NON-DESTRUCTIVE ACOUSTICAL METHOD FOR DETERMINING ROCK ANCHOR EMBEDMENT LENGTH IN SALT MINE 'WIELICZKA'

[1]MICHAŁ PIETRZAK, [2]JAN PRZEPIÓRA, [3]PAWEŁ PASŁAWSKI, [4]PAWEŁ PRZEJCZOWSKI

[1,2,3,,4]Faculty of Mechanical Engineering and Robotics, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland
E-mail: [1]mpietrz@student.agh.edu.pl, [2]przepial@student.agh.edu.pl, [3]paslawsk@student.agh.edu.pl, [4]przejczo@student.agh.edu.pl

Abstract - This article describes a technique for determining the depth at which a rock anchor is embeded in a rock face, without causing damage to the anchor or surrounding structure. The method involves using an acoustic measurement system that relies on the natural vibrations of the anchor to determine its embedment length. This allows for accurate testing without the need to physically manipulate or damage the anchor. The results of this technique have been compared to those obtained using traditional, destructive testing methods, and have been found to be reliable and accurate. The self-excited acoustic measurement system has the potential to be a useful tool for testing rock anchor embedment length in underground structures, as it is non-invasive and can provide accurate measurements without causing any harm.

Keywords - Rock Anchors, Determining Rock Anchor Embedment Length, Self-Excited Acoustical System, Non-Destructive Measurement System.

I. INTRODUCTION

In the mining industry, the stability of underground tunnels and shafts is crucial to the safety of workers and the overall stability of the mine[1]–[3]. One important aspect of ensuring the stability of these structures is the proper installation of rock anchors, which are used to reinforce the walls and ceilings. In the Wieliczka salt mine, located in Poland, determining the embedment length of these rock anchors is an essential task, but it can be challenging, particularly when it comes to non-destructive testing methods.

Rock anchors are used in mines to provide stability and support to the surrounding rock mass. They are typically installed in underground mines, where they help to prevent rock falls and cave-ins, which can be dangerous for workers and potentially cause damage to the mine.Rock anchors are installed by drilling holes into the rock and inserting the bolts into the holes. The bolts are then secured in place using grout or other types of anchors.[4]

The goal of this article is to determine the effectiveness of a self-excited acoustic measurement system as a non-invasive method for testing rock anchorembedment length in the Wieliczka salt mine. Non-invasive testing methods are preferred in many situations because they do not damage the structure or material being tested, allowing for repeated testing if necessary[5], [6]. In the case of rock anchors in the Wieliczka salt mine, the use of a non-invasive method for determining embedment length is especially important because the bolts are a critical part of the structural stability of the mine, and any damage to them could have serious consequences.

There are several methods that can be used for testing rock anchorembedded length, including:
1. Visual inspection: In some cases, the embedment length can be visually inspected by looking at the exposed portion of the anchor. This method is not suitable for anchors that are fully embedded or for materials that are not transparent.
2. Load testing: This method involves applying a load to the rock anchor and measuring its deflection to determine its embedment length. It is more accurate than visual inspection or hammer testing, but it can be time-consuming and may damage the rock anchor.[4]
3. Ultrasonic testing: This method involves using ultrasonic waves to measure the depth of the anchor. The time it takes for the ultrasonic waves to travel from the surface of the material to the bottom of the anchor can be used to calculate the embedment length[7]–[9].
4. Self-excited acoustic measurement: This method involves sending an acoustic signal through the rock anchor and measuring the response of the bolt to the signal to determine its embedment length. It is non-invasive and has been shown to be more accurate than other methods, such as ultrasonictesting[5], [6], [10].

The self-excited acoustic measurement system was chosen as a potential method for testing rock anchorembedment length because it is non-invasive and has been shown to be accurate[11]. The self-excited acoustic measurement system works by

sending an acoustic signal through the rock anchor and measuring the response of the bolt to the signal. By analyzing the response of the bolt, it is possible to determine its embedment length, as well as other important characteristics such as its diameter and length[12], [13].

In addition to its non-invasive nature, the self-excited acoustic measurement system has several other advantages over other methods of testing rock anchorembedment length. For one, it is quick and easy to use, requiring minimal setup and allowing for rapid testing of multiple bolts. It is also portable, making it easy to use in a variety of different locations.

Overall, the self-excited acoustic measurement system has the potential to be a valuable tool for non-invasively testing rock anchorembedment length in the Wieliczka salt mine and other similar environments. By providing accurate and reliable information about the embedment length of these bolts, it can help to ensure the stability and safety of the mine and its workers. This article aims to evaluate the effectiveness of this method and provide recommendations for its use in the Wieliczka salt mine and other similar environments.

II. MEASUREMENT SYSTEM

The measurement system for a self-excited acoustical system for the study of embedment length of rock anchors consists of emitter, power amplifier, FPGA, conditioner, accelerometer.First, the FPGA generates an electrical signal. The power amplifier then amplifies the signal to a level suitable for further processing. It is necessary to increase the strength of the signal to improve the signal-to-noise ratio, resulting in a clearer and more accurate measurement.The amplified signal is passed to theemitter. In this roleloudspeaker is used, which acts as a vibration emitter, generating vibrations that are transmitted through the rock anchor.

The accelerometer measures the acceleration of the vibrations using the piezoelectric effect. When the accelerometer is subjected to acceleration or vibration, the piezoelectric element is deformed due to the mechanical stress. This deformation causes the piezoelectric element to generate an electric charge, which is proportional to the acceleration or vibration being measured.

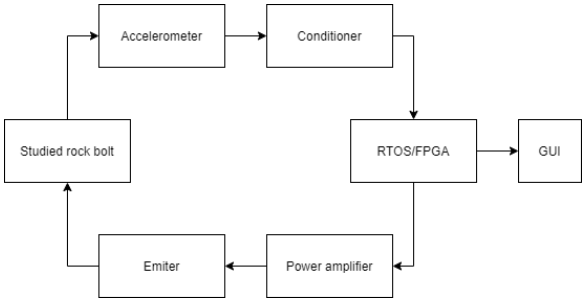


Fig. 1 Schematic of the measurement system.

A conditioner is used to filter out noise and unwanted frequencies from the signal. Its second role is to limit the range of signal values to between -10 and +10 V in order to match the signal to the FPGA.The conditioned signal is then passed to the FPGA where data analysis is performed. The core element of the measurement system is an FPGA platform with a processor operating under real-time control. This solution allows efficient management of computing power and reduces the latency of data exchange between the directly programmable gate array and the processor.The signal generation and filtering algorithms are implemented on the FPGA platform through hardware blocks that support signal processing. The system uses the FFT to determine the self-exciting frequency of the rock anchor. The results on the GUI, allowing the user to easily interpret and understand the data.

Overall, the measurement system for the self-excited acoustic system for rock anchor depth testing provides the ability to automate measurements and determine characteristic parameters ofrock anchors . By using this system, it is possible to ensure the stability and safety of underground tunnels and shafts in the mining industry.

III. STUDIED OBJECTS

The objects investigated were fibreglassrock anchors, a type of rock anchor made of a composite material consisting of glass fibre reinforced polymer (FRP). These rock anchors are used in underground mines and tunnels where the environment is corrosive, such as in the Wieliczka salt mine. Fibreglass bolts are corrosion resistant and can withstand the harsh conditions found in these environments[14]–[16].

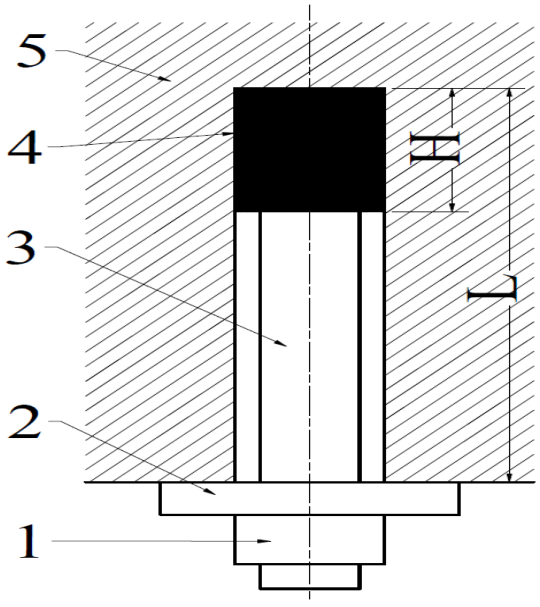


Fig. 2 Rock anchor fixing scheme: 1–nut; 2–washer; 3–anchor bolt; 4-glue; 5-rock.

In the study, fibreglass rock anchors were used to measure the embedment length, which refers to the depth at which the anchor is installed in the rock, as shown in Fig.2 it is denoted by the letter L. The anchor is installed using adhesive, the letter H in Fig.2 indicates the length of the rock bolt on which the adhesive is applied. The bolt is then sealed with a washer and a nut. This measurement is important as it helps determine the effectiveness of the rock anchor in providing support to the surrounding rock.

IV. RESULTS

To classify the depth of the anchor installation, an accelerometer was used to measure the vibration acceleration of four anchors that were mounted in the rock. An accelerometer is a device that measures acceleration, which is the rate of change of velocity over time. These anchors were acoustically excited by an emitter, which is a device that produces sound waves. The data from the accelerometer was collected using Labview, which is a software tool for data acquisition and analysis. The data was then stored in TDMS (Technical Data Management Streaming) format, which is a file format specifically designed for storing and accessing large amounts of data.

The data collected by the accelerometer was then analyzed using DIAdem, which isDIAdem is a software tool for data analysis and visualization developed by National Instruments. It is designed to help users analyze and understand large amounts of data by providing tools for data processing, visualization, and analysis. DIAdem can work with data from a variety of sources, including sensors, instruments, and files, and can analyze data in both the time and frequency domains. It also includes features for statistical analysis and machine learning, as well as the ability to create custom data processing and analysis scripts. DIAdem is commonly used in a variety of industries, including automotive, aerospace, and manufacturing, to analyze data from tests, simulations, and experiments.

To further understand the differences between the anchors, the time domain signal was transformed into the frequency domain using the Fast Fourier Transform (FFT). This allows for the identification of the different frequency components of the signal. The resulting waveforms, or graphical representations of the signal, in the frequency domain are shown in Fig. 4 and Fig. 5. The highest peak in these waveforms corresponds to the natural frequency of the rock anchor, which is a measure of the inherent stiffness and resonant behavior of the anchor. The natural frequency can be used to classify the installation depth of the anchors, as different depths may result in different natural frequencies.The results of this analysis are presented in Table I.

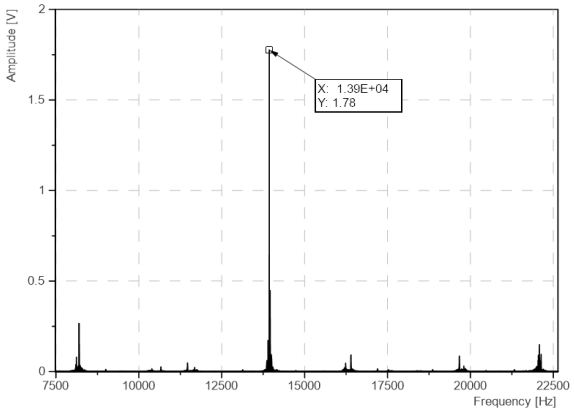


Fig. 3 Example of a signal graph in the frequency domain for a 5 meters long anchor.

To more accurately understand the behavior of the anchors, it was important to confirm that anchors with similar lengths had similar natural frequencies. To verify the lengths of the anchor installations and confirm that anchors with similar lengths had similar natural frequencies, the anchors that had been previously measured were removed from the rock and their lengths were recorded and summarized in Table I.

Initial analysis of the data showed that anchors with the same lengths did indeed have similar natural frequencies. However, in order to more thoroughly analyze the anchors and increase the reliability of the results, an additional group of anchors with known lengths was tested. This allowed for a larger sample size and a greater level of confidence in the conclusions that could be drawn from the data. The data from the measurements of the second group of anchors is presented in Table I.

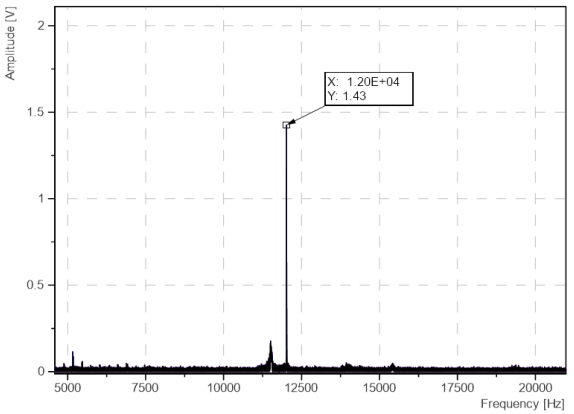


Fig. 4 Example of a signal graph in the frequency domain for a 10 meters long anchor.

Anchor	Natural frequency (Hz)	Embedmentlength (m)
1	13917	5
2	12015	10
3	12030	10
4	13924	5
5	12029	10

6	13920	5
7	13845	5
8	12009	10
9	13926	5
10	13923	5
11	12017	10
12	13930	5
13	12001	10
14	12017	10
15	13925	5
16	12049	10

Table I Results of measurements anchor natural frequencies.

To further analyze the data, the anchors were divided into groups based on the depth at which they were installed. For each group, the standard deviation and mean of the measurements were calculated and recorded in Table II.

The mean, standard deviation of the measurements and a 95% confidence level was applied to the uncertainty of the results. This means that the results of the analysis are 95% confident that the true value of the measurement falls within a certain range.

For the measurements taken on the 5 meter anchors, one of the measurements (anchor number seven) was outside the range of plus or minus two standard deviations from the mean. This means that the measurement for anchor number seven was considered to be an outlier and was rejected. All of the measurements for the 10 meter anchors, on the other hand, were within the confidence interval and were accepted as valid.

Embedment length (m)	Mean	Standard deviation
5	13912	26
10	12021	14

Table II Arithmetic mean and standard deviation for anchor groups.

V. CONCLUSION

The analysis initially used a smaller confidence interval, which is a range of values within which the true value of the measurement is believed to fall with a certain level of confidence.Using the smaller confidence interval resulted in the rejection of two results from the 10 meter anchor group. This means that these two results were considered to be outliers, or values that lie outside the expected range of the data. In order to include these results, a higher confidence level was used, meaning that a wider range of values was considered acceptable.Using a higher confidence level increases the chances that the true value of the measurement falls within the confidence interval, but it also means that the range of values considered acceptable is larger. As a result, there is a trade-off between the precision of the analysis and the confidence level used.

The non-destructive acoustical method for determining rock anchor embedment length in the Salt Mine 'Wieliczka' has been found to be effective in accurately determining the depth of anchor installations. The study produced a number of results, and all of the results that were considered acceptable (meaning they were not rejected as outliers) showed a strong correlation between the natural frequency of the anchors and their embedment length. This means that there is a relationship between these two variables: as the embedment length of the anchors increases or decreases, the natural frequency also changes.Based on this finding, the authors of the study conclude that this non-destructive acoustical method can be used to accurately determine the depth of rock anchors in the Salt Mine 'Wieliczka'. This suggests that this method could potentially be applied in other mines or similar environments to measure the depth of anchor installations.

The non-destructive acoustical method for determining rock anchor embedment length is dependent on the use of reliable measurement equipment. The specific equipment used in this study was a field-programmable gate array (FPGA) with a processor. The authors of the study found that this equipment was reliable for taking accurate measurements.

The non-destructive acoustical method for determining rock anchor embedment length involves using sound waves to measure the depth of anchor installations. In order to accurately measure the depth of the anchors, it is important to use reliable measurement equipment. The specific equipment used in this study was a field-programmable gate array (FPGA) with a processor. The authors of the study found that this equipment was reliable for taking accurate measurements. This is likely due in part to the fact that the FPGA is able to effectively manage and utilize the available computing power, which helps to reduce delays and ensure that the measurements are taken in a timely manner. The processor also plays a role in managing the overall operation of the FPGA, which can also contribute to the reliability and accuracy of the measurements. Overall, the use of a FPGA with a processor proved to be a reliable and effective tool for accurately measuring the depth of rock anchors in the Salt Mine 'Wieliczka'.

Overall the non-destructive acoustical method for determining rock anchor embedment length has the potential to greatly assist in automating the measurement process in mines. This method has been shown to be a quick and non-invasive way to obtain these measurements. Automating the measurement

process in mines can have numerous benefits. For one, it can save time by eliminating the need for manual measurement techniques, which can be time-consuming and labor-intensive. In addition, automating the process can also help to save resources by reducing the need for human labor and potentially reducing the need for specialized equipment.

REFERENCES

[1] R. Das and T. N. Singh, "Effect of rock bolt support mechanism on tunnel deformation in jointed rockmass: A numerical approach," Undergr. Sp., vol. 6, no. 4, 2021, doi: 10.1016/j.undsp.2020.06.001.

[2] P. Singh, A. J. S. (Sam) Spearing, K. V. Jessu, and P. Caroline Pinazzi da Silva Ribeiro, "Establishing the need to model the actual state of stress along rock bolts," Int. J. Min. Sci. Technol., vol. 30, no. 3, 2020, doi: 10.1016/j.ijmst.2020.03.002.

[3] K. Skrzypkowski, "An experimental investigation into the stress-strain characteristic under static and quasi-static loading for partially embedded rock bolts," Energies, vol. 14, no. 5, 2021, doi: 10.3390/en14051483.

[4] A. H. Høien, C. C. Li, and N. Zhang, "Pull-out and Critical Embedment Length of Grouted Rebar Rock Bolts-Mechanisms When Approaching and Reaching the Ultimate Load," Rock Mech. Rock Eng., vol. 54, no. 3, pp. 1431–1447, Mar. 2021, doi: 10.1007/s00603-020-02318-6.

[5] J. Kwaśniewski, I. Dominik, J. Konieczny, K. Lalik, and A. Sakeb, "Application of self-excited acoustical system for stress changes measurement in sandstone bar," J. Theor. Appl. Mech., vol. 49, no. 4, 2011.

[6] J. Kwasniewski, Y. Kravtsov, I. Dominik, L. Dorobczynski, and K. Lalik, "Self-excited acoustical system for stress measurement in mass rocks," J. Low Freq. Noise Vib. Act. Control, vol. 32, no. 1–2, 2013, doi: 10.1260/0263-0923.32.1-2.133.

[7] A. Taras and K. Saleh, "Non Destructive Inspection of Corrosion in Rock Bolts Using an Ultrasonic Waveguide Approach," in Lecture Notes in Mechanical Engineering, 2020. doi: 10.1007/978-981-13-8331-1_30.

[8] X. Z. Chen, P. Cui, D. H. Zou, and Y. Y. Zhu, "Effects of curing time and frequency on ultrasonic wave velocity in rock bolts with low-strength grout," Sichuan Daxue Xuebao (Gongcheng Kexue Ban)/Journal Sichuan Univ. (Engineering Sci. Ed., vol. 42, no. 1, 2010.

[9] V. Madenga, D. H. Zou, and C. Zhang, "Effects of curing time and frequency on ultrasonic wave velocity in grouted rock bolts," J. Appl. Geophys., vol. 59, no. 1, 2006, doi: 10.1016/j.jappgeo.2005.08.001.

[10] J. Kwaśniewski, I. Dominik, K. Lalik, and A. A. Sakeb, "Analysis of dependence between stress change and resonance frequency for Self-excited Acoustical System," Solid State Phenom., vol. 208, 2014, doi: 10.4028/www.scientific.net/SSP.208.194.

[11] K. Lalik, I. Dominik, P. Gut, K. Skrzypkowski, W. Korzeniowski, and K. Zagórski, "Non-destructive acoustical rock bolt testing system with intelligent filtering in salt mine 'wieliczka,'" Energies, vol. 14, no. 17, Sep. 2021, doi: 10.3390/en14175522.

[12] M. Saleem and A. Hosoda, "Latin Hypercube Sensitivity Analysis and Non-destructive Test to Evaluate the Pull-out Strength of Steel Anchor Bolts Embedded in Concrete," Constr. Build. Mater., vol. 290, 2021, doi: 10.1016/j.conbuildmat.2021.123256.

[13] M. Saleem, "Assessing the load carrying capacity of concrete anchor bolts using non-destructive tests and artificial multilayer neural network," J. Build. Eng., vol. 30, 2020, doi: 10.1016/j.jobe.2020.101260.

[14] H. Guo, D. Tang, C. Yao, and X. Zhang, "Study on Mechanical Characteristics of Support Structure in Tunnel Entance Section under Mechanized Construction," in IOP Conference Series: Earth and Environmental Science, Jan. 2021, vol. 643, no. 1. doi: 10.1088/1755-1315/643/1/012053.

[15] Thenevin, L. Blanco-Martín, F. Hadj-Hassen, J. Schleifer, Z. Lubosik, and A. Wrana, "Laboratory pull-out tests on fully grouted rock bolts and cable bolts: Results and lessons learned," J. Rock Mech. Geotech. Eng., vol. 9, no. 5, pp. 843–855, Oct. 2017, doi: 10.1016/j.jrmge.2017.04.005.

[16] Z. Liu, C. Zhou, Y. Lu, X. Yang, Y. Liang, and L. Zhang, "Application of FRP bolts in monitoring the internal force of the rocks surrounding a mine-shield Tunnel," Sensors (Switzerland), vol. 18, no. 9, Sep. 2018, doi: 10.3390/s18092763.

★★★