MIGS WP3 Monitoring of Bolt Load
Review of sensor technology for bolt load measurements

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Executive Summary

A review of possible sensor technology for rock bolt load measurements has been made. The measurements requirements is given by the MIG-WP3 specifications. The technology discussed is strain gauges, piezoelectric, piezoresistive, fiber optic, Pressductor and ultrasound.

In conclusion the most interesting sensing approach suitable for wireless bolt load measurement is a strain gauge technology by Hitec Corporation. This in combination with the Mulle sensor and communication platform forms a good basis for meeting the MIG-WP3 requirements.

Contents

1 Introduction

There is a general interest in continuous measurement of loads on rock bolt. This report reviews bolt load measurement technology.

Preliminary functional requirements for the load measurement are [15]:

- measure static and dynamic rock bolt load of $<$300kN.
- Dynamics to be captured are $<$100 Hz, thus a sampling rate of 1kHz will be sufficient.
- true load measured with an accuracy 2 % ;
- a robust load cell and sensor, which are not sensitive to moist, dust, corrosive environment or high voltage cables (1,000 volt);
- the load cell and cables are protected from minor impacts from rocks and machines
- less expensive than existing load cells on the market (i.e. load cells for this special application);
- a cable free system or at least a system with very robust cables and connections;
- continuous load sampling over time (with the possibility to set sampling intervals);
- results could be stored in a readable memory;
- not sensitive to uneven loading on the bolt plate;
- easy to install;
- repairable connections and cables;
- simple and robust reading units;
- reading units compatible to a PC;
- life time without changing power supply $>$3 month (using a battery).

For the sensor review the accuracy, insensitivity to unbalanced load and power consumption is regarded as critical.

Based on above requirements the literature and the Internet have been searched for possible technology approaches and for available commercial devices.

2 Sensor technologies

From the literature we do find a couple of generic approaches to the measurement of load on a bolt. These are:

- Force sensor based on strain gauge
- Force sensor based piezo technology
- Pressductor
- Fiber optic sensors
- Ultrasound sensors
- Fiber optic sensors
- Force indication using micro dye bubbles

Each of these are discussed in more detail below.

2.1 Fiber optic technology

A fiber optic force sensor can be designed. The force exerted upon an optical fiber which comprises a fiber Bragg grating will generate a wavelength shift. The wavelength shift caused by longitudinal strain ϵ is given by λ_{BS} [9]:

$\lambda_{BS} = \lambda_B(1 - \rho_\alpha)\epsilon$

where ρ_α is the photoelastic coefficient of the bre.

Features obtained with this approach is the non electric approach thus being immune to RFI/EMI disturbances. The measurement range found is for load considerably lower than 300kN. Accuracies of 0.1% is obtainable. Commercial devices are available but mainly for medical applications.

This technology is currently not suitable for the rock bolt application.

2.2 Strain gauge technology

A strain gauge is a device used to measure the strain of an object. Invented by Edward E. Simmons and Arthur C. Ruge in 1938, the most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. The gauge is attached to the object by a suitable adhesive, such as cyanoacrylate. As the object is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change, usually

Table 1: Strain gauge load cell approaches.

Type	Weight Range	Accuracy, full scale	Apps	Strength	Weakness
Bending Beam Load Cells	5-2,500 kg	0.03%	Tanks, platform scales,	Low cost, simple construction	Strain gauges are exposed, require protection
Shear Beam Load Cells	5-2,500 kg	0.03%	Tanks, platform scales,off-center loads	High side load rejection, better sealing and protection	
Canister Load Cells	to 250,000 kg	0.05%	Truck, tank, track, and hopper scales	Handles load movements	No horizontal load protection
Ring and Pancake Load Cells	2.5-250,000 kg	1-2%	Tanks, bins, scales	All stainless steel	No load movement allowed
Button and washer Load Cells	0-25,000 kg 0-100 kg typ.	1%	Small scales	Small, inexpensive	Loads must be centered, no load movement permitted

measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor, [6].

There are a number of common designs of strain gauges for different applications. Table 1 indicates a number of these with typical load range values and expected accuracy.

Compression load cells based on resistive strain gauges often have an integral button or ring design. A ring design is given in figure 1 They are ideal for mounting where space is restricted. They are claimed to offer excellent long term stability.

Typical specifications for a compression cells based on resistive strain

Figure 1: A ring design of strain gauge force sensors from HBM.

gauges can be found for high end product in table 2 [5] and for low end devices in table 3 [7]:

The maybe most attractive approach for strian gauges sensing applied to rock bolt load measurements was the MMT approach found with Hitec corporation [18]. They exhibit and custom device drilled into to the head of the bolt as shown in figure 2

The Hitec MMT uses foil strain gages configured as a full Wheatstone bridge and is claimed to provide maximum sensitivity to axial loads while minimizing the effect of bending, torque, and shear forces. The MMT uses a four wire connection for the full Wethstone bridge measurement. Which is fairly easy to integrate to the Mulle sensing and communcation platform.

HITEC Corporation provides 5 point NIST traceable calibration as part of the insert installation procedure and claimed accuracy is better than 2% in most applications.

The resistive strain gauge approach seams to be suitable for the roack bolt specification. The commercial devices found are not tailored to meet the power consumption requirements directly. A new design of the electronics measurements system has all the potential to bring power consumption to levels where the sensor life time in combination with communication plattforms like Mulle [10] clearly can exceed the specification.

2.3 Piezo resistive technology

Piezo resistive material can be used for load measurements. The material will change its resisitivity with pressure. Load cells based on piezo resistivity

Table 2: Typical high end strain gauge load sensor. Data taken from Vishay RLS series

PARAMETER	VALUE	UNIT
Standard capacities (E_{max})	0.25, 0.5, 1, 2, 3.5, 5, 10, 28, 60	ton
Accuracy class according to OIML/NTEP	NTEP IIIL	
Maximum no. of verification intervals (nlc)	10000	
Rated output (=S)	2	mV/V
Output accuracy for multiple LC systems	0.02	±%mV/V
Zero balance	1.0	±%FSO
Combined error	0.0200	±%FSO
Creep error (30 minutes)	0.0245	±%FSO
Temperature effect on zero	0.0010	$\pm\%FSO/^oC$
Temperature effect on sensitivity (output)	0.0008	$\pm\%FSO/^oC$
Minimum dead load	0	$\%E_{max}$
Maximum safe over load	150	$\%E_{max}$
Ultimate over load	300	$\%E_{max}$
Maximum safe side load	100% ≤10 ton 50% (28t & 60t)	$\%E_{max}$
Deflection at E_{max}	0.12-0.20	mm
Excitation voltage	5 to 15	V
Maximum excitation voltage	30	V
Input resistance	1110±50	
Output resistance	1025±25	
Insulation resistance	≥5000	M
Compensated temperature range	-10 to +40	^oC
Operating temperature range	-30 to +70	^oC
Storage temperature range	-50 to +80	^oC
Element material (DIN)	Stainless steel 1.4542	
Sealing (DIN 40.050 / EN60.529)	IP66 and IP68	
Recommended torque on fixation bolts	12 to 14	N*m

can have accuracies of 0.03% with very high sensitivity and high output signal levels. Drawbacks are high cost and nonlinera output.

An example of such sensor is Flexiforce Force sensor seen in figure 3[3]. Based on piezo resistive force sensor where resistance is inversely propor-

Table 3: Typical compression low end strain gauge load cell specification, example taken from Transducer Techniques modle LW0-60 capacity 300kN

Rated Output (R.O.):	2 mV/V nominal
Nonlinearity:	2.0% of R.O.
Hysteresis:	2.0% of R.O
Nonrepeatability:	1.0% of R.O.
Zero Balance:	1.0% of R.O.
Compensated Temp. Range:	60 to 160 ^oF
Safe Temp. Range:	-65 to 200 ^oF
Temp. Effect on Output:	0.005% of Load ^oF
Temp. Effect on Zero:	0.01% of R.O. ^oF
Terminal Resistance:	350 ohms nominal
Excitation Voltage:	10 VDC
Safe Overload:	150% of R.O.
Deflection Inches:	0.001 @ R.O.

tional to applied force. The particular Flexiforce sensor has a force range of 0 - 440N (4400N possible with special electronics). Typical specifications are found in table 4.

This technology is currently not suitable for the rock bolt application. Mainly since the load range can not be meet.

2.4 Piezoelectric force sensor

The function of a piezo electric force sensor is exemplified by the following description [8].

Two quartz discs are pre-loaded together between a lower base and an upper platen. Pre-loading is necessary to ensure that the crystals are held in intimate contact for best linearity and to allow a tension range for the instruments. The discs are put into vibration at its natural resonance frequency.

When the discs are stressed by an external compressive force the resonance frequency is altered. The frequency change can be detected electronically.

The force from such sensor is obtained in the following way. The natural frequency of the force sensors is always specified as unloaded and for a good reason. Placing a load on a force sensor creates in effect, an accelerometer. The load can be considered a seismic mass (M) and the force sensor

Figure 2: Hitec corporation approach to the measurement of bolt load with en insert to the bolt head.

represents stiffness (K). The natural frequency of this new combination is now:

$f_n = 1/2\pi * \sqrt{K/M}(Hz)$ Where: K is force sensor stiffness, (kg/m) and M = Mass of load,

It is easy to see by Equation 2.4 that the larger the mass, the lower the loaded natural frequency.

Using this approach a we will have an excellent dynamic load sensor technology. For static loads we will have a drift. Data found on commercial devices is typical less than 1% per 30 min. This is tough very dependent on the system and electronics design and much better designs can be made using state of the art system design and electronics [12].

This type of sensor technology has a potential to be very low power. This will tough require some new design of interface electronics to a wireless communication platform like Mulle [10]. Thus obtaining specification clearly exceeding the specification

2.5 Pressductor

The Pressductor [11] principle can be described as follows with the aid of figure 4. In the transducer body there are four holes. Two coils at right angles to each other are wound through these holes. One coil (the primary) is supplied with an alternating current; the other (the secondary) acts as a

Table 4: Typical compression load piezo cell specification, example taken from Teckscan FlexiForce sensor

Physical Properties	
Thickness	.208mm
Length	203mm
	152mm
	102mm
	51mm
Width	14mm
Sensing Area	diameter 9.53mm
Connector	3-pin male square pin
Thickness	.208mm
Typical Performance	
Linearity Error	<+/-5%
Repeatability	<+/-2.5% of full scale (conditioned sensor, 80% force applied)
Hysteresis	<4.5% of full scale (conditioned sensor, 80% force applied)
Drift	<5% per logarithmic time scale (constant load of 90% sensor rating)
Response Time	<5 microseconds
Operating Temperatures	-9^oC to 60^oC)
Force Ranges	4.4 N
	0-110 N
	0-440 N
Temperature Sensitivity	Output variance up to 0.36% per ^oC

measurement coil. Since the two are at right angles to each other, there is no magnetic coupling between the coils as long as there is no load on the transducer body.

The transductor is magnetized via the primary coil (a). A voltage proportional to the loading force is induced in the secondary coil (b).

If the transducer body is loaded as shown in diagram, the field pattern changes. The permeability of the steel is reduced in the direction of the force and increases in the right angle direction to the force. The result is a change in the symmetry of the magnetic flux, so that some of the flux induces a voltage in the secondary winding. The induced voltage is proportional to the load.

Figure 3: The Flexiforce sensor based on piezo resistive technology.

The Pressductor technology is provided by ABB

The main draw back of this technology for the rock bolt load application is its power consumption. Very special system designs has to be applied to meet the sampling criteria combined with the battery life time criteria.

2.6 Pressure indicating film

New material developments has generated pressure measuring film. Here the film contains micro capsules of different diameters. These micro bubbles hold ink. When the film is compressed the bubbles are cracked. The rate of compression tells the color intensity of the film. http://www.tekscan.com

If a color intensity reading device is applied and encapsulated such that color intensity can be read this can be a robust method.

To apply this method to the bolt load measurement will today require a substantial amount of sensor development. Thus it is not regarded as suitable.

2.7 Ultrasonic bolt load measurement

When a bolt is loaded then tension in the bolt is changed. This can effect the length of the bolt and the density of the bolt. An ultrasound wave is affected by both phenomena. Thus ultrasound can be used to measured bolt load through speed of sound measurements. Speed of sound c in the material is related to the density ρ as:

$c = \sqrt{E/\rho}$

The bolt length can in its simple description be found from:

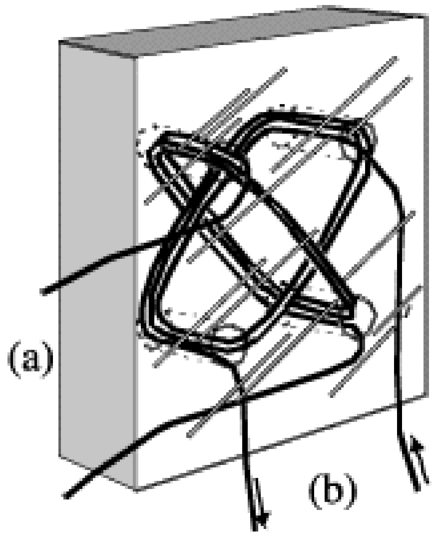

Figure 4: Principal sketch of the Pressductor technology.

$l = c * t$
where l is the distance and t is the transit time for the sound traveling that distance.

We do find several scientific papers and several patents in this field. One example is [**?**]. A number of suppliers of ultrasound measurement technology for bolt load measurements has been found.

- USM-3 by Norbar [16]
- Hevii - US bolt load technology [2].
- Boltscope-II by Hydratight [17]

The USM solution by Nobar is seen in figure 5.

This technology has the potential to give you the most information on the changes in the rock bolt. The technology is still rather young and much development can be expected in the future.

To meet the rock bolt specification I do expect some detailed work to be carried out on both ensuring accuracy specification and on power consumption. From known work in the area [14], these short coming will be solved in the future.

Figure 5: Ultrasonic bolt load measurement technology USM-3 by Nobar.

3 Discussion

Comparing the specifications to the available technology the following analysis can be given.

- measure static and dynamic rock bolt load of <300kN.
  Possible with force strain gauge sensors, force piezo electrics sensor and ultrasound bolt load measurement.

- Dynamics to be captured are <100 Hz, thus a sampling rate of 1kHz will be sufficient.
  Seams reasonable for all discussed sensor types. For very long bolts the ultrasound approach will not meet this requirement.

- true load measured with an accuracy 2 %
  Is reachable for strain gauge sensor, piezoelectric and ultrasound bolt load measurement. For some of the sensors extra care should be taken for mounting of sensors

- a robust load cell and sensor, which are not sensitive to moist, dust, corrosive environment or high voltage cables (1,000 volt);
  This is a final design and encapsulation requirement. Meeting this is mainly a cost related issue.

- the load cell and cables are protected from minor impacts from rocks and machines
  This is also a final design and encapsulation requirement. Meeting this is mainly a cost related issue.

- less expensive than existing load cells on the market (i.e. load cells for this special application);
  At this point in time this is hard to predict, since we partly are discussing new technology.

- a cable free system or at least a system with very robust cables and connections;
  This should be possible by combining one of the above considered sensors with Mulle wireless communication technology.

- continuous load sampling over time (with the possibility to set sampling intervals);
  Clearly possible with strain gauge, Pressductor and ultrasound. For piezoelectric there are shortcomings but possible solutions has been addressed in the literature. System solution approaches can also be considered here for further improving the piezoelectric approach.

- results could be stored in a readable memory;
  Clearly possible with above sensor and Mulle technology.

- not sensitive to uneven loading on the bolt plate;
  For strain gauge and piezoelectric sensors careful sensor design is needed to reduce such problems. There are solutions available on the market today. The ultrasound approach should be fairly insensitive to this problem.

- easy to install;
  For strain gauges the Hitec approach is the most appealing from installation point of view. Otherwise the ring type transducers using stain gauge or piezoelectric sensing would be the obvious approach to simplify installation. Here it may be to the cost of some accuracy for unbalanced loads. The ultrasound approach will required some development to ensure simple installation. The Pressductor installation should be straight forward with present technology.

- repairable connections and cables;
  Not necessary since no cable will be present

- simple and robust reading units;
  This is a SW and web page design issue

- reading units compatible to a PC;
  Since data will be available over Internet a standard browser will display the web page designed for the purpose.

- life time without changing power supply >3 month (using a battery).
  for the three major technologies here addressed this should be achievable. For strain gauges and piezoelectric sensors this can be meet with smaller development in the integration of the sensor to a communication platform like Mulle. With some system and electronics developments I do expect battery life time to become several years for all three technologies. The time line for the ultrasound approach is tough the longest. For the Pressductor technology this requirement in combination with the sampling requirement indicates a large development effort to be needed.

4 Conclusion

In conclusion we have four measurement technologies that has the potential to meet the specifications. These are:

- Resistive strain gauges
- Piezoelectric force sensors
- Ultrasound bolt load measurement
- Pressductor force transducers

For an experiment to address on-line wireless communication of data from rock bolts the resistive strain gauge approach probably is the simplest to test. A working solution with performance that gives data comparable to existing system could be obtained with reasonable efforts.

The second technology of choice is the piezoelectric approach. Since this technology has the best potential to become very low power.

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