-up was to place a bleed resistor in parallel with the film to bleed the charge. The film requires a large input impedance (>MΩ) for measurement; if the resistance value is too small then the bleed resistor will
act as a short in the circuit. Therefore, the solution of a simple carbon resistor did not work due to the difficult of obtaining appropriate resistance values. An instrumentation amplifier was proposed as a solution. An Analog Devices AD620 instrumentation amplifier was selected. (AD620 2002) The amplifier is used at unity gain, and, therefore, acts only as a buffer to condition the signal and act as a bleed resistor. Amplifiers tend to be described as having infinite input impedance, and in the case of most circuits this is true. The AD620 has low input impedance compared to most operational amplifiers. The AD620 has a 10 GΩ where as other amplifiers may have orders of magnitude greater input impedance. This can be viewed as a limitation of the amp, but in this application is an advantage. The input impedance of the amp acts as a bleed resistor in the sensor circuit. The other effect of the amp is to increase the current of the signal to allow easier integration with other hardware.

Using the known components of the sensor, a wiring diagram (Fig 5.13) and equivalent circuit (Fig 5.14) were developed. The equivalent circuit is identical to the circuit presented in Section 5.5 where C is the piezo film’s capacitance (1.3 nF) and R is the AD620’s input impedance (10 GΩ). Using Equation 5.1, the cutoff frequency is 0.012 Hz. The decay (roll off) of the signal is described by a first order system with a time constant of \( \tau = RC = 13 \) s. This decay was experimentally verified using the setup described in Section 5.6. The output from the amp after a single loading of the sensor can be seen in Figure 5.15. The time constant is estimated by the time at which the signal has decayed to 37% of its original value. A time constant of .72 seconds has been estimated. Therefore, the estimated cutoff frequency is .22 Hz. The difference between theoretical and actual is a factor of twenty. The difference is believed to be due to inaccuracies in the value of the AD620’s input impedance.
Figure 5.13 Amplifier wiring diagram.

Figure 5.14 Equivalent circuit.
5.10 Full-Scale Bit Tests

Full-scale bit tests were performed using EMI’s Linear Cutting Machine (LCM). The rock sample was a red sandstone. The operation and description of the LCM are included in Chapter 2. Data was only collected using the LCM’s load cell for most passes. One pass of data was collected using both the LCM’s load cell and the SmartSaddle piezo film output. This data set (SB05) lacks physical chip count data, however. A review of this data set is included in Chapter 6.

5.11 Sieve analysis

Physical data was required to calibrate the Pulse Count Algorithm (PCA) that is discussed in Chapter 3. This data consisted of counts of the physical chips collected from each pass. The cuttings were collected and analyzed using sieves sizes: 1.000”, 0.750”, 0.500”, 0.371”, 0.0930”, and 0.0232”. After the weight distribution was tabulated, a
count of the chips was performed on the top four sieves. The count for each tray was divided into two categories. The separation of the chips into two categories was based on the presence of any yellow marking on the rock sample, since yellow paint is used to identify the beginning and end of the inlaid rock sample. The removal of the edge data is standard in the LCM tests to provide in-rock-cutting data only. However for these tests, the edge data was allowed so as to provide more chipping information as well as information on the material boundary. Thus, the category separation was not used, and, therefore, the chip count used in the PCA is the sum of the two categories.

4.12 Chapter Summary

Presently, SmartBit prototypes, based on piezoelectric sensors, exist for both radial and conical bit types. The sensors require further work before implementation in-situ can occur. This work includes sensor hardening and calibration. Using the methods from above initial sensor calibration routines have also been developed and will be discussed in Chapter 6.
6.1 Thesis Objectives

A literature search of mechanical excavation instrumentation showed very little prior art. The search did reveal two laboratories focused on the topic, the Earth Mechanics Institute (EMI) and USBM Twin Cities Coal Cutting Facilities. All equipment at both facilities had little relevance to SmartBit sensors, because it is laboratory equipment and is impracticable in-situ. The USBM also developed an in-situ measurement device, but it lacked the real-time capabilities necessary for machine performance monitoring. Cross discipline machine monitoring techniques were also explored with little success. The lack of prior art forced the development of novel monitoring techniques.

After traditional machine monitoring techniques, such as Fourier analysis, failed to reveal bit/rock interface information from load cell data acquired with the Linear Cutting Machine (LCM), a processing technique was developed. The Pulse Count Algorithm (PCA) through the use thresholds was able to predict the formation of chips at the bit/rock interface. This prediction can be made with a >80% confidence. Presently, the PCA has only been applied to LCM load waveforms, but custom SmartBit sensors will produce data in later tests to be processed by the PCA.

Presently, SmartBit prototypes, based on piezoelectric sensors, exist for both radial and conical bit types. The sensor selection was based on Finite Element Analysis
This analysis directed the sensor selection towards ultra strain sensitive sensors due to the FEA model’s strain measurements of \( \sim 10^{-8} \text{mm} \), which is two orders of magnitude less than the sensitivity of commercially available strain gauges. Piezoelectric film was selected as the sensor. The film behaves as a \textit{dynamic} strain gauge, which requires no external power source. Laboratory prototypes have been constructed and are being tested at the time of the writing of this thesis.

The work reported in this thesis demonstrates that a piezo film sensor in conjunction with the proper algorithms can predict the occurrence of chip formation and the size of chip being produced as a bit is drawn through rock. This system, if it proves to be robust in an operational environment should be the basis for several new and exciting developments for mechanized mining.

\section*{6.2 Future Studies and Recommendations}

The future studies for SmartBit sensors primarily will be implementation and hardening of the sensor. Calibration for both conical and radial SmartBit sensors using piezo film data will be required. Also before in-situ tests can begin the device must pass MSHA (Mine Safety and Health Administration) inspection. This inspection tests the safety of the device for use in gaseous mines. As the sensor reaches a final design state more complex sensing capabilities will be explored.

\subsection*{6.2.1 Radial SmartBit Calibration}

Presently, calibration routines have only been run using LCM load cell data. The radial SmartBit sensor has been tested in sandstone samples but not calibrated. The output waveform of the piezo film can be seen below. (Fig. 6.1) The differentiator behavior is easily seen when compared to the LCM load cell data for the same cut. (Fig. 6.2) Large spikes occur in the piezo film data sets when the large unloads are seen on the LCM data. This comparison supports the theoretical differentiator behavior as discussed
in Chapter 3. Calibration of the sensor will include multiple rock types, bit spacings, and penetration depths. This will allow the PCA to sense chip formation under various cutting situations.

Figure 6.1 Piezo film data from prototype radial SmartBit sensor

Figure 6.2 LCM load cell data from prototype radial SmartBit sensors (same cut as in Fig. 6.1)
6.2.2 Conical SmartBit Prototype Completion

The conical SmartBit sensor will be implemented on site in the coming year. The sensor needs to be fully hardened before the installation. Prototypes are being developed and will undergo LCM testing for operation and calibration. Cyclic load tests will also be performed.

6.2.3 Conical SmartBit Calibration

After the completion of the conical SmartBit development, calibration of the sensor will take place. The expected behavior is similar to the radial SmartBit sensor, only differing in the magnitude of the output. The magnitude is predicted to be greater due to increase sensor size and more direct loading of the sensor due to geometry.

6.2.4 MSHA Intrinsically Safe Designation for Conical SmartBit Sensor

Before in-situ testing can occur, the device must be designated “intrinsically safe” by Mine Safety and Health Association (MSHA 1995). “Intrinsically safe” designation for piezo film applications is defined as a maximum energy allowed (Eq 6.1), where $C$ is the film’s capacitance and $V$ is the maximum output voltage from an impact. A two kilogram steel rod dropped from a height of one meter provides the impact energy of 19.6J. The maximum allowed energy output for an intrinsically safe piezoelectric device is 1500 $\mu$J. From preliminary tests our sensors have a safety factor of 10-20.

$$E = \frac{1}{2} CV^2$$  \hspace{1cm} [Eq 6.1]

6.2.5 Contact Sensing

A possible application for the SmartBit sensor would be the detection of rock type change. If the rock types have distinctly different cuttabilities, SmartBit sensors should be able to detect that change. Preliminary observation shows that detection is possible. For example, the sandstone used in preliminary tests was cast in concrete. The concrete
is much easier to cut than the sandstone. In Figure 6.2, the first ~6 inches of data is from cutting in the concrete. The magnitude of the load cell sensor response is much less in the concrete than after the bit enters the sandstone. The piezo film data also shows this event. The first large spike in the data corresponds to the first sandstone chip produced during the cut. Later studies may include multiple rock types in a pass during full-scale bit tests.

6.2.6 Bit Health Monitoring

In a manner similar to contact sensing, bit health can be monitored by observation of the maximum loads. As a bit wears the forces it experience increase in magnitude. (Roepke, 1983) Therefore, as the bit is worn it should produce fewer large chips and experience a higher average load. This monitoring can be done using thresholds, either by monitoring the increased average force or perhaps more easily by monitoring the number of chips being produced.
REFERENCES CITED


Ozdemir, L. (2000). Fall 2000 class notes


APPENDIX

GUIDE TO APPENDIX CD

The appendix CD contains the following files:

Mathematica Notebooks

<table>
<thead>
<tr>
<th>Notebook</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCMdataprocess</td>
<td>Initial processing of LCM load cell data using Fourier analysis. Includes data input code.</td>
</tr>
<tr>
<td>PCAFit</td>
<td>Development of Pulse Count Algorithm (PCA).</td>
</tr>
<tr>
<td>SingleSetDrag</td>
<td>Complete processing of single set or cut of data for drag force on a radial bit.</td>
</tr>
<tr>
<td>SingleSetNormal</td>
<td>Complete processing of single set or cut of data for normal force on a radial bit.</td>
</tr>
<tr>
<td>SinglePassDrag</td>
<td>Common threshold processing for drag force on a radial bit using a single pass’s data sets.</td>
</tr>
<tr>
<td>SinglePassRad1</td>
<td>Common threshold processing for normal force on a radial bit using a single pass’s data sets. (SB01 data set)</td>
</tr>
<tr>
<td>SinglePassRad2</td>
<td>Common threshold processing for normal force on a radial bit using a single pass’s data sets. (SB02 data set)</td>
</tr>
</tbody>
</table>
SinglePassRad3: Common threshold processing for normal force on a radial bit using a single pass’s data sets. (SB03 data set)

SinglePassCon1: Common threshold processing for normal force on a conical bit using a single pass’s data sets. (SC01 data set)

SinglePassCon2: Common threshold processing for normal force on a conical bit using a single pass’s data sets. (SC02 data set)

MultiPassRadNorm: Common threshold processing for normal force on a radial bit using all data sets.

MultiPassConNorm: Common threshold processing for normal force on a conical bit using all data sets.

MultiPassConDrag: Common threshold processing for normal force on a conical bit using all data sets.

Data Sets
SmartBit (Conical): LCM load cell data from conical bit.

SmartBit (Radial): LCM load cell data from radial bit.

SmartSaddle: LCM load cell data and Piezo Film data from SmartSaddle.

Solid Models
Block: Solid model of bit block.
Blockwohole: Solid model of simplified bit block with hole removed.

Bit: Solid model of bit block.

Bitwoshank: Solid model of simplified bit with shank removed

Electronic Thesis: Complete electronic copy of thesis