

Prospects of Frequency-Time Correlation Analysis for Detecting Pipeline Leaks by Acoustic Emission Method

V A Faerman¹, A G Cheremnov², V V Avramchuk³ and E E Luneva⁴
Tomsk Polytechnic University, Tomsk, Russia

E-mail: ¹csevladfaerman@gmail.com, ²8xandr@gmail.com, ³avs@tpu.ru, ⁴lee@tpu.ru

Abstract. In the current work the relevance of nondestructive test method development applied for pipeline leak detection is considered. It was shown that acoustic emission testing is currently one of the most widely spread leak detection methods. The main disadvantage of this method is that it cannot be applied in monitoring long pipeline sections, which in its turn complicates and slows down the inspection of the line pipe sections of main pipelines. The prospects of developing alternative techniques and methods based on the use of the spectral analysis of signals were considered and their possible application in leak detection on the basis of the correlation method was outlined. As an alternative, the time-frequency correlation function calculation is proposed. This function represents the correlation between the spectral components of the analyzed signals. In this work, the technique of time-frequency correlation function calculation is described. The experimental data that demonstrate obvious advantage of the time-frequency correlation function compared to the simple correlation function are presented. The application of the time-frequency correlation function is more effective in suppressing the noise components in the frequency range of the useful signal, which makes maximum of the function more pronounced. The main drawback of application of the time-frequency correlation function analysis in solving leak detection problems is a great number of calculations that may result in a further increase in pipeline time inspection. However, this drawback can be partially reduced by the development and implementation of efficient algorithms (including parallel) of computing the fast Fourier transform using computer central processing unit and graphic processing unit.

Introduction

Pipeline networks constructed for different purposes are an integral part of oil and gas production infrastructure. The exceptional value of the pipeline transportation for oil industry is explained by relatively transport costs, high reliability and the ability to maneuver flows [1]. Currently, crude oil and almost all petroleum products are transported through pipelines [2]. The environmental safety requirements relating to oil pipeline transport, especially to the places where pipelines cross rivers, railways, highways and ecologically sensitive areas, have been recently become much more stringent [3]. In connection with the above, failure-free operation of pipeline networks is a priority goal and rapidly developing field.

Failure-free operation of pipelines is achieved by the activities aimed at early detection and elimination of various pipe defects, such as destruction of the based metal, weld damage, defects in pipe insulation coating, etc. [1]. For these purposes, a wide variety of various domestic and foreign inspections techniques based on different operation principles is applied [2]. The most common inspection techniques are electromagnetic (eddy current) and acoustic emission testing which are



usually used together. For example, the pipeline inspection technique presented in [4] allows accurate estimation of residual wall thickness in corroded pipeline areas. In addition, such inspection is carried out in three stages:

- the damaged area of pipeline is detected by the long-wave method, with accuracy being from 3 to 4 meters;
- the corroded area of pipeline is defined by the eddy current method, with accuracy being from 2 to 4 square centimeters square centimeters;
- the residual wall thickness is estimated by the ultrasonic inspection.

Along with periodic pipeline inspection, the most important sections of pipelines can be continuously monitored by the stationary acoustic emission units [2].

However, despite pipeline requirements strengthening (particularly corrosion resistance specifications) and enhancement of early detection tools and control methods, accidents could not be completely avoided. This can be explained by the fact that the causes of pipeline accidents are not always related to the operation itself. Particularly, according to [5], 83 accidents were registered by ROSTECHNADZOR (Federal Environmental, Industrial and Nuclear Supervision Service) in the period from 2004 to 2012. The cause of 52 accidents was illegal tapping. Therefore, it is necessary to develop techniques for the rapid elimination of emergency situations and liquidation of their consequences, as well as inspection activities in order to minimize the economic loss and environmental damage during pipeline operation.

Theoretical analysis

Oil spill without fire outbreak is the most common result of pipeline failure [2]. However, in specific cases, petroleum fire is likely to happen. Because of oil loss and infrastructure damages, this leads to considerable financial expenses and dramatic degradation of environmental conditions [2]. In order to prevent oil loss, as well as the above-mentioned consequences, it is necessary to find out a damaged section of a pipeline, that represents a technical challenge due to the large burial depth and considerable length of pipeline. Many pipeline leak detection methods have been developed and implemented so far. All these methods can be divided in two groups: leak detection based on pipeline operation specifications (i.e. data provided by automatic process control system); leak detection based on nondestructive inspection tools [2].

The first group of methods is the most widely used due to the simplicity of their implementation. These methods usually do not require the use of a large amount of additional hardware, and they are easily implemented by means of automatics due to the well-studied and relatively simple mathematical models of pipelines and oil transportation processes [6]. Among these methods, the following methods can be named: method of pressure reduction; method of linear balance; method of comparing costs; flow velocity monitoring method. A common drawback of these methods is the low sensitivity that does not allow detecting small-scale leaks [2, 6]. Taking into consideration that measurement gauges of process-dependent parameters (pressure, flow) are permanently installed at special locations (often in pump stations) at both sides of the line pipe section, so that it is impossible to locate the leak in this line section [6]. Moreover, the comparison of costs and linear balance methods does not allow resolving the leak detection issue in principle [6]. Nevertheless, the important advantages of this group of methods are continuous monitoring, reliable and effective leak detection in the case of large scale leak [6]. Since principles of these methods are different, their combined usage allows increasing the reliability of leak detection and improving the accuracy of the decisions. In this connection, Russian leak detection system (SDAs), available on the market, is designed for simultaneous processing of the data coming from different sources and composed of appropriate mathematical models.

Among the methods of non-destructive testing, the following method also can be named: the fiberoptic method, method of acoustical emission, radioactive and ultrasonic methods. The method of acoustical emission is the most widespread [6]. This method is based on the registration of acoustic emission signals by piezoelectric sensors, when sensors are placed on the controlled section of the pipeline. The registered signals indicate the presence of cracks in the pipe wall where the leak may

happen [6, 7]. A leak spot is detected by estimating and analyzing indicated acoustic emission pulse damping and the time difference of pulse arrival at sensors. All required operations for leak spot detection are implemented by specialized software [6]. The following advantages of the acoustic emission method are: high sensitivity, flexibility (invariance to pipeline types and petroleum products) and the ability to locate the spots of small-scale leaks [6]. The main disadvantage of this method is the inability to inspect long pipeline sections, which complicates and slows down the inspection of line pipe sections of main pipelines [7]. Due to the low energy of acoustic emission signals, their detection on the background noise is a technical challenge [6], which effective solution significantly influences the quality of pipeline leak detection.

According to the above, when applying the acoustic emission method, the basic informative parameter is the difference in pulse arrival time to sensors. Particularly, in order to evaluate the difference, analysis of the cross-correlation function of the signals should be performed and its maximum should be located [6]. However, practically, due to low-energy of useful signals [7], the maximum of signal correlation function is often not well-marked. Therefore, detection of the leak location may represent a challenge [8].

To resolve this issue, advanced digital filtering of analyzed data can be applied, which allow improving signal-to-noise ratio against the background of the correlation device, which in its turn enables partially to eliminate random emissions in its output. However, this way of analysis cannot be implemented, because the frequency range of the leak acoustic signal is not known a priori and depends on the pressure and flow rate as well as on the shape and size of a leak spot [9, 10]. Determination of the leak signal frequency range is not trivial task that is poorly formalized and that's why it requires experienced and trained experts. Traditionally, the solution of this task is performed by such additional tools as cross-spectrum of the signals and coherence function calculation and analysis. These tools have some disadvantages: cross-spectrum does not give enough information in case of intense or narrow-band noise; due to the presence of several modes of vibration, coherence function could have false peaks that make almost impossible to evaluate frequency range of useful signal identically [9]. In this connection, developing alternative ways of signal spectral information processing and their further adaptation for solving leak detection problems by the correlation method are of great importance.

Time-frequency correlation approach

As an alternative method, the analysis based on time-frequency correlation function is considered. The time-frequency correlation function is termed as a correlation function that depends on two variables – response time and frequency. This means that this function represents the correlation between the spectral components of the analyzed signals [8]. Therefore, the method of timeprocedure-frequency correlation function calculation is also based on the decomposition of the original signals into the components localized in a specific frequency range and calculation of correlation functions of signals for each range. The above mentioned idea has become the basis of the algorithm [9] that is described below. Suppose that the problem is to obtain a time-frequency correlation function of signals $x(t)$ and $y(t)$ that are represented by discrete sequences $x_i, y_i (i = 0, 1, 2, \dots, 2^n - 1; n \geq 2, n - \text{algebraic integer value})$. It should be noted that the signal sample numbers are equal to a degree of two for further application of Fast Fourier Transform (FFT) algorithm. At the initial stage, by the multiplying the spectrum of the signals their cross-spectrum is determined ($P_j, j = 0, 1, \dots, 2^{n-1} + 1$):

$$P_j = F(x_i) F^*(y_i), \quad (1)$$

where F – discrete Fourier transform (DFT); F^* – complex conjugate representation of the results of the DFT.

At the second stage, the cross-spectrum separation is performed into m components (where m – number of selected frequency intervals). These m components contain spectral samples that are within the current interval. Mathematically, this procedure reduces to obtaining m vectors $M^k (k = 0, 1, 2, \dots, m-1)$ according to the following rule:

$$M_j^k = P_j \cdot w_j^k, \quad (2)$$

where w_j^k - the window function that is defined in the following way:

$$w_j^k = \begin{cases} 1, & \frac{k}{m} < \frac{j}{2^{n-1}+1} \leq \frac{k+1}{m} \\ 0, & \frac{k}{m} \geq \frac{j}{2^{n-1}+1} > \frac{k+1}{m} \end{cases}, \quad (3)$$

where $j = 0, 1, 2, \dots, 2^{n-1}+1, k = 0, 1, 2, \dots, m-1$.

At the final stage, obtained vectors M^k are subjected to fast Fourier transform:

$$Z^k = F^{-1}[M^k].$$

The obtained complex vector Z^k consists of m vectors and each of them represents correlation function of original signals in the i -th frequency interval. The simple change of the notation of the vector Z^k values enables to restore the time-frequency correlation function:

$$r_{xy}(\tau_i, f_k) = Z_i^k. \quad (4)$$

Since the time-frequency correlation function has two independent arguments, the most obvious way of its presentation is the surface constructed in the three-dimensional space. In this case the leak presence can be detected by peaks of the surface.

The advantages of the time-frequency correlation function in respect with pipeline leak detection issues are determined by its positive influence on the noise tolerance of acoustic emission method, which is particularly important when examining oil pipelines [6]. The capability assessment of the considered pipeline leak detection method was experimentally verified through the inspection of the water pipe section which is 20 mm in diameter and 18 m in length. A leak was located at a distance of 4m from the nearest sensor. The liquid was transported under the pressure of 2 atmospheres. Acoustic signals were recorded with a piezoelectric accelerometer with frequency of 44.1 kHz.

Experimental part

Calculation of time-frequency correlation function was made according to the above-mentioned algorithm. For the discrete signal, time interval of discrete samples was 11 seconds. The length of DTF window was 32768 sample units (743 ms). When calculating the time-frequency correlation function, the number of frequency intervals was 23. Final correlation functions were obtained by averaging the correlation functions calculated for different blocks, with their lengths being corresponded to the length of FFT window. The time-frequency correlation function of an experimental signal is represented as a surface in figure 1.

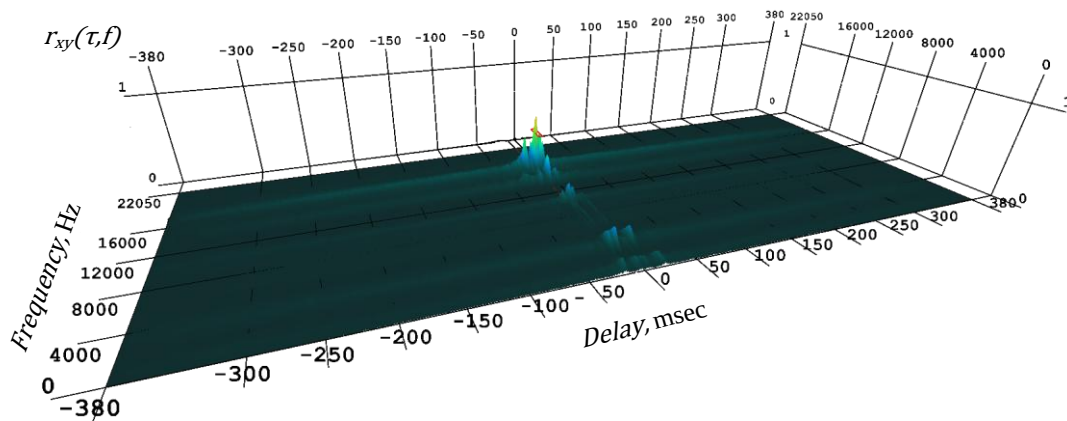


Figure 1. Time-Frequency Correlation Function

On the surface, there is clearly distinguishable peak which corresponds to the time delay -9.09 ms. Signal propagation velocity through the pipeline has been experimentally determined in advance, i.e. the value 1100 mps which corresponds to the distance of 3.99 m to the nearest sensor. Thus, the time-frequency correlation function demonstrates high efficiency in the determination of the time delay. Besides, by the location of the surface peak, a specific frequency band signal delay can also be detected – (16.2...17.2 kHz). As a comparison to the time-frequency correlation function surface, the one-dimensional plot of the correlation function is represented in figure 2. As illustrated, it does not contain a single evident peak. Thus, this function does not allow detecting identically the location of a leak.

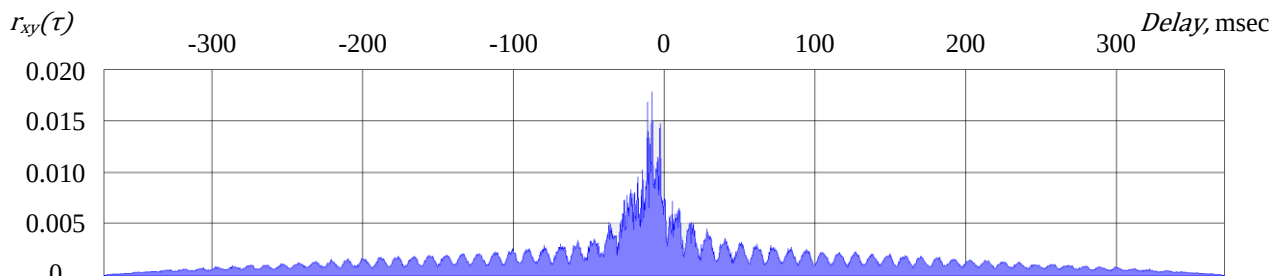


Figure 2. One-Dimensional Correlation Function Plot

Pre-filtering of signals in the frequency range of leakage signal can enhance the information content of one-dimensional correlation function. The graph of the one-dimensional correlation function after filter operation is represented in figure 3.

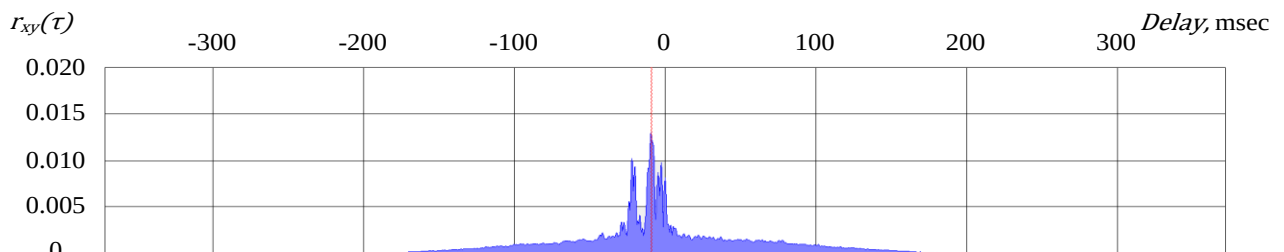


Figure 3. One-Dimensional Correlation Function Plot after Filtering

The time-frequency correlation function enables to suppress the noise components in the frequency range of useful signal more effectively, which makes a maximum of the function more pronounced [8]. In addition, this method allows representing processing signal data in more effective and

descriptive way. Particularly, through the visual analysis of the plot, difference in time arrival of signals at sensors (to pronounced peak), as well as approximate frequency content of leakage signal, can be determined. The information obtained as a result of the time-frequency correlation function analysis can be used for further research to detect the leak location and set up filters.

The main drawback of the time-frequency correlation function analysis lies in the necessity of a great number of calculations. This may increase pipeline inspection time [8]. A great number of calculations is required because of the calculation of $(m-1)$ additional inverse Fourier transforms for each block of analyzed discrete signals. However, this drawback can be partially reduced by the developing and implementing efficient algorithms (including parallel) of computing the fast Fourier transform based on the use of a computer CPU and GPU. Specifically, the use of CUDA technology combined with efficient parallel implementation of Fast Fourier Transform would improve processing speed by more than 80 times in comparison to the non-optimized algorithm.

Conclusion

Therefore, application of time-frequency correlation analysis could improve the efficiency of pipeline leak detection applying the method of acoustic emission due to the partial elimination of its critical drawbacks. Particularly, implementing the proposed procedure for digital signal processing enables to reduce noise effects and increase the potential differentiation of the useful signal. Above all, simultaneous presentation of temporal and spectral information in one plot (time-frequency correlation function) is more descriptive and simplifies an operator's work.

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