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Pipeline Leakage Detection by Means of Acoustic Emission Technique Using Cross-Correlation Function

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Abstract There are many difficulties and constraints when carrying out the inspection and maintenance of underground technological pipes. Accidental leakage occurs invariably and can represent a matter of great concern for the environment and the economy. In addition, during the last decade, reliable and secure systems are required for detecting leaks, due to stricter legal rules implemented in developed countries; the acoustic emission (AE) technique, which was widely used as a non-destructive testing (NDT) technique for detecting leakage in pipe lines, heat exchangers or pressure vessel structures, can be used for their inspection, although these structures are relatively large. The system for leak detection presented in this paper is based on the principle of leak location by means of the cross-correlation method using a data acquisition system, acoustic sensors and software application developed in LabVIEW programming environment. The system performs the following functions: storing in a database the image of the cross-correlation function graph of the pipeline leakage detection and generating automated reports of the pipeline leakage detection process. This method was tested successfully.

Keywords Cross-correlation, Acoustic emission, Leakage detection, LabVIEW environment

1. Introduction

Following the increasing public awareness and concern for the environment, pipeline leakage events indicated that financial losses incurred by a company can be more significant than the idle times and cleaning costs. In addition, reliable and secure systems are required for detecting leaks, due to stricter legal rules implemented in developed countries [1-5].

There are many difficulties and constraints when carrying out the inspection and maintenance of underground techno-logical pipes. Accidental leakage occurs invariably and can represent a matter of great concern for the environment and the economy.

In addition to the economic advantages, there are other benefits related to the timely detection of leakage, such as: the safety of water supplies, environment protection, water quality protection, preventing further pipe cracks in order to avoid additional damage [6-9].

Several sensors are usually installed along the line, given the limited area of detection. These sensors detect the acoustic signals in the pipe and differentiate between leakage acoustic emission and other sounds generated by normal operating changes [10-12].

The rapid development of electronics industry led to the development of the electroacoustic equipment, acoustic sensors, amplifiers, digital filters, data acquisition, storage, processing and transmission systems, which contribute to the improvement of fault detection efficiency.

The intensity of the sound depends on the distance to the noise source: it is the highest in proximity to the source and decreases proportionally to the distance from the source in all directions. The pipeline material significantly affects the sound propagation speed. For example: for steel and cast iron, the intensity can be traced on longer intervals from the fault, while in the case of PVC and HDPE the sound can only be detected near the source.

The exact location of the fault can be determined based on the sound propagation speed in the fluid or the pipe wall, by means of the acoustic correlation. There will be a time lag for the sound detected when the sensors (surface microphones or hydrophones) are placed on both ends of the section of pipe where the fault is assumed to occur, as opposed to the cases where the fault is located halfway between those two sensors. The signals transmitted by the two sensors will be analyzed by the basic unit of the correlator according to the time of advent. The correlator will specify the exact location of the fault based on the sound propagation speed.

During the first stage of the fault location procedure, the noise caused by cracks can be “heard” by using equipment

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which includes special microphones. This type of location is mostly based on user experience, by assessing the location of the crack with the help of headphones. The "precise location" represents the next stage of the procedure and is carried out by using a noise and vibration correlator [13].

The "cracking noises" or "leakage noises", as mentioned in the literature are generated by the flow of fluid out of the pipeline, through cracks, and they propagate through the fluid inside the pipe, to the material of the pipe and the soil around the pipe.

During the last decade, the acoustic emission technique was widely used as a non-destructive testing (NDT) technique for detecting leakage in pipe lines, heat exchangers or pressure vessel structures, and although these structures are relatively large, their inspection can be carried out by using this technique [14-16].

The system for pipeline leakage detection presented in this paper uses the acoustic emission technique based on the cross-correlation function. The system performs the following functions: estimating the position of the pipeline leakage based on LabVIEW graphical programming environment, storing the acquired data in a database type MySQL Server and automatically creating and printing reports [17-19].

The paper is an extension of work of [20] and is structured as follows: Section 2 describes the leakage location procedure based on the acoustic emission technique. Section 3 presents the hardware and software description of the acoustic emission monitoring system. Section 4 refers to the experimental results and a section of conclusions is included at the end of the paper, containing the main aspects and advantages of the developed system for pipeline leakage detection by using the acoustic emission technique.

2. The Description of the Leakage Location Principle by Using the Acoustic Emission Technique

In the case of noise and vibration correlators, the sensors come into contact with the pipe material. They will retrieve the cracking noises and transmit them to a noise and vibration correlator, and due to the fact that the noise propagates with the same speed, the sensor which is located closer to the fault will retrieve the signal faster. The propagation speed depends primarily on the material of the pipe. If this speed is known or determined by experiments, the difference between the moments in time when the cracking noise reaches the two sensors will indicate the crack location [13].

The correlator operating principle is shown in Figure 1.

The fault location, if the origin of the axis is by the sensor on the left is given by the formula (1):

$$L_1 = \frac{1}{2}(D - \Delta T \cdot C), \tag{1}$$

where:
- D – the distance between the sensors;
- C – the propagation speed of the acoustic signal in the pipe (constant);
- ΔT – sample frequency-1 * time lag.

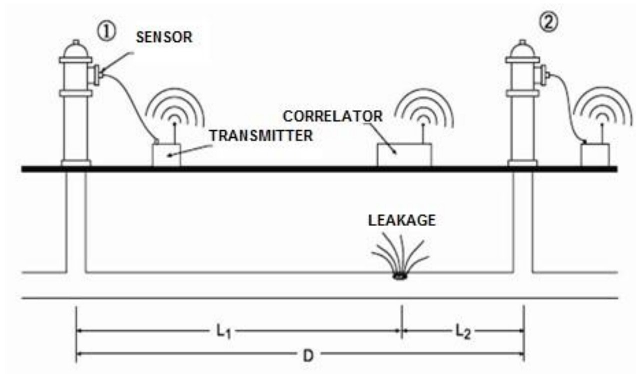

Figure 1. The principle of noise source location by means of correlation

The transmission of the signals picked up by the sensors to the correlators is achieved by means of radio waves or wires. The operation of signal processing algorithms for the identification of noise sources is based on the cross-correlation method.

The cross-correlation function identifies the degree of similarity between two data sets, and is an important tool for the statistical analysis of signals. The cross-correlation method makes reference to the relation between a signal and its lagged version; the cross-correlation method allows the determination of the difference in the propagation time in terms of the position of its peak value [14, 15].

If we consider the signals *x(n)* and *y(n)* as signals which propagate from the noise source to the two piezoelectric sensors (the signals contain N samples and are considered stationary with zero mean value), we can define the cross-correlation function as follows:

$$r_{xy}(l) = \frac{1}{N} \cdot \sum_{n=-\infty}^{\infty} x(n) \cdot y(n+l), l = 0, \pm 1, \pm 2 \ldots N-1 \tag{2}$$

The index *I* is considered to be the time lag. The order of the indices show that signal *x(n)* remains unchanged while *y(n)* is lagged by *I* time units, practically *y(n)* represents a lagged version of signal *x(n)* by *I* time units.

In order to obtain a normalized cross-correlation (with peak values in the range -1 ÷ 1) the following formula can be applied (3):

$$\rho_{xy}(l) = \frac{r_{xy}(l)}{\sqrt{r_{xx}(0) \cdot r_{yy}(0)}} \tag{3}$$

In special cases when the crack is located midway between the sensors, the peak value is negative concentration value. For example, if the index of peak value of FIC is r samples, then the lag value expressed in units of time D_{time} = r*T_e can be calculated, where T_e represents the value of the sampling period (see Figure 2).

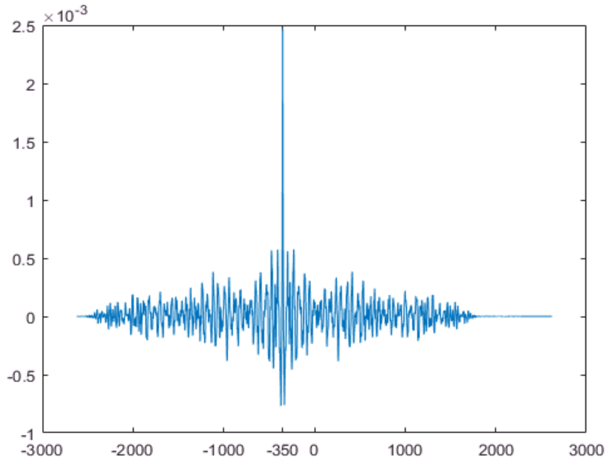

Figure 2. Non-normalized FIC calculated for signals x, y

3. Hardware and Software Description of the Leakage Detection System

The rapid adoption of the PC in the last 20 years catalyzed a revolution in the instrumentation for test, measurement, and automation. One major development resulting from the ubiquity of the PC is the concept of virtual instrumentation, which offers several benefits to engineers and scientists aiming for increased productivity, accuracy, and performance [17].

A virtual instrument consists of an industry-standard computer or workstation equipped with powerful application software, cost-effective hardware such as plug-in boards, and driver software, which together perform the functions of traditional instruments. Virtual instruments represent a fundamental shift from traditional hardware-centered instrumentation systems to software-centered systems that exploit the computing power, productivity, display, and connectivity capabilities of popular desktop computers and workstations. Although the PC and integrated circuit technology have experienced significant advances in the last two decades, it is software that truly provides the leverage to build on this powerful hardware foundation to create virtual instruments, providing better ways to innovate and significantly reduce costs. With virtual instruments, engineers and scientists build measurement and automation systems that suit their needs exactly (user-defined) instead of being limited by traditional fixed-function instruments (vendor-defined) [18].

The hardware and software architecture of the pipeline leak detection system is achieved for the implementation of the cross-correlation method.

3.1. Hardware Description

For the validation of the method, a hardware structure is presented, where the connection between the two sensors and the data acquisition and processing system is achieved by wire.

The designed structure is shown in Figure 3 and has the following components:

- S1, S2 – acoustic sensors - VS30-SIC-46dB;
- Data acquisition card (DAQ) NI-USB 6003;
- PC host.

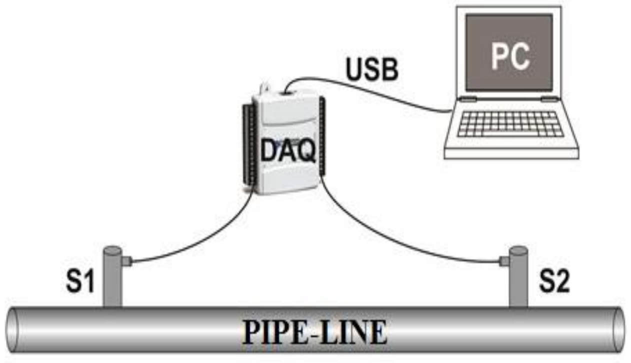

Figure 3. Hardware architecture of the leakage detection system

The VS30-SIC-46dB is a piezoelectric AE-sensor with integrated preamplifier. The low frequency response makes it particularly suitable for monitoring large objects or objects made of highly attenuating materials. The VS30-SIC-46dB can be used for tank floor corrosion and leak detection, leak detection in pipelines, partial discharge detection and integrity testing of concrete structures. The integrated preamplifier has a 46 dB gain and supports pulse through for automatic sensor testing [16].

The NI-USB-6003 is a low-cost, multifunction DAQ device. It offers analog I/O, digital I/O, and a 32-bit counter. Some specification of the NI-USB 6003 are 8 AI (16-Bit, 100 kS/s), 2 AO (5 kS/s/ch), 13 DIO USB Multifunction I/O Device [12]. The USB-6003 provides basic functionality for applications such as simple data logging, portable measurements, and academic lab experiments. The included NI-DAQmx driver and configuration utility simplify the configuration and the measurements.

A schematic diagram for the module of supplying power and decoupling of the AC component from the signal is presented in figure 4.

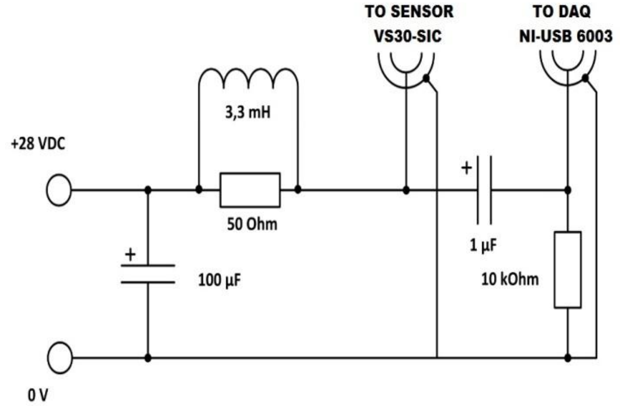

Figure 4. Module for supplying power to the preamplifier and decoupling the AC component from the signal [16]

3.2. Software Description

LabVIEW is a graphical programming language which uses icons instead of lines of text to create applications. In contrast to text-based programming languages, where instructions determine program execution, LabVIEW uses dataflow programming, where the flow of data determines execution. The programming language used in LabVIEW, also referred to as G, is a dataflow programming language. Execution is determined by the structure of a graphical block diagram (the LV-source code) on which the programmer connects different function-nodes by drawing wires. These wires propagate variables and any node can execute as soon as all its input data become available. Since this might be the case for multiple nodes simultaneously, G is inherently capable of parallel execution. Multi-processing and multi-threading hardware is automatically exploited by the built-in scheduler, which multiplexes multiple OS threads over the nodes ready for execution [17, 18].

The software architecture of the pipeline leakage detection system is presented in Figure 5.

The application software for pipeline leakage detection by using the acoustic emission technique by means of the cross-correlation function is based on state machines. A state machine consists in programming architecture which can be used to implement any algorithm that can be explicitly described by a state diagram or flowchart.

The main software modules of the application perform the data acquisition and filtering of the acquired signal in order to reduce noise and the filtered data are written in the MySQL Server using the Database Write Module. The following modules are used to view the instant evolution of the acquired values, to estimate the pipeline leakage value using the cross-correlation function, to achieve automatic reports: Data Acquisition, Cross-Correlation Function, Leakage Detection Estimation and Automatic Report Software Module.

Figure 6 presents the software interface of the proposed pipeline leakage detection system and Figure 7 presents the block diagram of the software application.

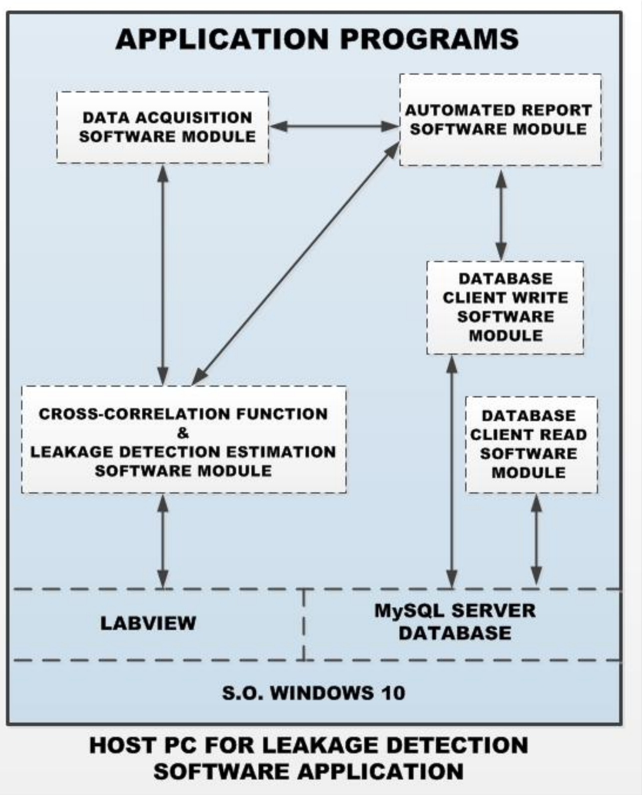

Figure 5. The software architecture of the leakage detection process

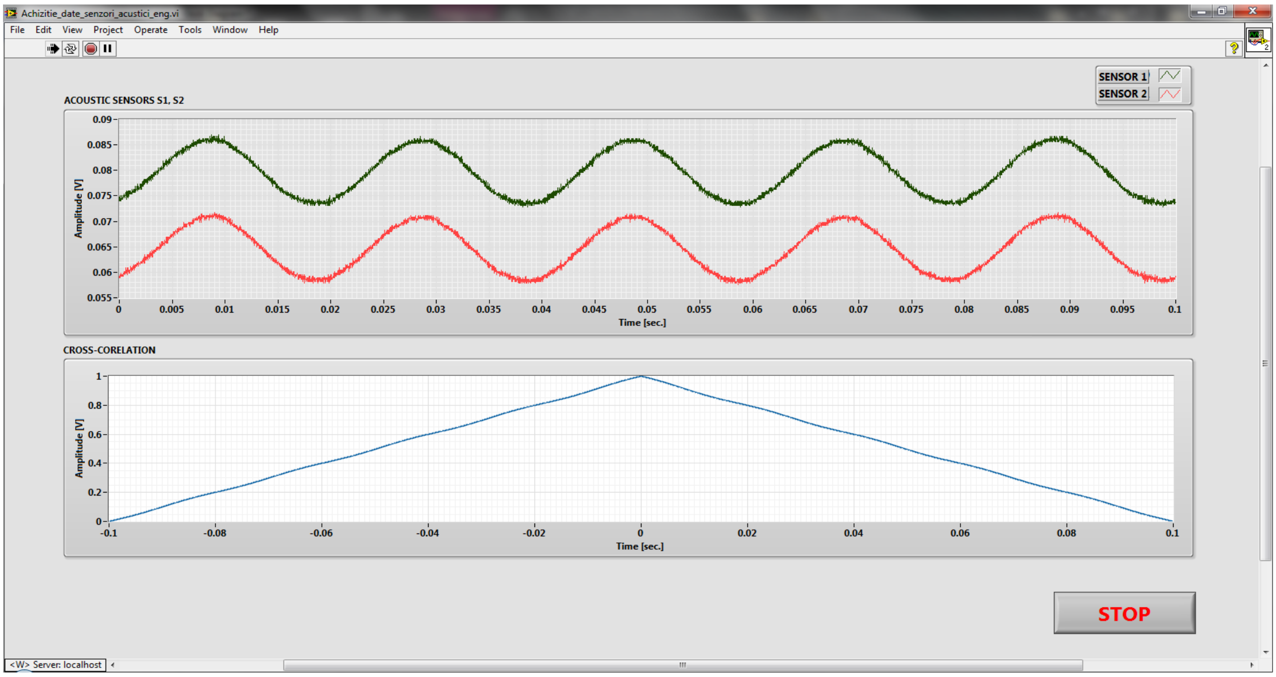

Figure 6. Software interface of the application

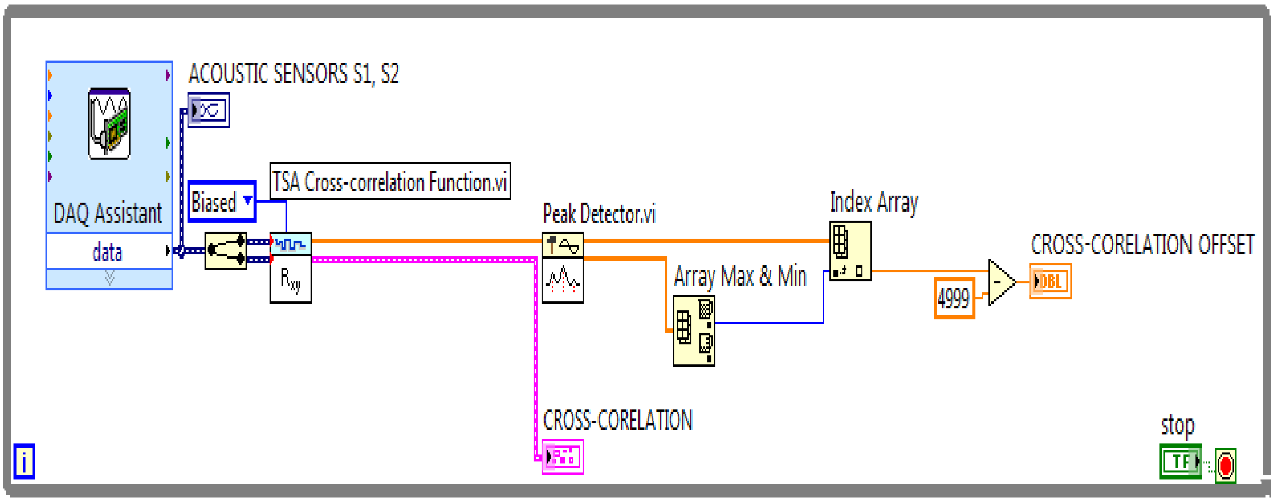

Figure 7. Block diagram of the application software

The following block diagram shows one way of indexing the Cross-Correlation function by a VI [14, 15].

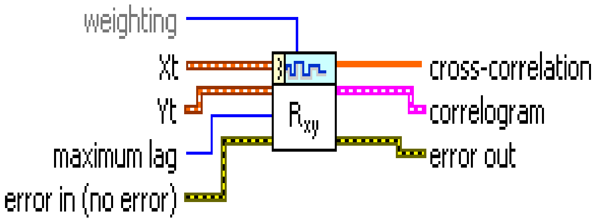

Figure 8. Cross-Correlation VI

The elements of VI are:

- Weighting specifies the use of biased or unbiased weighting in the cross-correlation calculation. The default weighting is Biased. Refer to the Details section for information about this parameter;
- Xt specifies the univariate time series;
- Yt specifies another univariate time series and is used to perform cross-correlation with Xt;
- Maximum lag specifies the maximum value of the lag used by this VI to compute the cross-correlation. The default is –1, which means the maximum lag equals max(M, N)–1, where M and N are the lengths of Xt and Yt, respectively;
- Cross-correlation returns the cross-correlation values between the two time series Xt and Yt;
- Correlogram returns, on an XY graph, the cross-correlation values against the lag.

The cross-correlation $R_{xy}(t)$ of the sequences x(t) and y(t) is defined by the following equation [14, 15]:

$$R_{xy}(t) = x(t) \otimes y(t) = \int_{-\infty}^{\infty} \dot{x}(\tau) \cdot y(t+\tau) d\tau \qquad (4)$$

where the symbol $\otimes$ denotes correlation.

The discrete implementation of the Cross-Correlation VI is as follows [15]. Let h represent a sequence whose indexing can be negative, let N be the number of elements in the input sequence X, let M be the number of elements in the sequence Y, and assume that the indexed elements of X and Y that lie outside their range are equal to zero, as shown by the following equations:

$$x_j = 0, j < 0 \quad or \quad j \ge N \qquad (5)$$

and

$$y_j = 0, j < 0 \quad or \quad j \ge M \qquad (6)$$

Then the Cross-Correlation VI obtains the elements of h by using the following equation:

$$h_j = \sum_{k=0}^{N-1} \dot{x}_k \cdot y_{j+k} \qquad (7)$$

for j = –(N–1), –(N–2), … , –1, 0, 1, … , (M–2), (M–1).

The elements of the output sequence R_{xy} are related to the elements in the sequence h by

$$R_{xyi} = h_{i-(N-i)} \qquad (8)$$

for i = 0, 1, 2, … , N+M–2.

LabVIEW arrays cannot be indexed with negative numbers, the corresponding cross-correlation value at t = 0 is the Nth element of the output sequence Rxy. Therefore, Rxy represents the correlation values that the Cross-Correlation VI shifts N times in indexing.

$$R_{xy(biased)} = \frac{1}{\max(M,N)} \cdot R_{xy} \qquad (9)$$

for j = 0, 1, 2, … , M+N–2, where R_{xy} is the cross-correlation between x and y with no normalization.

The automatic report software block diagram is presented in Figure 9.

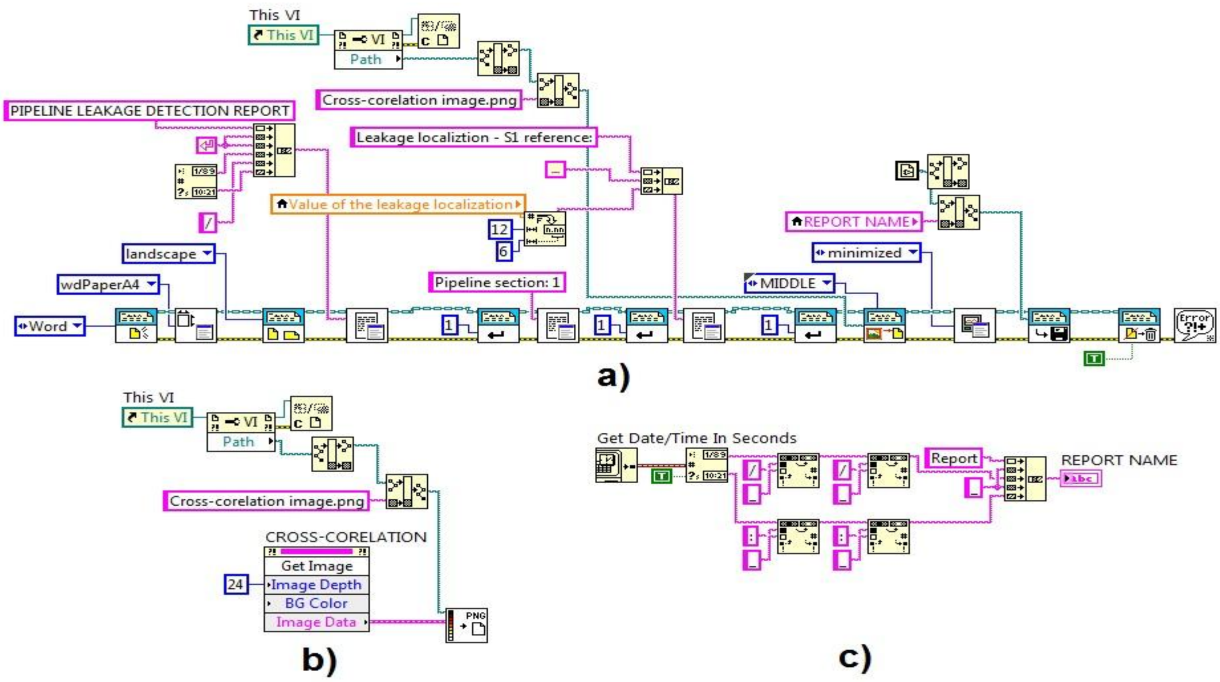

Figure 9. Automated report generation

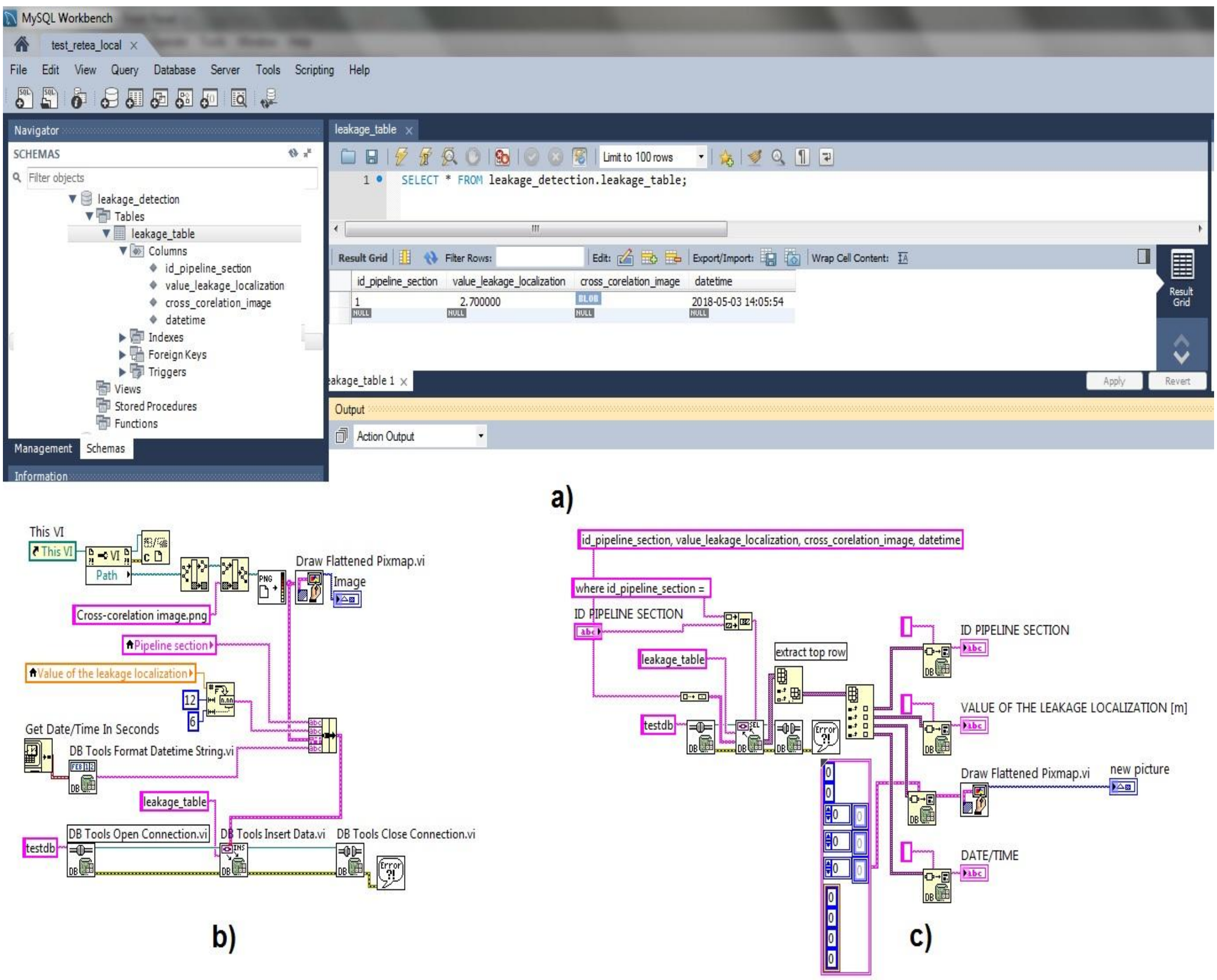

Figure 10. The software block diagram for Database connection: (a) Database structure, (b) Database Write Module, (c) Database Read Module

A DataSources (ODBC) type connection, through which the application program performs the writing and querying of the DataBase type MySQL Server is used for storing the image of the cross-correlation function graph of the pipeline leakage detection, the identificator of the section of the pipe, the localization value of the leakage indicated by the acoustic sensor. The MySQL database structure and the software block diagram for read and write database are presented in Figure 10.

4. Experiments

Figure 11 presents an experimental model which will follow the steps described in the previous sections for pipe leak location. The origin point of the axis system is fixed in sensor S1 and the axis is oriented towards sensor S2. The length of the studied pipe section is of 12 m and the sound propagation speed in the pipe is of 5500 m/s.

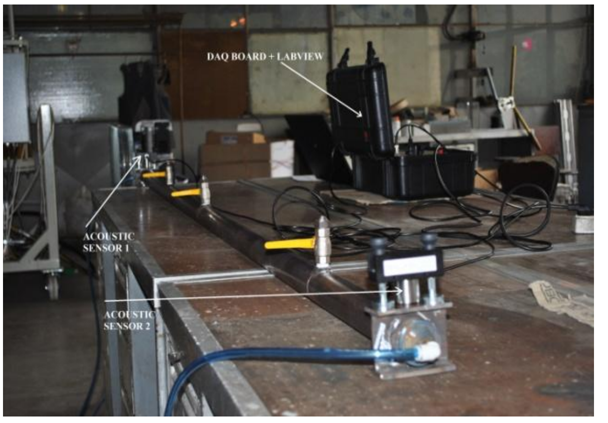

Figure 11. Experimental image

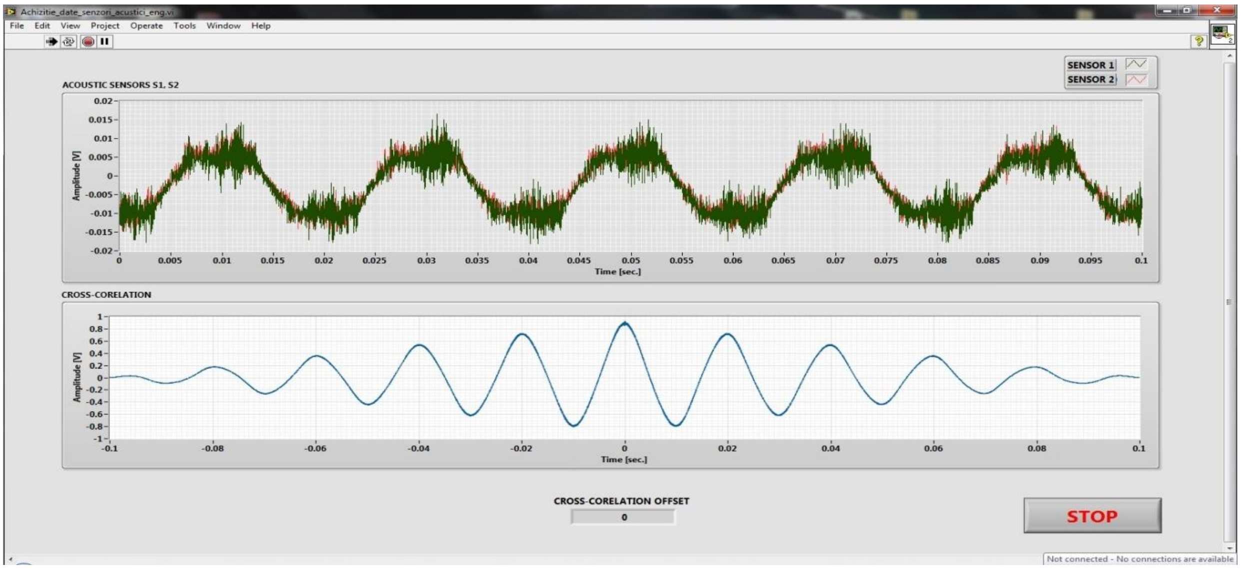

Figure 12. Software interface for simulation of the leakage in the middle of the sensors

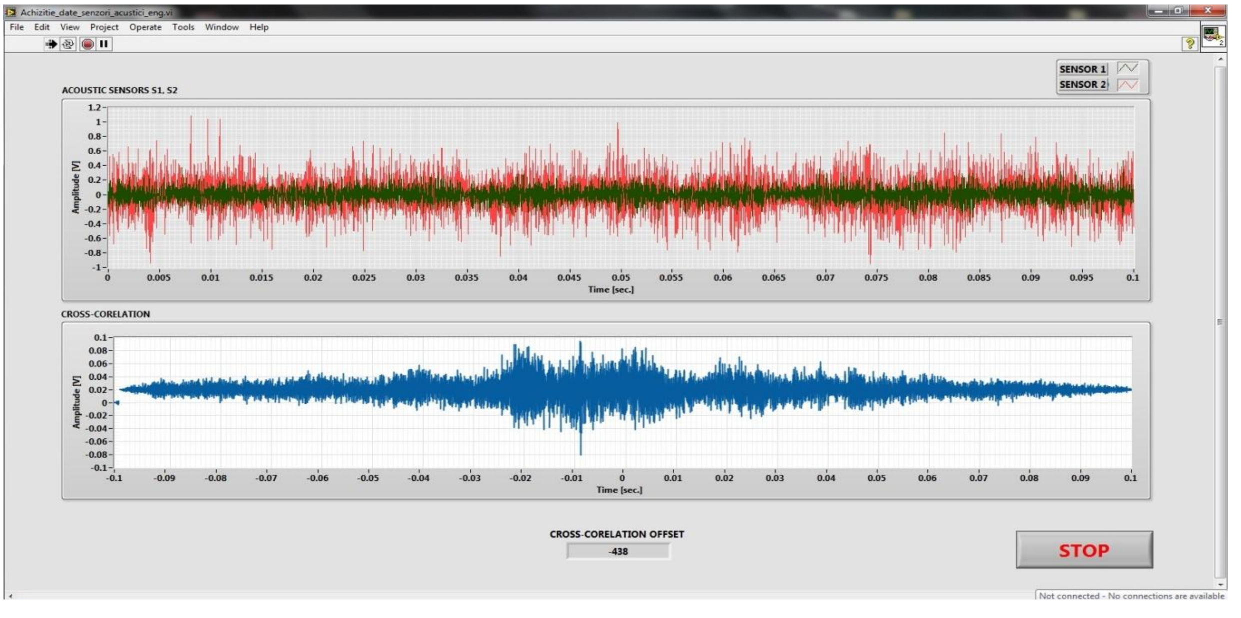

Figure 13. Software interface for simulation of the leakage near to S2

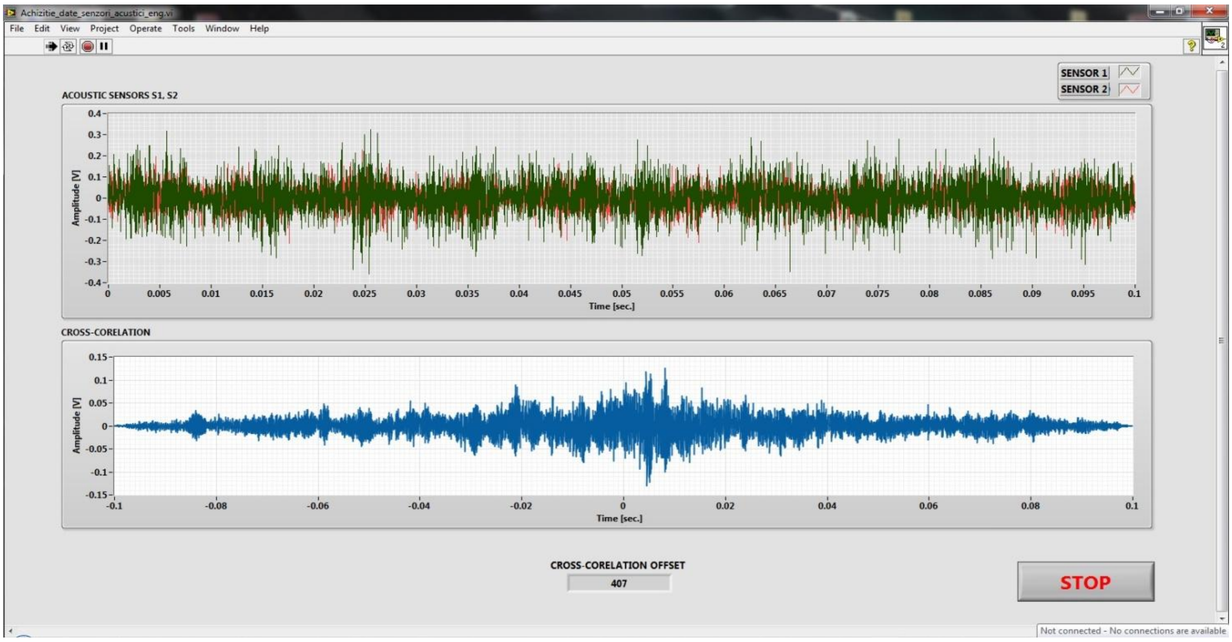

Figure 14. Software interface for simulation of the leakage near to S1

Following the tests carried out for simulating a pipe leak in the middle section (the middle valve opens), the cross-correlation function in Figure 12 is obtained. By applying the formula (1) the fault location is determined in the middle section of the pipe with an error of less than 0.01 m.

Figures 13 and 14 show the acoustic readings for a fault near S2 sensor (the right end of the pipe) and near S1 sensor (the left end of the pipeline). Generally, after a series of experiments, a relatively good localization error is obtained (for a practical system) of less than 2%.

5. Conclusions

The use of acoustic emission technique for leak-off location is the top method, made possible due to the development of electronics (high-performance sensors, data acquisition systems) as well as the development of high-performance software with computing power and precise pipe fault location.

By following the steps specified by the EA technique, a pipeline leak-off detection system was developed and presented based on the cross-correlation method. The system estimate the position of the pipeline leakage based on LabVIEW, graphical programming environment, stores the acquired data in a MySQL Server type database and automatically creates and prints reports.

As a result of experiments it was found that the system has a relatively good accuracy, subsequent developments will focus on expanding the system to a wireless multi-sensor network for leak-off detection in intertwined pipeline sections.

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