An overview of torque meters and new devices development for condition monitoring of mining machines

B. Zietek1,*, P. Krot1, P. Borkowski1

1Faculty of Geoengineering, Mining and Geology, Wrocław University of Science and Technology, Na Grobli 15, 50-421 Wrocław, Poland

*Corresponding author: bartlomiej.zietek@pwr.edu.pl

Abstract. Condition monitoring and diagnostics of minerals mining machines is a challenging task for operating companies and their maintenance staff. Conventional approaches based on measurements of vibration, temperature and other parameters are still not widely implemented in the mining industry due to non-stationary loading conditions. Registration of overloading and resonance modes is not sufficient by the electrical motors current in case of heavy mobile vehicles or stationary mounted mining machines having multi-body structure. Telemetric torque measurement tools installed in the drivetrains of mining machines allow accounting the variation of loads and gives valuable information on damages in geared transmissions. This paper represents the different methods of torque measurement and digital telemetry device under development based on strain gauges. The focus is on the functionality required for industrial applicability and issues in course of machines operation and maintenance. The additional features, which the torque meters afford for mining machines diagnostics, are considered.

1. Introduction

Presently, the real-time condition monitoring and diagnostics of mining machines are among the most demanding and quickly expanding areas of research and development. Existing sensors and wireless data transmission technologies based on Internet of Things (IoT) and cloud-computing approaches allow taking and storing huge measurement data in real-time. Besides, the exponential growth of microcontroller processing power allows creating price-efficient measuring systems and provides the possibility to get insight into dynamical changes of the machine state during its operation [1]. It is important from the machine maintenance point of view, because some parts of machines, such as shafts, clutches, or other torque transmissions elements are subjected to dynamic loads, which are difficult to predict in design.

Creation of a well-suited mathematical model of industrial plant can help in dynamical loads controlling [2] but can be difficult when it comes to the multi-body geared drivetrains [3] with non-smooth stiffness characteristics [4] causing complicated chaotic behaviour [5]. The models are not always able to reproduce all aspects of the real working conditions, especially for underground mining machines. That is why numerous trials are needed to verify models by the reliable wireless torque measuring system. On the other hand, there are obstacles related to a harsh environment, where mining
machines are usually operated. Particularly, there is often no stable wireless connection underground. Moreover, the continuous repairs and replacement of damaged parts in the mining machines restrict the possibility of torque sensors deployment significantly. Installation of torque meters based on gauge sensors requires special skills and downtime of a machine or even the whole production line, e.g. long conveyors, that is generally undesirable.

Therefore, the detailed analysis is conducted in this paper to figure out the functionality and design of torque meters applied in different areas. Nowadays, the torsional vibrations measurements on rotating shafts are commonly used in the following applications [6]:

- automotive transmissions measurements;
- marine drivetrains with high-power diesel engines;
- aviation engines testing;
- oil and gas equipment, drilling rigs;
- electric power stations, turbines and generators;
- drivelines of rolling mills in steel processing lines [7];
- minerals processing, ore and coal drum mills, cement kilns.

The analysis of abrupt failures in heavy machinery, e.g. rolling mills [8] or belt conveyor drives [9], shows that the most of them are caused by one-time overloads and originated from the accumulated cycles of excessive torsional loads. Torsional vibrations caused by internal resonances [10] or stick-slip friction-induced loads [11] can lead to even more severe damages in the drivelines or product quality deterioration [12]. Therefore, mechanical torque signal, if measured with special tools, is a profoundly informative diagnostic parameter for complicated planetary gearboxes [13], reciprocating machines like diesel engines, pumps and compressors [14].

Measuring torque oscillations along with other parameters, such as magnetic field variation in belt conveyor drives [15] allows detection of operational cycles of stationary and mobile machines [16], compaction parameters of bulk materials briquetting [17]. In parallel, angular clearances can be monitored [18] as the parameters of powertrain elements wear.

Although the monitoring of electrical drives currents allows estimating loads, their values are not strongly correlated with peak dynamic torques and have delays from oscillations at higher natural modes above 10-20 Hz. In case when the industrial plant is equipped with the digital control with a pass-band up to 25-30 Hz, some procedures can be applied for DC motor armature current to extract the natural modes [19]. However, such a method is only applicable to a two-mass drivetrain layout “electric motor – working tool”. In the multi-body powertrains, which include gearboxes, flywheels or other inertial components or synchronous AC motors, mechanical torques are not similar to motor armature current. One of the possible approaches to dynamic machines monitoring is to extract static electric motor currents and compute the remaining useful life (RUL) based on multi-body models [8].

The examination of the consequences of torsional vibrations on machine subassemblies, including pneumatic and hydraulic systems, allows for a better understanding of the real operating parameters of the process. The application of down hole drilling vibration analysis and big data analytics is represented in [20]. Methodology and experimental verification of a drilling system optimisation based on torsional vibrations suppression are represented in [21]. Assessment method of reliability calculation for mine machines, e.g. belt conveyor, is shown in [22].

2. Classification of torque sensors

Torque is the most significant parameter, describing the mechanical powertrain and has useful information to understand machine dynamics and overall efficiency. It is essential to take signals for analysis on-line. In the case of the mining industry, issues of permanent torque monitoring are the harsh environment and wireless connection stability. Moreover, there is an obstacle with a permanent power supply for sensors and shafts replacement caused by damage or failure. When it comes to higher torques, it is needed additional methods for sensor calibration.

There are several features for the classification of torque meters shown in Fig. 1. First, the principle of measurements determines how the system would be installed, and other parameters such as power
supply, methods of sensor installation. Accordingly, certain types of torque meters can be assigned for specific mining machines, e.g. mobile or stationary.

Figure 1. Classification of torque meters.

An example of the use of the magneto-elastic effect for torque metering is shown in Fig. 2a, which is used in the testing of car transmissions and ship drives with internal combustion engines. The sensor detects changes in the permeability of ferromagnetic materials under the influence of tension and compression forces. Second, the most common design of torque sensors in the market consists of two discs with measuring elements based on piezoelectric effect and plug-in bearings to take signals from rotating shafts (see Fig. 2b). This device is practically not feasible for mining machines because it needs installation inside the transmission. The most practical approach is the use of strain gauges (see Fig. 3) with wireless power supply. In some torque sensors, the Surface Acoustic Waves (SAW) are used, which are sensitive to shaft strains [23].

Figure 2. a) Magneto-elastic torque sensor (ABB); b) Piezoelectric torque sensor (PCB).
Figure 3. Strain gauge based torque meter with inductive power (ACIDA Torqcontrol).

The main application areas in mining machinery focus on torsional loads monitoring in multi-body powertrains for machine failures analysis and prevention. It could be done a diagnostics of elements, such as local defects of gears, wear of couplings. Torsional vibration has a direct influence on the workability of blast holes drilling machines. Applications related to the detection of malfunctions in the Internal Combustion Engines (ICE) are also available.

3. Parameters of mining machines

Amongst vast mining machines, where it is needed to acquire torsional vibrations signals, a single boom drill rig Facemaster 1.4 (Fig. 4), load-haul-dump (LHD) vehicle (Fig. 5) and belt conveyor drive (Fig. 6) were chosen as the examples of mobile and stationary machinery.

The Measurement-While-Drilling (MWD) systems are successfully implemented in deep oil wells development. Dynamical changes in a power transmission line can be noticed implicitly through hydraulic oil pressure, vibrations or sudden changes of drill bit rotational speed. For a boom drill rig, although a considerable number of parameters is monitored now, torsional vibration signals are out of them. The main cause of the absence of torque signals is difficulties in access to the drilling system of the machine and harsh conditions during the process. The drilling driveline is designed with standard components and there is no possibility merely to add a torque sensor. On the other hand, torque is a crucial parameter of the operation and can be used for chatter vibrations control detection and rock properties determining. An additional condition is that a torsional vibration sensor should be installed in a specific area, where a maximum torque signal exists – position of the vibrational node.

Another fruitful example of torsional vibration monitoring is the underground Load-Haul-Dump (LHD) vehicles, which exposed to intensive reversal loads of transmission and stoppages when the bucket is in the process of filling with bulk material. Their on-board monitoring systems can be improved by adding torque signals reflecting the condition of powertrain without the need for numerous vibration sensors.

Torsional vibrations measurements can be very well applied for belt conveyor, compared with the drill rig machine. Localization of the sensor is often chosen close to the motor, behind the clutch. Unfortunately, the continuous characteristics of belt conveyor work make the installation of measuring equipment severely limited. Moreover, the presence of ore stream there and its chaotic movement can often damage the set of sensors.
4. Development of a digital torque meter
The design solutions of the developed torque meter account all operational issues and requirements for its use in the harsh conditions of the mining industry:

- high noise in radio channel;
- high temperature and humidity;
- mechanical damages;
- oil, water and metallic dust;
- restricted power supply on the shaft;
• receiving of the shaft rotation signal;
• the wide frequency range for different machines.

A block diagram of the digital torque meter is shown in Fig. 8. The telemetric channel includes strain gauges (half-bridge), low-pass filter, DC amplifier, 12-bit ADC and DAC, 8-bit microcontroller, two digital FM transceivers, a computer with an ADC board and input ports for recording digital measurement data. The carrier frequency of data transmission via the radio channel is 433.92 MHz and is fulfilled in a digital code by frequency-modulated signals, which allows a sufficient range of data transferring up to 20 m. This favourably distinguishes the developed scheme from the similar systems with a carrier frequency of 100-600 kHz, which require the installation of receivers at a distance of 10-30 mm from the shaft. The data exchange protocol between the circuit elements is performed in the Manchester code, which has a high noise immunity.

![Figure 7. Block diagram of a digital torque meter.](image)

The sensor circuits (see Fig. 9) used components from reliable producers (transceivers, microcontrollers, ADC and DAC, amplifiers, voltage sources), which are widely used for convenient replacement in case of sensors damages.

![Figure 8. Transmitter (left) and receiver (right) of telemetry torsional loads monitoring system.](image)

Data transmission from the receiver to the recording unit (PC) can be performed both as an analogue signal after a digital-analogue conversion and in a digital code. The ADC board used in the PC incorporates 8 digital inputs and outputs and allows to generate control signals to change the torque meter settings from a remote computer. For use in a stationary torque monitoring system, the transmission of signals over a long line the standard RS485 protocol should be implemented.

The permissible temperature range of the system circuits operation is an important factor in the reliability and accuracy of the measuring, since it causes a signal drift, and at sufficiently high temperatures, a failure of electronic components. The temperature range of most of the used circuit components is +85°C and the permissible temperature range of the transceiver chip is +70°C. This allows using the torque meter in the hot conditions. It should be noted that when the shaft rotates, the
transmitter would be cooled by the airflow to less temperature. To isolate the transmitter from heating, a sealed polymeric case and a heat-insulating gasket between the shaft and the mount are used. Also, algorithmic temperature compensation can be provided depending on working conditions.

The structural design of the torque meter concerns the following units:

- transmitter housing and the location of the transmitting antenna;
- shaft mounting of the transmitter housing with a power supply;
- receiver housing and its location close to the receiver.

The design of the system and fastening clamps should protect against mechanical damage during machine operation and repairs, as well as oil, water and metallized dust. The design determines the reliability of the torque meter, and, of course, the cost of its operation, taking into account the time spent on equipment downtime and the cost of the failed system blocks and connecting cables.

The high carrier frequency (short wavelength) of the transceiver allows antennas to be placed inside a sealed plastic housing, which greatly simplifies the operation of the meter. In some systems with a lower carrier frequency, antenna winding is required around the perimeter of the shaft.

Primary sensors (strain gauges) of different vendors can be used with a resistance of 100-700 Ohms. Increasing the resistance of the sensors reduces the power consumption of the transmitter circuit, which is desirable for continuously operating plants but long data transmitting distances or noisy working conditions require higher power consumption. At this system, the transmitter uses a DC amplifier with a stabilizer having a low voltage drop, which reduces the power consumption on the shaft.

The installation of a transmitter on a rotating shaft can be performed in two ways: by glueing on the thoroughly polished surface and by welding on the rough surface the plate with previously glued strain gauges. The second method is preferable and easier for implementation but restricted in coal underground mines with methane explosion threat.

The proposed torsional load monitoring system was tested on the laboratory rolling mill (Fig. 9a). In Fig. 9b the signals from 12 bit ADC converter are presented. The load on the shaft has been changed and for all 8 experiments, the charts are put on one graph.

4.1. System improvements

More details on torque meter parameters are given in Table 1. This version is planned for improvements based on earlier gained experience and new capabilities in the field of electronics components development. The following functions are intended for inclusion for the convenience in operation:

- contactless power supply or energy harvesting on the shaft;
- automatic zero calibration of a bridge from the receiver side;
• input signal scaling from the receiver side;
• measurement of shaft revolutions;
• diagnostics of angular clearances.

Besides, multi-channel registration of signals from rotating shafts and utilization of ADC with high resolution (16-24 bits) in a transmitter is under consideration.

Further testing of the torsional measurement system will also allow determining metrological characteristics such as sensitivity to transverse and axial impacts on the shaft, frequency response functions of the whole device. Other factors, for instance, include temperature influence on the sensor, especially creep of the adhesive compositions, the effectiveness of sealing materials against moisture and dust in the underground conditions will be investigated. Further work is focused on the application of the improved system in powertrains of mobile vehicles and multi-motor drives of belt conveyors. One more application of torque meters is the realisation of feedback control loops for active damping of torsional vibrations in the multi-body drivetrains.

| Parameter                                      | Value                        |
|------------------------------------------------|------------------------------|
| Measurement range factor                       | 2, 4, 8                      |
| The primary sensor type strain gauge           | 200-700 Ohm                  |
| Current consumption up to                      | 30 mA                        |
| Sensor power supply on the shaft battery or inductive | 3...4 V                     |
| Type of signal frequency modulation            | FM                           |
| Frequency deviation                            | 15 kHz                       |
| Sampling frequency of the transmitter          | 600-750 Hz                   |
| Data sampling                                  | 8 bits                       |
| Frequency range of the measured signal         | 300 Hz                       |
| Data transfer rate via the radio channel       | 19-38 Kbps                   |
| Distance to the receiving antenna              | 10-20 m                      |
| Allowable shaft rotation speed                 | 3000 rpm                     |
| Allowable vibration on the shaft in all directions | 100g                        |
| Operating temperature in the measurement zone  | -10… +85 C                  |
| Measurement accuracy                           | 0.3...0.4%                   |
| Carrier frequency (two frequencies allowed)    | 433.92 MHz                   |
| Output signal digital, analog                  | 0...10 V                     |
| Protection                                     | IP67                         |

**Table 1. Parameters of the torsional vibrations measurement system.**

5. Conclusions

Torque sensors on the rotating shafts can be categorized as a new class of digital “moving sensors”, which are usually associated with the automatic drones able to inspect industrial and civil structures. The single telemetric torque sensor and real-time acquired signal allow simultaneous recognition of numerous defects like cylinders phasing and fuel injection in ICE, transmission errors and switching issues, friction forces in clutches, oil viscosity in damping hydraulic couplings, inhomogeneity of gear meshing and angular gaps of kinematic pairs with backlashes. Torsional load measurement can help to detect hidden malfunctions in the technological process of mining and material transportation by conducting a trend-based analysis of events, which caused incidents in machines.

Among the existing contactless methods of torsional vibration measurement, the most appropriate solution is the usage of strain gauges with data transmission via a radio channel. In a digital telemetry meter under development, some improvements are presented, thanks to which it can be used as a permanent monitoring tool. The installation of such a torque measurement system in the mining machines allows optimizing technological regimes to reduce overloads and can assist in developing operation scenarios for responding to stochastic strains. Application of the presented low-cost
electronic devices in mining machines will enable to calculate the remaining useful life of components based on multi-mass dynamic models, especially in gear drivelines of heavy underground vehicles.

Acknowledgements
This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation. This work is supported by EIT Raw Materials GmbH under Framework Partnership Agreement No. 19036 (SAFEME4MINE. Preventive Maintenance System on Safety Devices of Mining Machinery) and No. 17031 (MaMMa. Maintained Mine and Machine).

References
[1] Worek C, Krzak Ł, Mrowka R, Barszcz T 2018 *Applied Condition Monitoring* 10
[2] Wu Z 2009 8th International Conference on Reliability, Maintainability and Safety Chengdu pp 844-848
[3] Krot PV 2019 *J of Vibroengineering* 21 pp 2064-2081
[4] Krot PV 2010 *Proc. of the 3rd Int. Conf. on Nonlinear Dynamics (ND-KhPI2010)* pp 21-24
[5] Margielewicz J, Gaska D, Wojnar G 2017 *Scientific Journal of Silesian University of Technology. Series Transport* 97 pp 105-115
[6] *Transmission Dynamics* http://www.jrd ltd.co.uk
[7] Radionov A A, Gasiyarov V R, Tverskoi M M, Khramshin V R, Loginov B M 2017 *Proceedings 2nd Int. Ural Conference on Measurements* pp 450-455
[8] Krot P, Prihodko I, Raznosilin V and Zimroz R 2020 *Advances in Asset Management and Condition Monitoring* pp 399-416
[9] Savkovic M, Dedic M, Pavlovic G, Arsic M, Stamenic Z 2019 *Tehnicki vjesnik* 26 5 pp 1333-1338
[10] Chen X and Feng Z 2017 *IEEE Access* 5 pp 21918-21926
[11] Marjuta A N and Krot P V 1997 *Proc. of the 1st Int. Symposium on “Multi-Body Dynamics Monitoring and Simulation Techniques”* pp 407-419
[12] Krot P V, Prihodko I Y, Chernov P P 2008 *4th European Conf. on Structural Control (ECSC), IPME RAS*
[13] Mones Z, Alqatawneh I, Zhen D, Gu F, Ball A D 2019 *25th Int. Conf. on Automation and Computing (ICAC) (IEEE)*
[14] Liu S, Li W, Shuai Z, Chen M 2019 *Shock and Vibration* 2019 pp 1-9
[15] Kozlowski T, Wodecki J, Zimroz R, Blażej R, Hardygóra M A 2020 *Appl. Sci.* 10 6259
[16] Krot P, Sliwinski P, Zimroz R, Gomolla N 2020 *Measurement: J. of the Int. Measurement Confederation* 151 107111
[17] Baiul K et al 2020 *Mining Science* 27 pp 7-18
[18] Krot PV 2008 *Metallurgical processes and equipment* 2 pp 45-53 (in Russian)
[19] Putnoki A Y et al 2003 *Stal’* 10 pp 56-58 (in Russian)
[20] Ren Y, Wang N, Jiang J, Zhu J, Song G, Chen X 2018 *ASME J. Risk Uncertainty Part B* 5(1) 010801
[21] Pavkovic D, Cipek M, Plvac F, Sprljan P, Jurisic G 2019 *18th International Conference on Smart Technologies (IEEE)*
[22] Morshedlou A, Dehghani H, Hoseinie H 2019 *Mining Science* 26 pp 7-20
[23] Silva D, Mendes J C, Pereira A B, Gegot F, Alves LN 2017 *Sensors* 17 1547