

# Cutter Instrumentation System for Tunnel Boring Machines

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**ABSTRACT:** Installing instruments on TBM cutters increases the efficiency of boring and improves cutter life. The benefits of an instrumentation system and findings from field tests will be presented. Instrumentation systems allow the operator to view in real-time how adjusting operating parameters dynamically impacts the cutting environment. By analyzing vibration data, cutter rpm, and cutter temperature, it is possible to infer the rock face condition and how it is affecting cutter operation. Knowing these data provides the operator an indication of cutter wear without entering the cutterhead to inspect the cutters and also alerts the operator to any abnormal cutter conditions.

## OVERVIEW

Since the advent of tunnel boring machines, operators and manufacturers of these machines have desired to know how the cutting device interacts with the material being bored. With this information, an operator can achieve maximum efficiency of the tunnel boring operation by varying the operating conditions of the machine. Costly delays due to cutter failures can be avoided by monitoring boring conditions in real-time.

Additionally, cutter manufacturers can adjust the design of components based on this data. Previous attempts at measuring cutter conditions have included theoretical mathematical models, simple force measurement devices, and inference of the interactions through ancillary evidence provided by operating conditions of the machine itself.

## HISTORY

Attempts have been made in the past to obtain some data about the loads and characteristics of a cutter operating on mechanical excavation machines. Strain gages have been placed inside the shafts of cutters, with the deflections measured and equated to a force acting on the cutter. Wireless transmitters have been installed on cutters, which would only be powered while the cutter is turning. With this system, when no signal is detected from the device, it can be inferred that the cutter is not rotating.

Most of the cutter information becomes available only after the machine has finished its boring stroke and the cutter inspection crew enters the cutterhead to check the cutters. Therefore, no immediate remediation of undesirable cutter conditions is possible while the machine is boring because there is no

real-time information available. When damaged cutters are found, the inspection crew can only speculate on when the damage occurred—not only in reference to the time it occurred, but also at what point in the cutterhead rotation the damage happened.

## NEW SYSTEM

Previous efforts to instrument cutters have offered the operator limited data, but to date, no comprehensive approach to placing instruments on cutters has been attempted. It is not feasible to run electrical cables to each cutter to relay the signals, which has precluded the operation of electrical instruments on cutters.

The Robbins Company has developed a patent-pending wireless instrumentation system designed to provide the TBM operator with the most complete idea of cutter performance ever available. With the advances made in wireless technology within the last several years, it has become possible to create a network of wireless devices, with one installed on each cutter. Packages consisting of measurement devices, a power source, and a wireless transmitter housed in a protective case can be installed in each cutter housing to detect the specific operating characteristics of each cutter (see Figure 1).

## Cutter System Components

The instrumentation system consists of the components described below.

### *Cutter Sensor*

Each cutter is fitted with an electronic sensor and a bracket meant to fix the sensor in close proximity to the cutter. The cutter sensor consists of a power

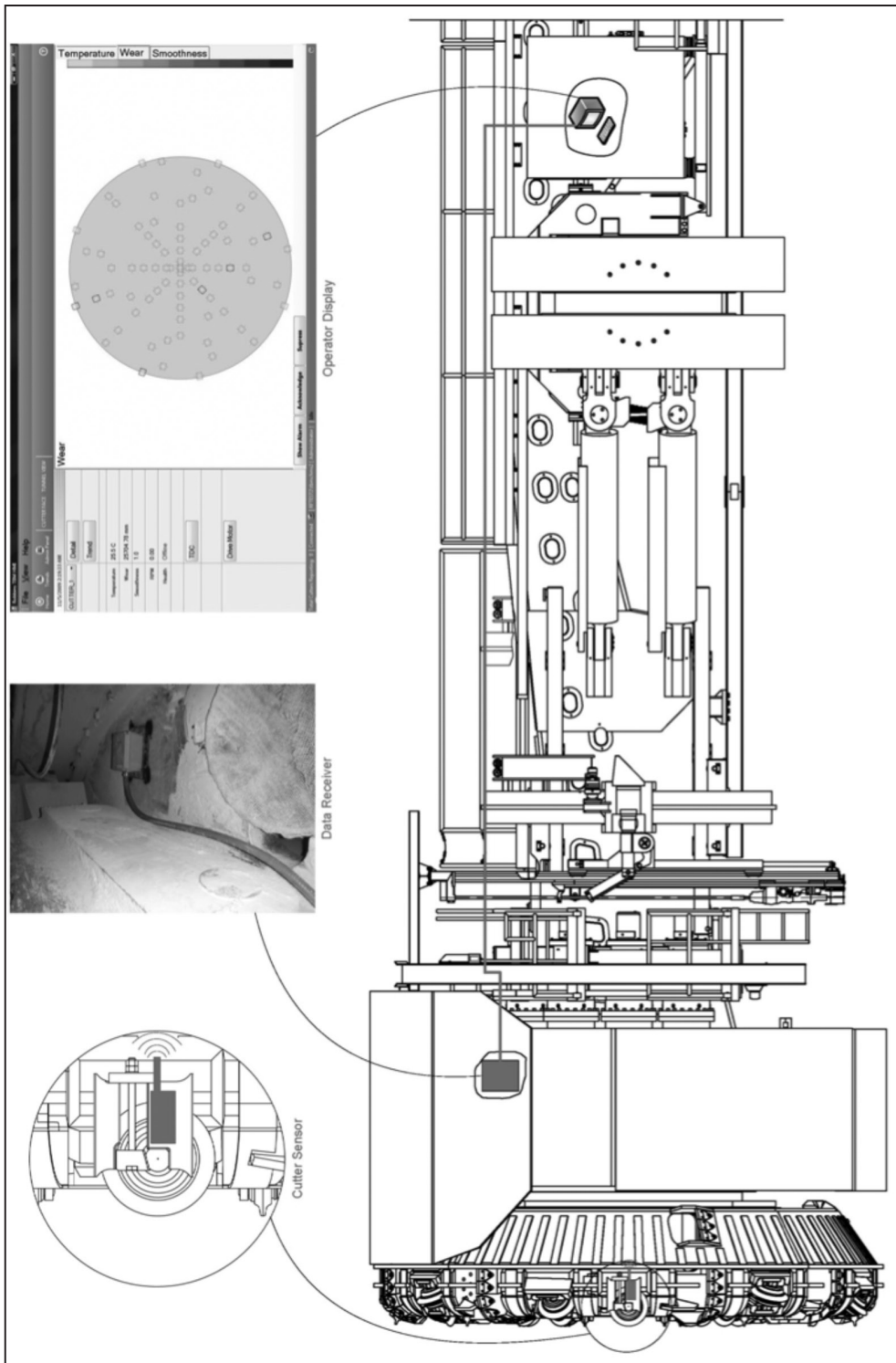


Figure 1. Instrumentation system schematic

source, measurement devices, a processor, and a wireless transmitter. The power source could be batteries or even a small motion-activated electrical generator. The measurement devices on the current generation of sensors include accelerometers, rotational sensors, and temperature sensors. Expanding the suite of sensors in the devices is an option, with inclusion of a camera and microphone as possible enhancements.

The processor is downloaded with operating parameters which can be adjusted for optimal data collection. The processor polls the measurement devices for data at a pre-defined sample rate and then prepares the data for transmission. The wireless transmitter takes the encoded data from the processor and emits an electro-magnetic wave containing the encoded data.

### **Data Receiver**

The data receiver is mounted in a protective housing and installed behind the cutterhead. The receiver detects and processes the transmissions emitted from the cutter sensor. The data receiver contains a processor that is programmed with the same information as the cutter sensors and so is able to detect and process the signal from each cutter sensor. The receiver then takes the received data and transmits it to the operators display computer either over wire or wirelessly.

### **Operator Display**

The operators display takes the data relayed from the data receiver and presents it in a manner which allows the operator to identify the cutter operational parameters currently of interest. The data is available in several formats. A chart with a column for each cutter can display the data of interest for all cutters at once. Additionally, a graphical image of the cutterhead, with cutter locations noted, can flag cutters which are operating outside a pre-established safety range. A touch screen is used for the display, allowing the operator to touch the cutter that is flagging for an anomalous condition and read the data values causing the alarms directly.

### **Database**

The computer running the operator's display keeps an archive of all information received on a local database. The database is searchable for historical data, and data can be displayed in several formats, including graphically or in a table. The database can also be accessed remotely if the computer has an internet connection. This setup makes it possible to monitor the cutter performance without traveling to the jobsite.

## **Machine System Components**

In addition to the information provided by the sensors installed on the cutters, some machine operating data needs to be collected to correlate the data from the cutter sensors. In particular, the head rpm and some type of reference point on the cutterhead must be known in order to identify where a particular cutter is located on the cutter face at any given time. For a machine with variable frequency drives (VFDs), the rpm of the cutterhead can be calculated by getting the motor speed from the VFD and the gear ratios of the motor to cutterhead interface. The reference point is still needed even if tying in to the VFDs, because the head rpm alone cannot identify how far along in one rotation of the cutterhead the cutter has traveled.

## **DATA**

Various sensors can be included in a cutter sensor to detect physical characteristics helpful to cutter operations. Data applicable to cutters operating on a tunnel boring machine includes rotational data, vibration data, and temperature.

### **Rotational Data**

Knowing the cutter rpm provides an indication of how smoothly the cutters are performing. Rotational data can be used to detect cutter conditions but can also be used to infer the conditions of the rock face. A constant cutter rpm indicates that the cutter bearings and seals are functioning properly, and also indicates that the rock being bored is competent and without major variations. A variable rpm provides a warning to the operator of many possible undesirable situations, including a locked-up cutter, improper machine thrust, or blocky ground.

By measuring the rotational speed of a cutter and knowing at what distance away from the axis of the cutterhead a cutter is located, along with knowing the cutterhead rpm, the diameter of the disc ring can be calculated:

$$D = \frac{2rd}{R}$$

where

$D$  = disc ring diameter

$r$  = cutterhead rpm

$d$  = distance to the cutter from the center of the cutterhead

$R$  = cutter rpm

### **Vibration Data**

By measuring the amount of vibration a cutter is experiencing, some idea of the loading that a cutter is under can be determined. Changes in how much

vibration the cutter is under could indicate a change in the geology, a blocky face, or a possible problem with the cutter, among many other things. With proper filtering, detailed analysis of cutter vibration can reveal such conditions as a bearing being overloaded, mounting system problems, or damaged disc rings.

### Temperature Data

Measuring the temperature of a cutter can provide indications of anomalous operating conditions. If a cutter is blocked and is not rotating, it will show a rapid increase in temperature. The effectiveness of water spray or chemical spray systems intended to cool the cutters can be tested by measuring cutter temperature in real-time.

### BENEFITS

There are many benefits to installing sensors on cutters. In general, with an instrumentation system, it is now possible for machine operators to obtain a true picture of how the cutters are operating in real-time and how changes in machine operating parameters affect the cutters.

### Identify Problems Before Failure

If an anomalous condition is detected on a cutter, the operator will be notified of the condition immediately, and proper action can be taken before the anomaly can lead to a failure. Some of the anomalies which could arise and would be detected by the instrumentation system include a non-turning or intermittently turning cutter, high vibration shocks, and high temperatures.

A non-rolling cutter could indicate a problem with the cutter bearings, which would be a very serious problem needing to be addressed immediately. A cutter turning only intermittently could be due to a bearing problem as well, but it could also indicate that there are voids in the face of the rock where the cutter is not contacting any rock. When a void is present, there are fewer cutters to take the machine thrust load, which loads the bearings of the cutters in contact with the face greater than the nominal load. TBMs specify a maximum allowable thrust force, which is often calculated simply as the cutter maximum bearing load multiplied by the number of cutters. If the machine operator is operating at the maximum specified thrust rating and voids are present, the cutters in contact with the face are exceeding their design load limits (see Figure 2).

High vibration shocks could be indicative of a mixed face/blocky face condition and could also indicate that there is debris in the invert of the tunnel. A shock would occur every time the cutter came back into contact with the rock face after traveling



**Figure 2. Failed cutter bearing**

in a void. If a cutter is seeing a series of vibration shocks and the operator can identify where in the cutterhead rotation this is occurring, the options for what may be causing the shocks can be narrowed and fewer options for remediation would need to be considered.

High temperatures on one cutter would indicate a problem with that specific cutter and, if severe enough, the machine could be stopped and the cutter inspected before failure occurs. If all cutters show a temperature approximately equal and not elevated, then no problems with the cutters are indicated. Also, the effectiveness of any water or chemicals sprayed in front of the head, for instance to reduce wear or cool the cutters, while monitoring the cutters in real-time, can be evaluated as it is being sprayed on the face through real-time monitoring.

### Improved Cutter Life

When a TBM is operating, it is often difficult to tell how efficiently the excavation is being performed. TBMs are very solidly supported in the tunnel while boring, so it can be difficult to tell from the machine reactions how well the rock fracturing process is being accomplished. Looking at the rock chips being formed can help indicate how well the cutters are performing, but it does not provide the complete picture that is possible with an instrumentation system.

Tunnel boring machines usually have enough power installed that the cutterhead will turn no matter how efficiently the rock chipping is performed—non-rotating cutters will not cause enough drag force on the cutterhead rotation to stop the cutterhead. By receiving real-time information about the cutting environment, the machine operator can be alerted

to any anomalous situations and also adjust the head rpm and machine thrust to achieve the ideal operational envelope.

### Fewer Cutter Inspections

Disc ring wear is the most common reason for replacing cutters. Maintenance crews spend a portion of their shift in the cutterhead or in front of the machine measuring the wear on each cutter. Cutter inspections are usually a daily occurrence while boring, with each cutter's disc wear measured and recorded.

As described previously, when real-time cutter rotational speed data is available, the diameter of the cutter's disc ring can be calculated. Knowing the disc ring wear in real-time while boring allows the operator to eliminate some cutter inspections. Fewer cutter inspections means the machine has more available time to bore. Additionally, on machines employing cutters that are loaded on the head from the front of the machine, fewer cutter inspections means that the maintenance crews spend less time in front of the machine, where they are exposed to an unsupported section of tunnel. This reduces the risks to workers when the geology of a tunnel is unstable and rock cave-ins or collapses are possible.

### Stop Wipe Outs

When one cutter gets blocked and stops rotating, it leads to a higher load on adjacent cutters, with a possibility of a cascading failure (wipe out) of all the cutters in the worst cases. Wipe outs are costly both because of the damaged cutter components and because of the time needed to replace all of the failed cutters. Severe wipe outs can also cause damage on the cutterhead, which could possibly require extensive head repairs. With the real-time rotational data, an operator can be notified immediately when a cutter stops rotating (see Figure 3).

## CHALLENGES

As with any new technology, challenges to fully realizing the potential of the invention will arise during the development and testing phases. Installing electronic instruments in a cutter housing, ensuring that the instruments can survive the rugged tunneling environment, and maintaining signal transmission and receipt are some of the specific challenges experienced when developing the cutter instrumentation system.

### Installation of Instruments

There is a certain minimum size of protective enclosure which must be designed to house the electronics of the instruments. Finding a location on the cutter housing to install the sensor while keeping the device



**Figure 3. Non-rotating cutter damage**

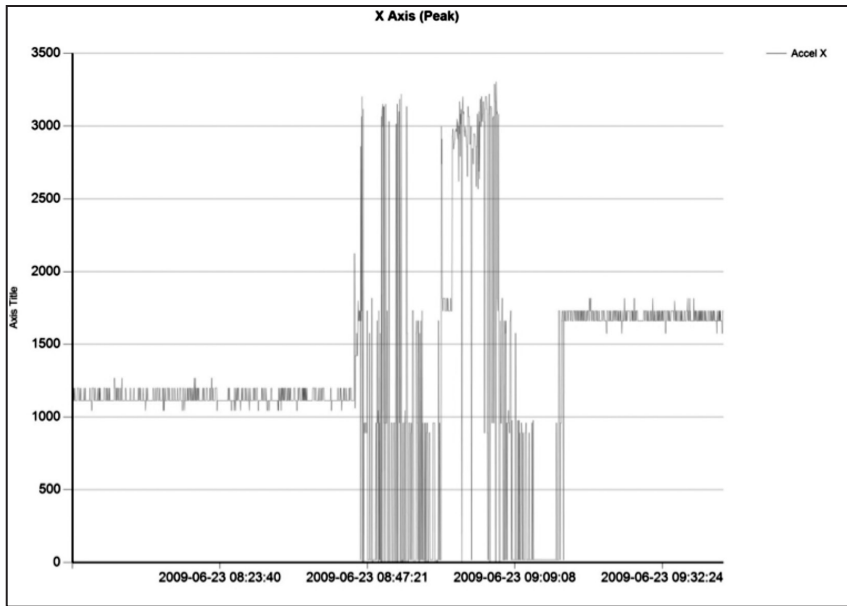
protected and maintaining a clear wireless transmission path are all key factors which need to be adequately addressed to ensure a reliable system.

### Survivability

The cutterhead of an operating tunnel boring machine is not a hospitable place for sensitive electronic devices. Dust, water, chemicals, and chipped rock fragments are all found on most machines. Electronic devices are regularly subjected to shock, wear, moisture, and heat, and therefore must be designed to withstand this extremely harsh environment. The material chosen for constructing the protective enclosure must be selected with all of these concerns in mind. Steel is inexpensive and provides protection against impact and abrasion but can interfere with wireless communications. Highly-engineered plastics with good wear resistance are available which do not interfere with wireless transmissions, but they cannot provide the same level of wear protection as steel and are often prohibitively expensive. Using a mix of steel and plastic components provides the best solution to addressing the short-comings of each kind of material.

### Signal Detection

The cutterhead on a TBM contains a great deal of steel, which can interfere with detection of the wireless signals emitted from the cutter instruments. Additionally, wireless instruments can usually be expected to be reliable as long as there is a line-of-sight pathway between the transmitter and the receiver. This is not always possible for all cutter positions on a rotating cutterhead. On many machines, there is a hopper for channeling the muck from the buckets onto the conveyor, and this area



**Figure 4. Raw vibration data**

could possibly isolate instruments for a period of time when they are near the top of the cutterhead. Also, on very large machines, the outer cutter positions may be greater than 6 meters from the axis of the machine and the signal may have to travel between a series of steel plates to reach a receiver.

### Vibration Filtering

Tunnel boring machines operate in a very dynamic environment which causes a background level of vibration which will always be present. Additionally, the centrifugal and tangential accelerations associated with the cutters rotating around on the cutterhead are detected by the vibration sensors.

Some of the issues associated with these extra forces acting on a cutter can be mitigated in part by orienting the sensor so that only the cutter forces attributed to actual rock fracturing cause data to register on the sensor. Sensor orientation alone, though, won't eliminate enough of the environmental interference to allow direct analysis of the vibration data. It is also necessary to filter out some of the noise by computational algorithms designed to identify and remove repetitive noise. Noise filtering is a well-developed field with many models available, but each application of noise filtering methods is unique. Placing vibration sensors on cutters is a new concept and, therefore, a large amount of data must be collected and analyzed to determine the best way to filter out noise and get the most useful data for analyzing cutter performance (see Figure 4).

### LOOKING FORWARD

Much of the data obtained from the cutter instrumentation system can help TBM operators right now, from calculating the amount of cutter wear to indicating difficult geological conditions. Rotational data indicates how well the cutter is turning, which in turn clues the operator into the amount of wear on a cutter. Temperature data can indicate when a potentially harmful operating condition has arisen. Vibration data provides an indication of how well the cutters are fracturing the rock and the condition of the rock face.

Ultimately, these data will make it possible to generate a real-time map of the geological profile of the tunnel. Operators will be able to combine all of the possible data and note how certain phenomenon relate to the machine operational parameters as well as the condition of the material being excavated. The instrumentation data can also be tied into the TBM control system, which allows for conditions to be set in the machine's operation. The conditions will modify operational parameters if certain data are received. For example, thresholds might be set that would automatically change the thrust force or cutterhead rpm if a high vibration condition is detected.

What remains for the instrumentation system is to develop corollaries between filtered data and what physical phenomena this data represents and then to fully integrate the data with the operation of the machines, putting tunnel boring machines one step closer to an automated method of excavation.