A Smart Disc Cutter Monitoring System Using Cutter Instrumentation Technology

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ABSTRACT

Current disc cutter instrumentation technology is designed to be a conveniently mounted instrumentation package that monitors individual cutter rpm, wear, temperature, and vibration. A data logger service receives the cutter information wirelessly using low-power radio technology and displays cutter conditions in real time. With cutter instrumentation, the operator continuously monitors cutter conditions, which results in higher efficiency, lower incidence of down time, and prevents unexpected ring wear-related damage from causing further damage to bearings and hubs. Cutter instrumentation technology has been tested on Robbins' rock machines and results from previous and recent projects are presented. Design improvements for longer lifetime and increased reliability are discussed.

WHY CUTTER INSTRUMENTATION?

In mechanized tunneling continuous information from the excavation face is essential. The ultimate goals of cutter instrumentation are to monitor real-time individual cutter operation, acquire more realistic cutterhead thrust force values, and gain a better knowledge of the geology in front of the cutterhead. Analysis of this information can provide in-depth knowledge of machine excavation. Information about cutter operation has direct and indirect advantages: It helps better predict and monitor cutter usage rates, and it can reduce the cost of unplanned cutter or ring replacement, which can result in a better planning of inventory, manpower, and cutter rebuild requirements. Another merit of cutter instrumentation is to maintain assembly health by monitoring individual cutter operation. An instrumentation system can notify an operator of uneven or harsh ring wear and makes it possible to prevent unnecessary seal or bearing changes. Additionally, it can prevent cutterhead damage caused by a late cutter change (see Figure 1).

HISTORY

Instrumentation at Robbins has about 25 years of history, which can be divided into two period: the time before 2007 and after 2007. In the late 1980s a cutter instrumentation system was developed in-house and installed on a few projects such as Svartisen



Figure 1. (A) Wiped out cutter wear; (B) damaged bearing; (C) face of excavation



Figure 2. Niagara Machine first attempt (2008)

in Norway. The cutter monitoring system provided two main functions, consisting of cutter load measurement and cutter rpm. A magnetic sensor was installed along with a strain sensor in the cutter housing and a small permanent magnet was pressed into a hole in each cutter hub. The strain measurements and cutter rpm on individual cutter housings were read, amplified, converted to a digital signal, and transmitted to a computer where they were recorded. This information was logged as history of the rock formation type and homogeneity. Load and wear could be combined to better predict usage rates versus penetration to plan inventory and cutter rebuild requirements. The actual cutter instrument on the cutter housing was wired to a junction box and then to the data acquisition computer (DAQ) through hydraulic hoses. A slip ring was used to transfer data from the DAQ to the operator cabin, which couldn't accommodate continuous data collection. However, a fair amount of data was recorded to determine cutter force in different materials. In the 1980s and 1990s several projects implemented the systems. In 1993, Robbins mobile miners were instrumented with strain gages and DAQ and monitored cutting action and forces. The issue of interrupted and short time data collection remained the major obstacle until early 2000s when the idea of wireless transmission was developed with available technologies. The new wireless configuration was successfully tested later in 2007.

During an experiment in 2007, successful radio communication was established with a radio transducer and a receiver. Further in 2008, in an attempt to read cutter rotation, one instrument was built and installed in the Niagara TBM-a 14.4 m diameter open type, hard rock machine and the largest in the world of its type. The instrument was installed in the cutter housing and mounted to the wedge bolt. The system survived for a short period of time and provided spotty cutter speed data (See Figure 2). In 2009, an attempt at resolving the data readings problem led to the design of a new instrument prototype. In the same year five of those instruments were welded to cutter housings of a 12.4 m diameter open type hard rock machine for China's Jinping-II Hydropower project. This effort improved the system and outlined the outstanding issues. The welded mounting was not convenient for field staff, instrumentation enclosure worn out quickly, and the readings were spotty. As a result, the wedge bolt mounting option was selected as the most reliable design that maintained a good life for the enclosure. Furthermore a stainless steel sleeve was used to cover the plastic enclosure to prevent abrasive material from damaging the instrument. Between 2010 and 2012 the Niagara TBM, as well as three more open-type TBMs for Malaysia's Pahang-Selangor Water Tunnel, were equipped with the new prototype. Cutterhead speed was entered manually to calculate the cutter wear on the Niagara TBM (See Figure 3a) and later acquired from the PLC in Malaysia (See Figure 3b). Longer survivability of the instrument along with better radio communication was a turning point in the prototype design. The cutter instrumentation issues were alleviated to a certain extent and the enclosure survived longer than previous prototypes. However some issued remained.



Figure 3. (A) Niagara second attempt (2010); (B) Malaysia Pahang-Selangor (2012)

Cutter speed measurements in Niagara were clearly correlated with the locations showing a decrease in speed from the gage toward the center. In Malaysia the cutter speed was fluctuating within 5 rpm and not enough data was available to analyze and smooth the data. Wear results were fluctuating within a 25mm (~1in) boundary. Although the wear measurements were not satisfactory, it was helpful to demonstrate that cutter speed was in the correct range. A computer screen was developed as an interface to control the operation (see Figure 4).

In 2014 after some design improvements on SmartCutter, 10 instruments were installed on the cutter housing wedge bolt and transmitted data for less than a month at Norway's Røssåga project (1.5 hours data is shown in Figure 5). Battery capacity was insufficient to provide longer data collection. Cutter data such as speed, wear, temperature, peak vibrations, instrument status, and battery status was displayed on the operator cabin interface. The magnets that were installed in the cutter hub were used to detect rotation. As the hub wore out the magnet occasionally fell out, which was also an issue during previous projects, and at Røssåga a few magnets failed during mining and caused issues with cutter speed. Wear values were not compared to the job site measurements to confirm the accuracy.

In 2016, a longer test was undertaken at the AMR project in India after making some critical technical improvements on the new prototype called SmartCutter to assure the reliability of the system. The previous battery was replaced with a higher capacity version. The magnet installation process was changed by using a special potting technique to secure the magnet from falling out due to wear or vibration induced breakage. Sealant was used on the enclosure that protects the instrumentation board and



Figure 4. Røssåga TBM, Norway—SmartCutter data analysis (2014)



Figure 5. Malaysia Pahang-Selangor operator SmartCutter display

battery from moist, mud, and water infiltration. Five instrument units were installed on the cutterhead and two receivers were mounted in the shield. A field service person was assigned to commission the system and monitor its operation.

AMR Double Shield Hard Rock TBM

The AMR cutterhead diameter is 10.0 meters with a total of 70 cutter positions. Five instruments (SC1 to SC5) were initially installed at the gage area in position 60 to 64. Throughout July, August, and September 2016, the location of these cutters changed from the gage area to the face area as the cutters were moved inward to positions where the allowable cutter wear is greater. To take an in-depth look into the wear patterns and data evaluation, two sets of data analysis were designed: a micro analysis that investigated short report timing and a macro analysis that provided overall trends throughout a cutter's wear life.

Figure 6a shows the AMR SmartCutter system diagram. Each instrumentation box was installed on the wedge bolt of the cutter housing. Two gateways were installed on the structure of the machine conveyor (See Figure 6b). Two gateways ensured the communication link was maintained at all times. In the event of a loss of communication the



Figure 6. AMR project (2016) (A) system diagram; (B) equipment installation; (C) test monitoring platform

operator was alerted on the monitor with a red alarm (See Figure 6c). The instrumentation battery capacity was increased beyond the normal cutter wear life, meaning that instrumentation could operate throughout one or more cutter changes. Additionally, the battery capacity and status was continuously reported and displayed on each instrument at the operator screen.

AMR Speed and Wear Analysis

The magnetic sensor inside the instrument enclosure senses the time of each cutter revolution in milliseconds and reports the cutter speed (ω_{DC}). Knowing the disc cutter radius, the cutter's distance from the cutterhead center line, and also the cutterhead speed (ω_{CHD}), one can derive the cutter speed. Now using the same correlation and knowing the ω_{DC} , the cutter radius, hence its wear, can be calculated. Defining a reasonable sampling and radio data transfer rate is critical to generating meaningful data. At the same time a data filtering algorithm is required for representative and accurate wear calculation.

Figure 7 shows eight minutes of unfiltered data for a single cutter. In this plot anticipated cutter speed at a certain amount of wear and instant ω_{CHD} are presented. ω_{DC} of both a brand new disc and a worn out disc are shown in orange and black dashed lines, respectively. The blue line represents the anticipated ω_{DC} at 20mm wear. The ω_{DC} reading is shown in green dots. This value is calculated from reported cutter



Figure 7. Eight minutes of unfiltered SmartCutter data from AMR (micro analysis)



Figure 8. SmartCutter wear reading in comparison to job site measurements for SC1

complete revolution time. In a normal cutter operation ω_{DC} is expected to remain between anticipated minimum and maximum anticipated cutter speed. From this figure one can determine that the highest speed that has the majority of the data represents the normal speed in which the cutter is rolling without interruption. If there are any hiccups where less than true rolling occurs, a reduction in ω_{DC} is to be expected. The cutter wear is calculated from ω_{DC} and is plotted in the red line. ω_{DC} perfectly correlates with the changes in ω_{CHD} at every step between 9:59 to 10:01 as it was expected.

Because cutter radius from the cutterhead center is about 20 times larger than a 20 inch cutter radius at the last gage location, a small change in ω_{CHD} can have large influence in the wear calculation. Even the second decimal of the ω_{CHD} number have influence. Although wear values showed the same trends as the jobsite measurements, an offset was observed initially. It was believed that the gap was inherited from the ω_{CHD} degree of accuracy at AMR TBM. With applying 1.03 factor in ω_{CHD} wear, the offset was resolved. Using an encoder on the drive in this particular project can increase ω_{CHD} accuracy.

Figures 8 and 9 shows the wear results of all five SmartCutters after increasing the ω_{CHD} by 1.03. The Cutter relocation is also displayed on these plots. This macro analysis shows a very close correlation of SmartCutter average wear values and the actual field measurements on the cutters, especially within the bold increases in wear (i.e. Figures 8 and 9c).









Figure 9. SmartCutter wear reading in comparison to job site measurements for SC2 to SC5

Figure 9d shows an error, which means although sensor status was correct the rotation was not measured quite satisfactorily. This is the result of interruption in cutter rolling (i.e. an uneven cutter ring wear), which caused longer revolution time and consequently lower wear values. In such conditions an error is displayed to alert the operator regarding ω_{DC} and the program will only post the maximum previous wear. The latest cutter disc radius is used to plot and display the anticipated ω_{DC} and the operator can review ω_{DC} timeline and locate when the problem starts (in this case 8/22/16). Figure 9a shows an alert that informs the operator that the cutter is close to the maximum wear. Operators can set certain wear limits for each cutter in the program alert setting. In many cases alerts can prevent unexpected cutter ring wear-related issues from causing further damage to bearings and hubs.

AMR Temperature and Vibration Analysis

The cutter instrumentation system constantly monitors the cutter assembly's temperature and displays it on the operator's screen. The main purpose of recording this parameter is to scan the cutter assembly function and identify abnormal ring temperature. In highly abrasive geologies or high strength rock material, disc cutter ring temperature will ramp up. This can cause higher wear and, if it passes the lubrication boiling temperature, it can cause bearing damage. In extreme cases it can result in seal failure due to rapid increase in internal pressure. Board temperature is also shown to confirm that in the current design the electrical board and battery is kept at a low enough temperature to maintain reliable performance. Additionally, this information can be coupled with other cutter parameters and provide an insight into cutter operation. Figure 10a shows the temperature of a brand new cutter throughout several mining periods during one day. During cutterhead standstill natural ground temperature can be observed (i.e. time 3:00 to 5:00 and 9:00 to 12:00). This plot shows that the temperature of the brand new cutter was high in the beginning (125°C) and decreases gradually. One possible explanation is that the cutter experiences high stress at the brand new cutter rounded tip corner at the gage area and as it wears for a few millimeters, the stress reduces and temperature drops under 100°C. Figure 10b also confirms it by correlating wear and temperature in macro analysis within successive days of excavation. In this plot the blue dash line shows the wear. Temperature is shown with a maximum, minimum line, and average values in green dashed line.

The wireless radio technology that is used in the SmartCutter configuration provides some limited bandwidth for data transmission. The accelerometer used in the SmartCutter reports acceleration in the X, Y, and Z direction as well as the peak acceleration. The time domain analysis of these data can provide some insight into cutting action and the geology in front of the machine. However, for distinguishing ground characteristics, frequency domain analysis will be essential, which requires an enormous amount of data to be transmitted and processed. Excavation propagates a certain range of vibration that is influenced by cutting action, cutter assembly mechanism, disc cutter ring condition, geology, and other machine noises. The hidden dimension is the power and frequency of all individual parameters. For instance, one can claim that geology-related vibration frequencies vary with material type or changing conditions within identical geologies. Figure 11 shows a time domain macro analysis on average of peak acceleration perpendicular to cutting surface within a homogeneous geology. It is very clear from this plot that as the cutter wears out the acceleration drops down gradually. Although frequency domain analysis is believed to reveal useful information on geology and cutting pattern, it is not included in the current SmartCutter package.



Figure 10. SC1 cutter temperature (A) during one day of mining; (B) during continuous days of mining



Figure 11. SC1 peak vibration in comparison with cutter wear within continuous days of operation

Future Development

The SmartCutter system has been successfully tested on several projects and the results from the AMR project have been discussed in this paper. Cutter instrumentation for other Robbins products is presently under development.

SmartCutter Version I is currently capable of measuring and recording cutter speed, wear, temperature, and vibration. A separate user-oriented screen with alerting system is designated to control the operation. The alert system can take a step forward and communicate with the PLC to reduce the TBM thrust, in case of a continuous abnormal cutter force report or identified higher strength ground through vibration. In some geologies SmartCutter can be programmed to control the cutterhead speed and thrust to achieve highest cutter production.

Lighter instrumentation, ease of installation, and longer life will lead to the SmartCutter version II design consideration. Cutter positioning sensors and strain gages are additional instruments under the design and testing phase for the next generation. As discussed earlier in this paper, about a quarter century ago Robbins tested cutters with strain gages on several projects. The results of the future testing and historical data will be presented in a separate paper. An alternative communication system is also under development to provide communication in pressurized conditions.