Rock Bolt Inspection by Means of RBT Instrument

Tadeusz STEPINSKI 1, Karl-Johan MATSSON 2
1 AGH University of Science and Technology, Krakow, Poland
2 Geosigma AB, Stockholm, Sweden

Abstract. In this paper we present a new digital ultrasonic instrument for nondestructive inspection of rock bolts using guided waves. The Rock Bolt Tester (RBT) instrument applies long-range ultrasonic to investigate bolt’s status, especially its grouting condition. RBT features an application tailored ultrasound probe that transmits high-energy, low frequency (below 100kHz) guided waves and is capable of receiving weak echoes reflected from the discontinuities at the bolt surface as well its end-echo that have propagated in the range of up to four meters. The RBT is a portable instrument that consists of specially designed analog electronics for generation and reception of guided waves and an embedded digital computer for signal processing, operator communication and data storage.

Results of the RBT’s evaluation using prepared rock bolts installed at a number of sites (tunnels and mines) are presented in the paper. The test bolts with different lengths in the range of 2 to 4 m were manufactured by shielding a certain steel bolt length with plastic tube sealed with silicon. Plastic end cups were installed on many bolts to create uniform conditions for end echo measurements.

Approximately 3,200 tests have been conducted; selected results are presented in the paper for illustration and comparison of the results of the applied signal processing techniques.

1. Introduction

Rock bolts are commonly used to reinforce the roof and the walls of tunnels or other rock facilities to increase staff security as well as to minimize the risk of interference during the work. Rock bolts are steel bars of different types that are anchored and often grouted in deep boreholes in the rock using a grout (cement or epoxy) as illustrated in Fig. 1. Many types of rock bolts are manufactured; typically, they take the form of several meters long steel bars with diameter in the range of one inch.

NDT of rock bolts after their installation is a vital issue to ensure safety of staff working at the rock facility as well as sustainable rock reinforcing [1],[2]. Techniques for the inspection of rock bolt integrity have been an issue addressed by various researchers [2-6]. The most natural method is the pullout test, which unfortunately, is a time-consuming and destructive process. A need to develop a NDT technique that could be used to determine bolt condition in situ has driven a number of projects. The most promising way has appeared to be the application of elastic waves propagating in the bolt embedded in grout. Low frequency vibrations were used in the GRANIT instrument developed at Univ. of Aberdeen, GB, [2]. The vibration signals arising from an impulse produced by the
The instrument’s impact device are sensed by an accelerometer positioned on the impact device. The bolt condition is determined using neural networks that had been trained to interpret the accelerometer’s signals. The approach used for signal interpretation is the main disadvantage of the GRANIT instrument that can be used only on the rock bolts that have been fully characterized before [1],[2].

Fig. 1. Tunnel in a rock reinforced by rock bolts (left). Different types of rock bolts (right).

Ultrasound elastic waves are utilized by the Boltometer, which was developed in Sweden in 1970s. The Boltometer has a sandwich piezoelectric transducer that transmits compressional and quasi-flexural waves into a rock bolt and receives echoes reflected from the bolt discontinuities as well as the discontinuities in grout. The echo signals are amplified and presented in the form of A-scans at a small instrument’s screen. Unfortunately, the Boltometer, despite that its usefulness has been demonstrated (mostly in Scandinavia), is not any longer commercially available. Motivated by that, and by the needs of the rock bolt installing companies as well as the supervising authorities, the Swedish company Geosigma AB initiated in 2010 the research project with the aim to develop a modern improved version of the Boltometer [7].

In this paper we present some details concerning the project’s result – the new instrument for nondestructive inspection of rock bolts, Rock Bolt Tester (RBT). The RBT is a digital PC based ultrasonic instrument that applies guided waves to perform a long-range ultrasound NDT test to asses rock bolt’s status.

2. Operation Principle – Guided Waves

Guided waves are the ultrasonic elastic waves that propagate in solid media with hard boundaries. This type of ultrasonic waves is subject to both reflection and refraction with the boundary of the solid, which results in mode conversion between compression and shear waves. This results in different modes of guided waves that can propagate in a cylindrical solid or a tube. Guided waves are dispersive and are characterized by two different velocities, the phase velocity and the group velocity. This means that the wave phase propagates with different velocity than the wave envelope (wave energy). Each propagating mode has a particular wave structure and frequency dependent velocities. Normally, there are two main mode types propagating in rods, the longitudinal (L) and flexural (F) modes. For higher frequencies ultrasonic energy can travel in multiple different modes that propagate simultaneously, an example is shown in Fig. 2, [4],[5]. From Fig. 2 it can be seen that velocities of the wave modes (especially longitudinal) propagating in a rod also depend on the acoustical properties of the surrounding medium, for example, vacuum
and rock. Furthermore, acoustic properties of the grout used to fix a rock bolt determine amount of energy leaking from the bolt to the grout and further to rock, that is, wave attenuation.

![Fig. 2. Frequency dependent phase velocity for a steel bar in vacuum (left). Frequency dependent phase velocity for a steel bar embedded directly in rock (right). (Courtesy M.D. Beard [5])](image)

Attenuation of the guided waves propagating in a bare rod in air is much lower than that for a bolt grouted in a rock. Complex physical nature of guided waves limits their useful frequency band to rather low frequencies and also is one of the main reasons for their limited use in industrial NDT applications. The use of guided waves for rock bolt inspection has been investigated by a number of researchers [4-8]. The only test setup that is feasible in practical applications is the pulse-echo configuration with a transducer applied in contact to an accessible end of rock bolt. An application tailored ultrasonic transducer, excited by high-energy pulses from the instrument, generates elastic waves that propagate in the steel bolt embedded in grout. The waves propagate along the bolt and a part of their energy leaks to the grout. An echo formed by the reflections from the discontinuities in the bolt and its vicinity (e.g., break, air pockets or corrosion) as well as at the bolt end, is received by the sensing element of the transducer.

3. The RBT Instrument

The RBT is a PC based instrument built up of specially designed, digitally controlled analog electronics and a National Instruments DAQ card. The analog electronics consists of the signal generator and signal receiver boards connected as illustrated in the block diagram in Fig. 3. The analog boards are connected to the National Instruments DAQ card, which performs communication with the PC as well as acquisition and conversion of analog signals from specially designed probe.

![Fig. 3. The portable, battery supplied RBT instrument (left), and its simplified block diagram (right).](image)
The programmable pulse generator is capable of emitting high-energy long pulse trains, for example, windowed chirp sequences. Two separate pulse sequences generate the compressional and quasi-flexural waves in the bolt. The programmable receiver has two separate channels capable of amplifying small echo signals received by the mode sensitive probe.

The application tailored RBT’s probe contains, integrated into a single handle, broadband piezoelectric stack elements that serve as actuators and sensors. The actuators transmit elastic waves, possibly broadband compressional (L) and quasi-flexural (F) modes, into the inspected rock bolt. An echo signal formed by the reflections from the discontinuities in the bolt and grout is received by the sensor part of the probe that is mode-sensitive, i.e. has a limited ability to distinguish between the L and F modes. It appears that both wave modes propagate with different velocities and are sensitive to different types of flaws.

Note that velocities of the L and F wave modes depend on the state of rock bolt’s grouting, i.e. velocities in the bare rod are considerably higher than those in the grouted one.

The problem related to high signal attenuation in the grouted bolt has been solved by two means: firstly, high energy, wideband pulse trains are transmitted, and the resulting echoes are captured by the sensitive piezoelectric elements and amplified by the high gain receiver channels. Secondly, the received signal is processed by the digital matched filters that perform pulse compression, which results in a considerable increase of the signal to noise ratio.

![Fig. 4. Example of ultrasound echo signals registered by the RBT instrument. Raw signals before filtering (left) and the matched filter processed signals (right). Compressional component in the upper panels and the flexural signals in the lower panels.](image)

An example of the raw signals, registered for a partly grouted 2m long rock bolt is shown in the left panel of Fig. 4. It can be seen that the filtered signals, shown in the right panel, feature much higher amplitudes and SNR than the raw ones. The large pulses at 1.8m at the right panel are the reflections from the simulated end of grouting while the small echoes seen at approx. 4m are the double end reflections.

### 4. Experimental validation of the RBT instrument

The primary goal of the NDT performed using the RBT is to verify whether the inspected test bolts meet the requirement, i.e. they have been well installed. To verify the RBT’s capacity test sites were set up in Stockholm and in the locations close to Stockholm in order to be able to conduct the number of test measurements necessary to verify the performance of RBT in a simple and feasible manner. The test sites were set up in the tunnel projects underneath Stockholm, and in the Dannemora Minaral AB mine in the Northern Uppland.
At each test site, 22 identical test bolts were installed using cement grout (one bolt was rejected, which means that in total 65 test bolts have been used).

The method of creating an operating test bolts with artificial defects enabling technique evaluation has been adopted from the NDT field. This technique is based on a number of representative cases that are assumed to apply to a broad class of defects/deviations. Generally, each particular flaw/deviation is unique, which means that it is impossible to create a test bolt that captures all infinite variants.

The basic hypothesis behind the tests was that the most commonly occurring flaws are caused by the failure to insert pump hose into the bottom of the bore hole, alternatively by the water-cement ratio being too high, which leads to the cement-mix slipping out of the hole. In both cases, the cavity should be formed in the bottom of the borehole. It is possible that cement-mix could slip out of the outer segment of the borehole and form a cavity there, but there, the damaging effect would be easy to detect and possibly smaller.

The test bolts were manufactured by shielding a certain length of a steel bolt with plastic tube sealed with silicon to protect this part from contacting grout. The bolts used in the experiments are shown schematically in Fig. 5 where it can be also seen that plastic end cups were installed on many bolts to create uniform conditions for the end echo measurements. Note that amplitudes of the end echoes for grouted bolts can be highly attenuated due to the weak reflection if the bolt’s end is in good contact with the grout.

Thus the end-echo amplitudes correlate strongly not only to the length of the grouted part of bolt but also to the presence of end cups. An end cup isolates the bolt’s end from the grout and in this way prevents energy leakage. Moreover, the energy leakage and wave velocity depend on the grout type, i.e., on the difference in the acoustical impedance between the grout and steel used for the rock bolts [7],[8].

Approximately 3,200 tests have been conducted during the period October 2012 to November 2015. A number of tests was performed for each bolt while the probe was rotated. The tests, which were repeated at various time intervals after successive probe modification, strive towards obtaining maximum echo in the received ultrasonic signals.
scattered at artificial discontinuities. The most recent test series was performed in October 2015 after certain instrument and probe improvements.

The most representative results gathered from the prepared rock bolts installed at the Dannemora Mineral AB mine are presented below. Both L and F components are presented in the form of amplitude plots produced by the RBT’s LabView software. The A-scan amplitude in the plots (y-axis) is in an arbitrary scale that depends on the instrument gain, length of the generated test sequence and the digital filter setting (kept constant during the test). Rock bolt length in the x-axis is calculated based on the mean wave velocity 3000 m/s.

4.1. Example A-scans obtained for the 3m bolts

Example signals A-scans recorded for two 3m bolts are presented in Fig. 6 where distinct end echoes for both 3m bolts are well pronounced. Also two echoes, reflected from the 0.5m air pocket in the middle of bolt 3006, are clearly pronounced. Note the secondary echoes for the bolt 3006 where attenuation is lower due to the presence of air pocket.

![Fig. 6. A-scans obtained for the bolt 3000 (perfect grout, no end cup) (left), and the 3006 (0.5m tube in the middle, end cup) (right). Compressional component in the upper panels and the flexural in the lower panels.](image)

4.2. Example A-scans obtained for the 3.5m bolts

Aggregated A-scans obtained from a couple of tests of the same bolt with rotated probe are presented in Fig. 7. From Fig. 7 it can be seen that the presence of void in the end of the

![Fig.7 A-scans obtained for the 3.5m rock bolts. Left panel: bolt 3501 (1.5m long tube at the end, no end cup). Right panel: bolt 3502 (1.5m long tube in the middle, end cup).](image)
bolt results in a higher end echo that the same void in the middle of the bolt. This seems to be reasonable since the middle void results in two distinct echoes that return back a large portion of the wave energy. The void at the end decreases the overall attenuation and even the double echo at 7m can be distinguished for the bolt 3501. This means that the maximum test range of the RBT instrument is at least 4m.

5. Conclusions

A new RBT instrument for the inspection of rock bolts using guided waves was presented in the paper. The RBT is a PC based instrument operating under Windows 10 that consists of application tailored electronics for generating and sensing high-energy pulse trains. The instrument is provided with a specially designed handheld probe including a separate transmitter and receiver capable of transmitting and sensing longitudinal and quasi-flexural wave modes in rock bolts. Excellent test results were obtained in the field (tunnels and mines) – it has been verified that end echoes for 3.5 to 4m long rock bolts could be detected and artificially introduced voids of the lengths 0.5 m and more could be reliably detected.

References