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DEVELOPMENT OF NEW COMPLEX SOFTWARE FOR INVESTIGATING ACOUSTIC VELOCITIES UNDER PRESSURE

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Abstract: Studying the pressure dependence of acoustic wave velocities in the laboratory provides important information to interpret seismic measurements in relation to petrophysical parameters. For this purpose, accurate measurement data are required, especially P and S wave velocity. In this study new software was developed in LabVIEW to measure longitudinal and transverse wave velocity under pressure on rock samples. A geophysical inversion method was used for data processing in which quantitative petrophysical model equations explaining the pressure dependence of wave velocities served as response equations. The inversion algorithm was realized in MATLAB, which was implemented in the LabVIEW measuring and data acquisition program, resulting in a complex software.

Keywords: *acoustic measurements, LabVIEW software, seismic velocity, pressure*

1. INTRODUCTION

Extrapolation of seismic/acoustic properties measured on rock samples in laboratory at a given pressure state plays a significant role in the interpretation of seismic data. Based on the velocities, estimates of pressure dependent porosity – a key characteristic in well logging – can be derived [1], [2]. It has been observed that pressure has a greater influence on velocities in the beginning phase of loading and later lessens, and that the velocities tend to a limit value. The most frequently used mechanisms for explaining this process are based on the closure of microcracks [3] or pores [4] in rocks under pressure. For an analytical description of the nonlinear velocity vs. pressure relationship, exponential functions are most commonly used [5], [6].

Rock properties can be described by material characteristic parameters. The dynamic elastic moduli, e.g. compression *(K)*, shear *(G)*, Young's modulus *(E)*, or Lamé coefficients *(μ and λ)* are important and often specified quantities and can be expressed by the acoustic propagation velocities [7]

$$K = \rho\left(\alpha^2 - \frac{4}{3}\beta^2\right), \tag{1}$$

$$G = \mu = \beta^2 \rho\,, \tag{2}$$

$$\lambda = \alpha^2 \rho - 2\mu \,, \tag{3}$$

$$E = \beta^2 \rho \frac{3\alpha^2 - 4\beta^2}{\alpha^2 - \beta^2} \,. \tag{4}$$

The pressure dependence of the density of a rock is assumed negligible in comparison of velocities (i.e. the density ρ is considered to be a constant value). It can be seen that for the description of the pressure dependence of the elastic parameters, pressure-dependent velocity data measured in laboratory are required. In this paper new software is presented that allows us to measure velocities accurately, which is important for the precise deduction of the pressure dependent elastic parameters.

2. EQUIPMENT FOR LOADING THE SAMPLES

Measurements on different cylindrical sandstone samples under uniaxial stresses were performed. The digitally controlled test system *(Figure 1)* includes a pressure cell, a load frame (max. 300 kN) and a pressure generator (max. 80 MPa).

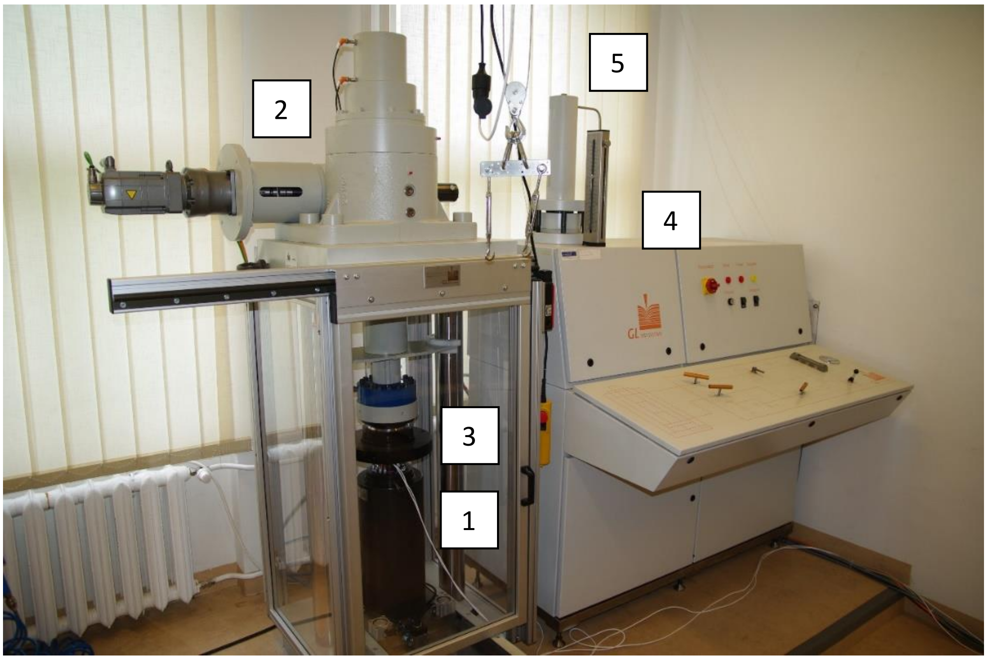

Figure 1
Equipment: (1) pressure cell; (2) load frame; (3) pressure plate; (4) pressure generator; (5) piston

The pressure cell enables triaxial loading ($\sigma_1 \neq \sigma_2 = \sigma_3$) of 35 mm diameter cylindrical, maximum 100 mm height specimens. The pressure stamps include piezoelectric crystals for acoustic measurements. Transducers in the stamps have 1 MHz eigenfrequency and are sealed against confining pressure.

3. LabVIEW software to measure P/S wave velocities under pressure

Acoustic longitudinal (P) and transverse (S) wave velocities are measured in the laboratory, primarily by using the pulse transmission technique [8]. The arrival times of the pulse can be detected by the software, i.e. if the length of the sample is known, it is possible to measure P and S wave velocities. This is the so-called pulse transmission technique. Note that to calculate the correct velocity one has to measure first the arrival time of acoustic wave propagates only in the pressure stamps. By pushing the stamps together one can measure the time belonging to the first arrival, the so-called "t deads" (P: 17120 ns, S: 31380 ns).

The new measuring & data acquisition program was designed in LabVIEW. For the development of the software a National Instruments PCI-6251 card connected to an NI BNC-2110 adapter as well as LabVIEW installed on a PC. The adapter has 15 BNC connectors and a 30-pin terminal block. Since the pressure cell has an ED4-200 RT-type electrical lead-through and I would like to connect the analog signal to the adapter by BNC connector, an FFA.0S LEMO-BNC shielded twisted pair cable was used for signal transmission. A Tektronix AM502 differential amplifier was used to increase the amplitude of the signal.

The measuring equipment provides the possibility to measure the propagation times of both P and S waves. The software should be suitable for measuring, visualizing (real-time) ultrasonic waves, supporting data export in .txt, and also evaluating the measured data by geophysical inversion method. Since it can happen that the parameters (such as the channels to be measured) should be changed while the program is running, but elementary functions were applied when writing the program, rather than the built-in DAQ Assistant. In the task framework for the core of the program the following parameters were defined: channels, timing, triggering and reading *(Figure 2)*.

It can be seen that analog voltage signal measurement was set at the created channel. The specific physical channel can be selected via a drop-down menu on the front panel (e.g. AI0-channel). The measurement range is ±5 V and at the Input terminal configuration common ground point measurement was set (referenced single ended – RSE). In RSE mode one can measure the signal relative to the ground point. The measurement starts by clicking on the button called "Mérés indítása". The timing of the detected samples from the physical channel can be adjusted by the AI Sample Clock, for which a 1 MHz sampling rate and finite sampling (8192 sample) were set. The AI Start Trigger Signal function block (hereinafter FB) ensures the start of sampling. As can be seen in *Figure 2*, rising edge trigger mode was chosen with a 2 V trigger level, i.e. the sampling starts if the detected analog signal exceeds 2 V.

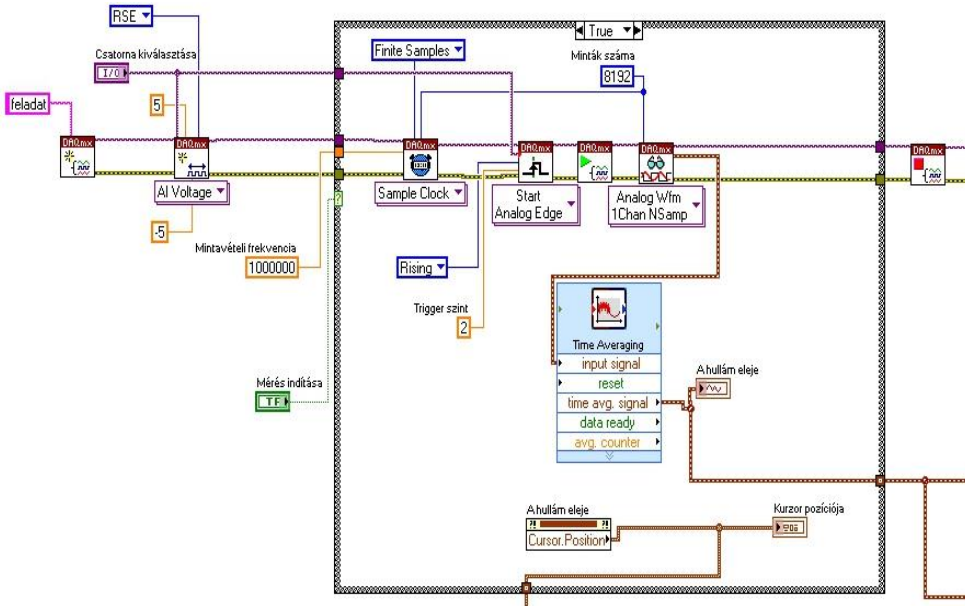

Figure 2
Core of the LabVIEW software

The DAQmx Read FB is responsible for reading the detected voltage values (a total of 8192). The values were read out in waveform format, because then the time axis data are automatically obtained from the timing data of sampling, so the wave can be visualized immediately. A 256-fold summary was applied in the software (Time Averaging FB), which means a running average of 256 consecutive measurements. With this method the amplitudes of external noises in the displayed wave were significantly reduced; consequently, the first arrivals can be determined accurately. After stacking the signal it can be easily displayed in a waveform graph (lower graph in *Figure 3*). Since the first arrival is expected in the first/second quarter of the signal (of course this depends on the length and material of the sample) a second graph was created (the upper graph in *Figure 3*).

The actual value of the signal can be obtained by adding a cursor to the upper graph, which is represented by a yellow cross in *Figure 3*. The X–Y coordinates belonging to the easily picked first arrival can be seen in the indicator called "Kurzor pozíciója". Since the propagation velocity is calculated from the arrival time and the sample length, the operator can specify the length of the sample in the front panel (the actual velocity is displayed in the upper right corner in *Figure 3*).

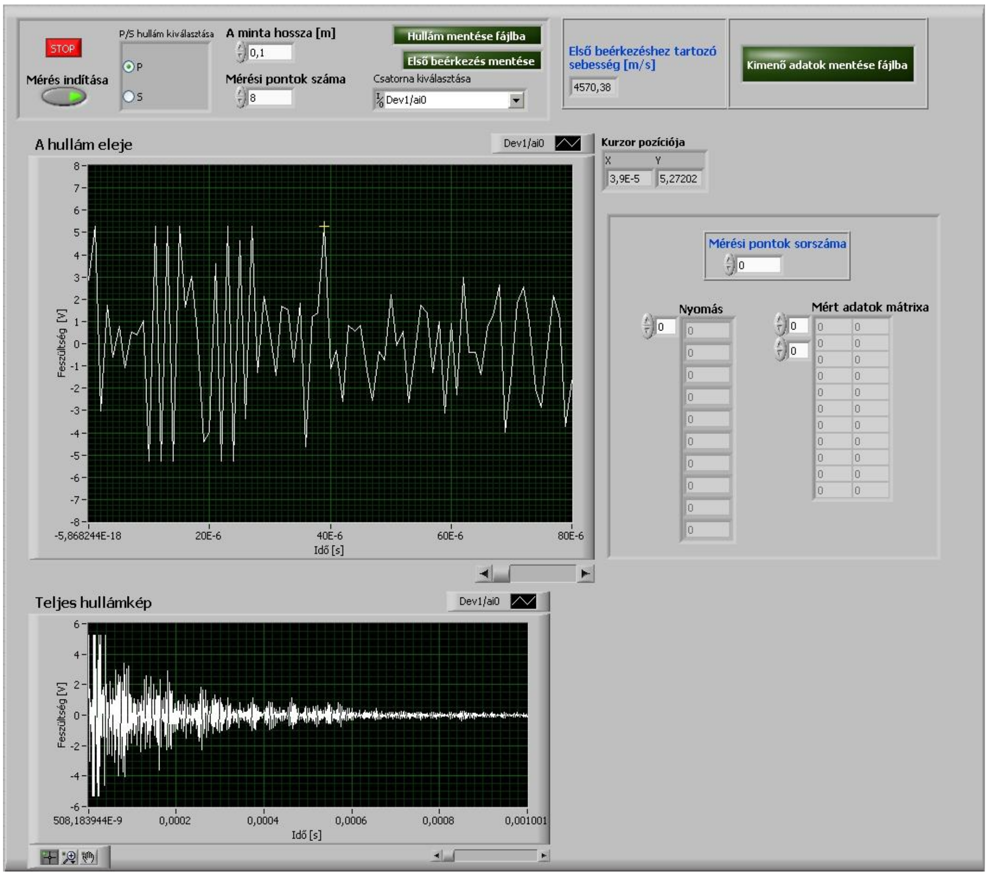

Figure 3
The user interface of the developed LabVIEW software

The so-called “t deads” should be taken into correction at velocity calculation. Since “t deads” are different for the P and S waves, with the help of a radio button one can select what kind of wave is to be measured. The block diagram belonging to this program section can be seen in *Figure 4*.

The voltage-time values related to the picked first arrival (activated when the button called “Első beérkezés mentése” is pressed) as well as the entire signal (the button called “Hullám mentés fájlba” activates Write to speadsheet file.vi) are enabled to save due to the possible subsequent data processing (e.g. the modification of the first arrival). These two saving methods can be seen in *Figure 4*. Since a .txt file can be imported easily into the often used Reflex software for seismic data processing, it was advisable to save these data in .txt format. It is important that in the pop-up window the operator should enter the file extension (.txt) beside the name of the file, as indicated in the documentation of the button *(Figure 4)*.

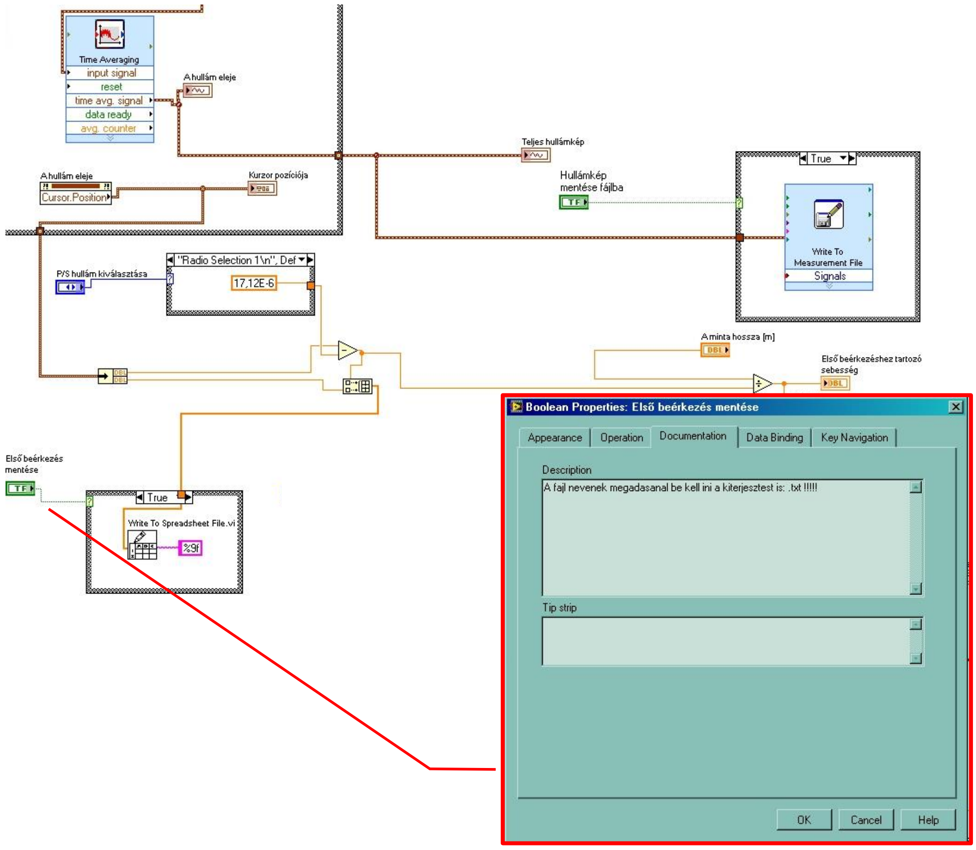

Figure 4
Program section of wave selection and saving

The next step is to load the velocities belong to the first arrivals at a given pressure into a matrix, i.e. the data acquisition. We can see in *Figure 5* that a vector called “Mért adatok vektora” was created by the Initialize array FB. Its number of rows is determined by the control “Mérési pontok száma” (on how many pressure steps we want to measure). This vector is filled with the velocity data belong to the first arrival on each pressure step by the Insert into array FB. The location of each velocity value (row index) in the vector is indicated by the control called “Mérési pontok sorszáma”. As we increase this number the velocity value is inserted into the proper row *(Figure 5)*.

A case structure ensures that the program section for number shifting is executed repeatedly (its input is a condition inquiry). In order to avoid the overwriting of each line with the actual velocity value, a *for* cycle was necessary (N in *Figure 5* is equal to the value of the control called “Mérési pontok sorszáma”). In the cycle the Index array FB removes the velocity data due to the running index from the indicator called

"Mért adatok vektora". Therefore the output of the *for* cycle will be a new vector that already contains all the measured velocities *(Figure 5)*.

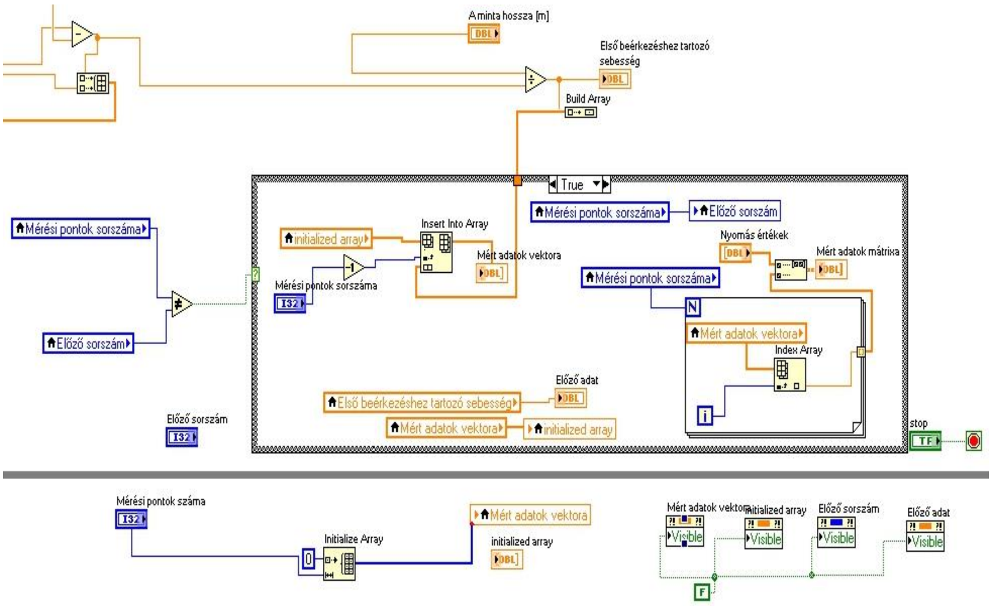

Figure 5
Program section for data acquisition

We can see in *Figure 3* that the operator can input the pressure data manually on the user interface (i.e. the column vector called "Nyomás értékek" will be filled). Thus a matrix called "Mért adatok mátrixa" is created whose first column contains these pressure data and the second the velocity values. Obviously the measurement stops when pressing the Stop button (the program exits from the while loop). Saving the measured pressure-velocity data into a matrix in LabVIEW (by the button called "Kimenő adatok mentése fájlba") enables immediate data processing. In the next section, the data processing by inversion method will be described.

4. DATA PROCESSING BY INVERSION METHOD

In [7] petrophysical models were developed which provide the relationship between P and S wave velocities as well as rock pressure, thus creating the possibility to determine the velocity values at any pressure by the model equations (α: P wave, β: S wave)

$$\alpha = \alpha_0 + \Delta\alpha_0\,[1-\exp(-\lambda_V\sigma)]\,, \qquad \beta = \beta_0 + \Delta\beta_0\,[1-\exp(-\lambda_V\sigma)]\,. \qquad (5)$$

These equations provide a theoretical connection between the P and S wave velocities and rock pressure in case of loading. In these equations λ_V is the logarithmic stress sensitivity of the propagation velocities [9], α_0 and β_0 are the propagation velocities at a stress-free state, which can be measured in the laboratory, $\Delta\alpha_0$ and $\Delta\beta_0$ can be considered the velocity drops (relative to the fully compacted state where the pore volume equals zero) caused by the presence of pores at zero pressure [10]. During development BIRCH's qualitative consideration [4] was followed, stating that the main factor determining the pressure dependence of propagation velocity is the closure of pores, i.e. decreasing of pore volume (parameter V as the unit pore volume of a rock). Due to increasing pressure from the unloaded state, first the large pores close in the rock sample, and after the slower compression process of smaller pores, nearly all pores are closed. Since the model is based on the pore volume, or rather the change in pore volume, it is suitable to describe the pressure dependence of longitudinal and transverse wave velocities, respectively.

In the terminology of geophysical inversion, *Equation (5)* represent the solution of the direct problem. Parameters α_0, $\Delta\alpha_0$, β_0, $\Delta\beta_0$, λ_V appearing in these equations are not known, but can be determined indirectly by inversion processing of the measurement data. In the inversion program written in MATLAB the least squares method was used [11]. P/S wave velocity data belong to the first arrivals at each pressure measured by the new software provided the input data. The output data of the data processing were the estimated model parameters and the quantities characterizing the goodness of the inversion procedure. Due to the faster data interpretation the measured and calculated data were also displayed graphically.

5. TESTING THE NEW SOFTWARE

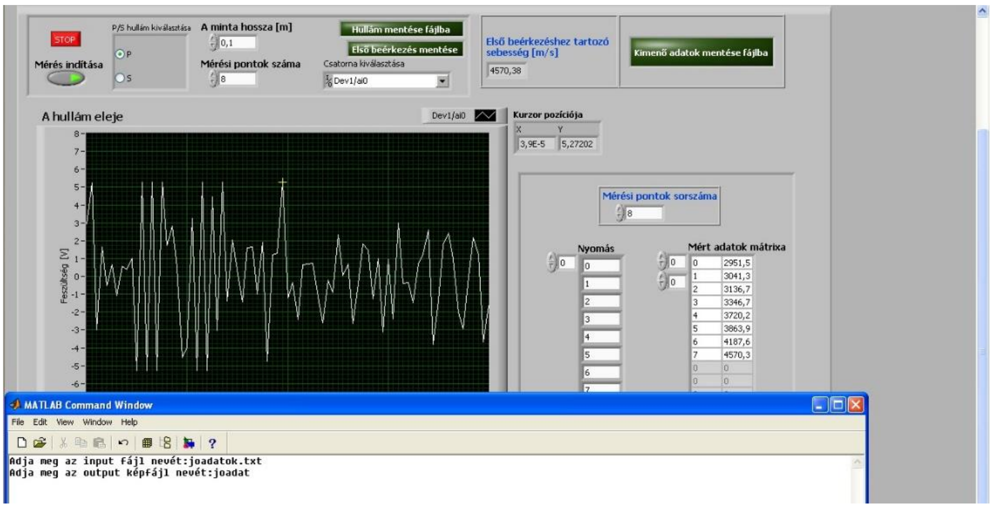

Figure 6

MATLAB under LabVIEW

In this paper one test result is presented. Longitudinal wave velocity was measured on a sandstone sample. The uniaxial loading of the sample was carried out with the measurement equipment detailed in Section 3 (during measurement ramp function was used at 0.05 kN/s velocity). To avoid the failure of the samples it was loaded only up to 1/3 of the uniaxial strength. A 256-fold stacking was applied to increase the signal/noise ratio. During testing the longitudinal wave velocity data measured on the sample together with pressure values were saved in a .txt file.

For data processing the inversion algorithm was executed in the MATLAB Command Window, which opens automatically after LabVIEW starts. This can be seen in Figure 6. This function is only available under the Windows operation system and works in MATLAB version 6.5 and above.

The inversion results (calculated model parameters with estimation errors, RMS and mean spread) can be seen in *Figure 7*.

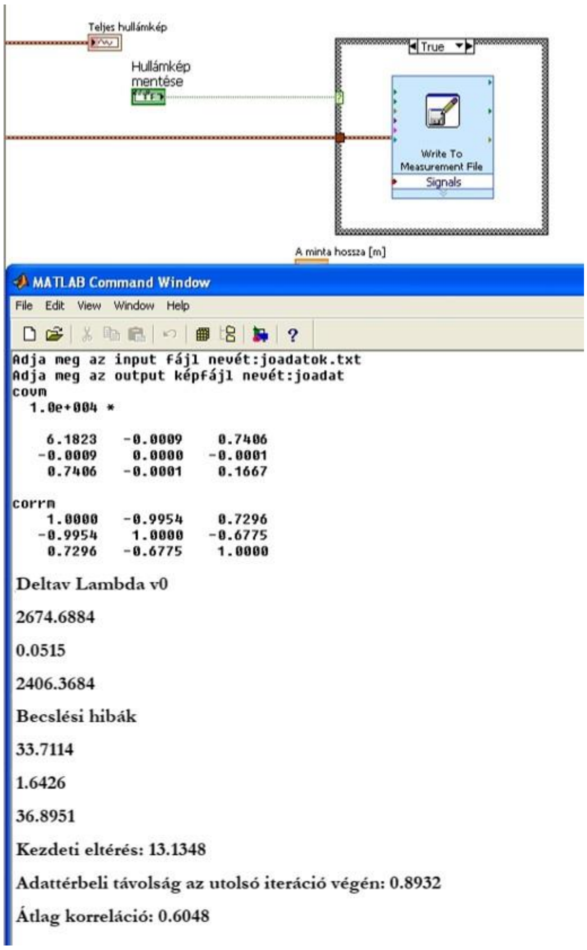

Figure 7
Inversion results

Using the model *Equations (5)* the velocity values at any pressure can be calculated, which can be seen in *Figure 8*. Dots mean the measured values while the solid lines represent the calculated values (one can see that the calculated graph is exponential, which is in conformity with the literature). It can be seen that in the lower pressure range, the increase in velocity with increasing pressure is steep and nonlinear. This is due to the closure of pore volume, which significantly affects the elastic properties of rock and thereby the velocities. In the higher pressure range, the increase in velocity (with increasing pressure) becomes moderate as the closeable pore volume lessens.

Figure 8 shows that the calculated curves are in good accordance with the measured data, proving that the petrophysical model applies well in practice and that the new software as well as the MATLAB algorithm under LabVIEW worked properly.

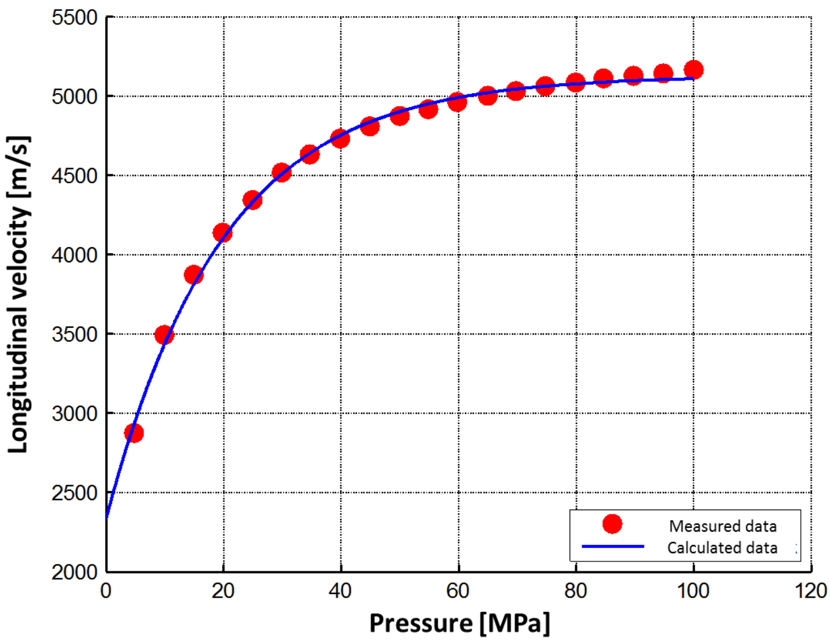

Figure 8

Measured and calculated P wave velocity vs. pressure

6. Conclusions

In this paper new LabVIEW software was presented to measure longitudinal and transverse wave velocity on rock samples under uniaxial pressure. Measured data were processed in a geophysical inversion procedure (MATLAB algorithm for least squares method) based on the developed rock physical model, which describes the pressure dependence of acoustic velocities. The decreasing pore volume [4] explanation for the pressure-velocity relationship was used in development of the petrophysical model. To confirm the reliability of the acoustic software, laboratory measurements were made on cylindrical rock samples and data were processed with the inversion software. One example of successful application was presented in the paper. As a result of the developed software, it is possible to use one computer instead of three for a complex measurement.

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LIST OF SYMBOLS

Symbol	**Description**	**Unit**
E	Young modulus	N/m^2
G	shear modulus	N/m^2
K	compression modulus	N/m^2
V	unit pore volume of a rock	m^3
α	longitudinal (P) wave velocity	m/s
α_0	longitudinal (P) wave velocity at stress-free state	m/s
β	transverse (S) wave velocity	m/s
β_0	transverse (S) wave velocity at stress-free state	m/s
$\Delta\alpha_0$	longitudinal (P) wave velocity-drop at zero pressure	m/s
$\Delta\beta_0$	transverse (S) wave velocity-drop at zero pressure	m/s
λ	first Lamé coefficient	N/m^2
λ_V	new material quality dependent petrophysical parameter	1/MPa
μ	second Lamé coefficient	N/m^2
ρ	density	kg/m^3
σ	stress	MPa

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