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LEAKAGE DETECTION IN PIPELINES - THE CONCEPT OF SMART WATER SUPPLY SYSTEM

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Summary: *The paper presents investigation concerning leakage detection system for water supply pipelines. A screening system is presented based on transient leak detection methods. Transient waves in a pipeline were excited by a very fast dedicated closing/opening valve system. The system response was acquired using a dynamical pressure sensor. The matched filtration method and cepstral analysis were tested to extract useful information from the signal responses. The experimental work was performed using a dedicated laboratory test stand with the overall length of pipeline 80 meters. The pipeline system consisted of pipes with different diameter and materials to mimic real water supply systems. The presented in the paper focuses on research undertaken to define basic parameters required for implementation of the system.*

1 INTRODUCTION

Leakages occur in every, even well-maintained, water pipeline networks. It is estimated, that average water loss in public water network ranges from about 5% in well-maintained, to 30% in older pipeline networks. Taking into consideration large quantities of transported water, these losses have considerable economic and environmental impact. Table 1 summarizes the number of failures in the Municipal Waterworks and Sewer Enterprise in Krakow in the years of 2005-2013.

Pipelines are the most important (or even the only) way of water transporting. The pipes are ubiquitous but unfortunately are exposed to various kinds of adverse symptoms like weather conditions, vibration, chemical components of soil, changing pressure or incorrect installation. Many leakages occur in pipelines due to landslide and freezing. The leakages localization is very difficult because most of the water supply systems are under the ground. Taking into account the length of water supply systems, their complex structure and (in most cases) the lack of visual assessment, it is easy to realize that localization (and repair) of damages in pipelines is a huge problem.

Year	Diameter range [mm]	Failures number	Failures Sum
2005	350-1200	54	885
	80-325	831	
2006	350-1200	78	995
	80-325	917	
2007	350-1200	42	790
	80-325	748	
2008	350-1200	41	695
	80-325	654	
2009	350-1200	56	883
	80-325	827	
2010	350-1200	48	923
	80-325	875	
2011	350-1200	47	782
	80-325	735	
2012	350-1200	57	1104
	80-325	1047	
2013	350-1200	41	704
	80-325	663	

Table 1: Number of failures in pipeline system in the Municipal Waterworks and Sewer Enterprise in Krakow in the years of 2005-2013.

Leak detection methods can be classified into two groups: external and internal. The first group includes methods where failure (leakage) can be found using signals collected outside pipelines. Visual inspection (if possible) or thermographic methods are the best examples. Internal methods are based on signals collected inside pipes. This category includes methods based, for example, on wave propagation phenomena or volume balance.

Changes in steady-state operating conditions of fluid transportation system excite a guided wave. The guided wave can have a number of modes that can propagate with different velocities along pipeline systems. Wave propagation in such systems is complicated, leading to phenomena that can be affected by many factors, including: geometric properties of the system, pipeline network configuration or existence of hydraulic fitting. In addition, medium flow characteristics can also influence wave propagation It is well known that wave propagation velocity can be dependent on frequency, temperature, pressure, medium density and pipe's material [1].

Pressure waves can result in so-called "water hummer" effect. If liquid in the pipe under the pressure is greater than atmospheric pressure - and a valve is rapidly closed - then a positive pressure wave is generated and propagates upstream along the pipeline system. The secondary wave - called rarefaction wave - is also excited but propagates downstream.

Typical pipeline systems consist of many elements like: junctions, valves, elbows or flanges. These elements not only cause discontinuities in the fluid flow but also act as a sources of reflected waves. Leakages can be also treated as sources of reflected waves.

Majority of the existing leak localization techniques is based on laborious, manual detection by an operator, [2-6]. As an effect, there is a growing need for reliable methods, based on a permanently mounted network of sensors. In this article, investigations concerning novel leak detection system for the Krakow Municipal Waterworks and Sewer Enterprise is presented.

2 THE LABOLATORY STAND

The main design objectives for the test rig are:

- modelling of real water-supply networks;
- simulation of conditions that exist in water-supply networks;
- simulation of leaks in different sections of the network.

In order to reflect the real water-supply networks, all pipes and fixtures used were the same as in the water-supply installations in Krakow. The project of the test rig was based on plans of the real water-supply installation located in the Bronowice district of the Kraków city. The features of fitting attachments and joints in pipes were the same as in real water networks. In order to simulate both the main line and the lines that feed water to individual buildings the stand consisted of two separate circuits with a common water supply and drainage.

The first circuit was designed as a model of the main water-supply line. This circuit consisted of 4 horizontal segments that have the length of 12.5 m each and are connected with curved pipe segments. The vertical distance between all horizontal pipe segments was 0.5 m. The pipe used for this circuit was the PE 100 SDR 17 Ø 90. The scheme of the circuit with all relevant dimensions is shown in Figure 2.

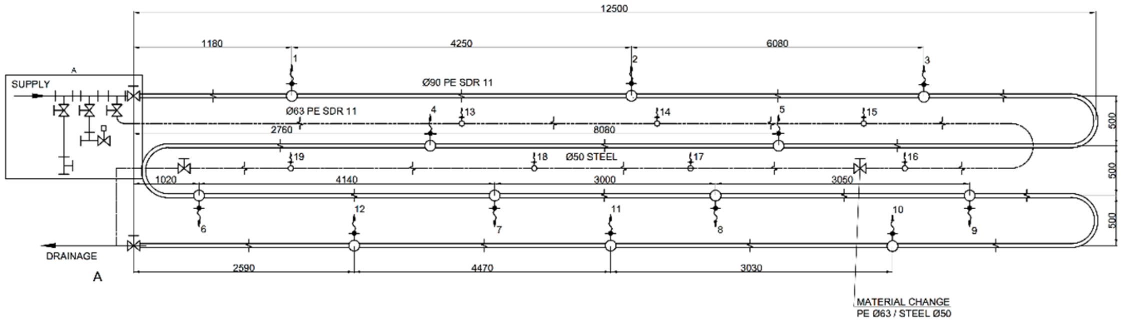

Figure 2. Schematic diagram of the test rig with dimensions of the first water circuit.

The second circuit was designed as a model of a line feeding the water to individual buildings. It consisted of two horizontal segments that were each 12 m long. These segments were connected with elbows and vertical pipe elements. The vertical distance between these horizontal segments was 0.5 m. In order to accurately model real water-supply installations the second segment consisted of pipes made of two different materials. The first segment was constructed from the PE 100 SDR 11 Ø 63 pipes. The second segment was constructed from the PE 100 SDR 11 Ø 63 pipes and DN 50 galvanized steel pipes. Schematic drawing of the secondary circuit with all relevant dimensions is shown in Figure 3.

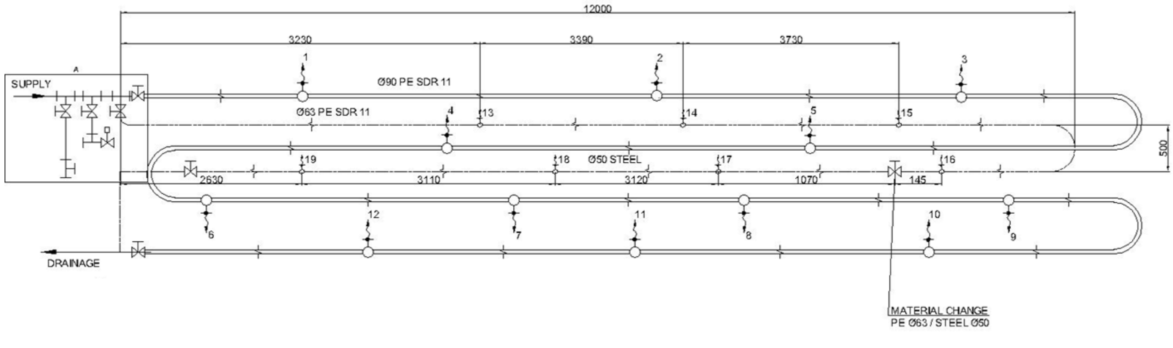

Figure 3. Schematic diagram of the test rig with dimensions of the second circuit.

In order to maintain simulation conditions in real water-supply networks, a pressure regulator with a pressure gauge was installed on the supply line. This regulator allowed adjusting pressure to be within the range used in modern water-supply networks. The ability to change the pressure in both circuits enabled studying performance of the investigated leak detection method also in the conditions of under- and overpressure in the network.
Leaks are simulated in different ways, depending on the type of pipe. Saddle clamps with DN 25 ball valves attached were used for the PE 100 SDR 17 Ø 90 pipes (Figure 4a). Tees with DN 25 ball valves attached were used for the PE 100 SDR 11 Ø 63 pipes (Figure 4b) and DN 50 galvanized steel pipes (Figure 4c).

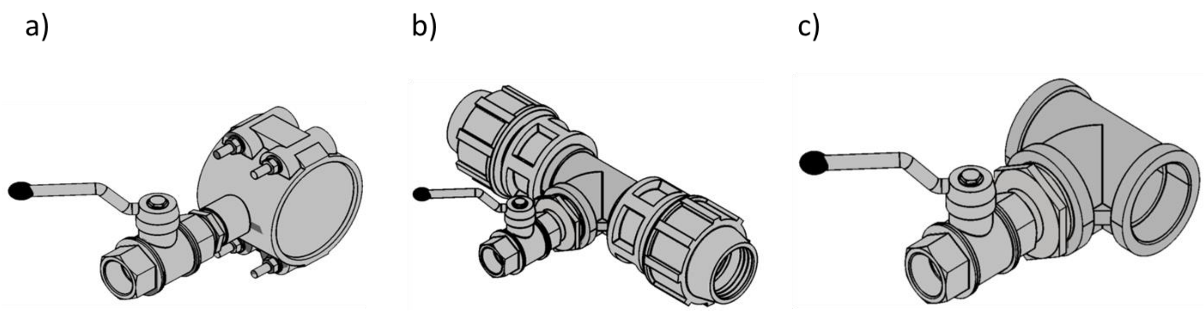

Figure 4. The fixtures used to simulate the leak for: (a) Ø 90 pipe; (b) Ø 63 pipe; (b) Ø 50 pipe.

Two devices were used for impulse generation, i.e. the solenoid valve and the pulse wave generator. The latter device is a hydraulic valve designed and built specifically for very fast closing and opening action of the valve, resulting in short and intensive impulses to be generated. Figure 5 presents locations of the excitation devices used. The solenoid valve was situated in the proximity of the pressure sensor. This scenario is consistent with the layout of the real water network.

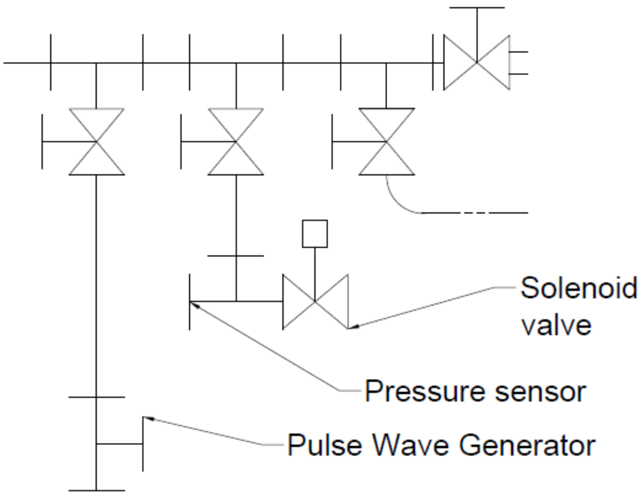

Figure 5. Schematic diagram showing the signal generation and acquisition area of the network.

The cycle of closing and opening of valves was controlled using a programmable logic controller. The PCB 112A22 pressure sensor was used for data acquisition together with data acquisition system TEAC. Figure 6 shows an example of the acquired data. The signal presented can be divided into two major parts. The first (between approx. 43 and 44 s) and the second (between approx. 50 and 51 s) parts start with peaks corresponding to the valve opening and closing, respectively. The most interesting parts of the signal are the echoes marked with black squares. These echoes were used for leak detection analysis presented in Section 3.

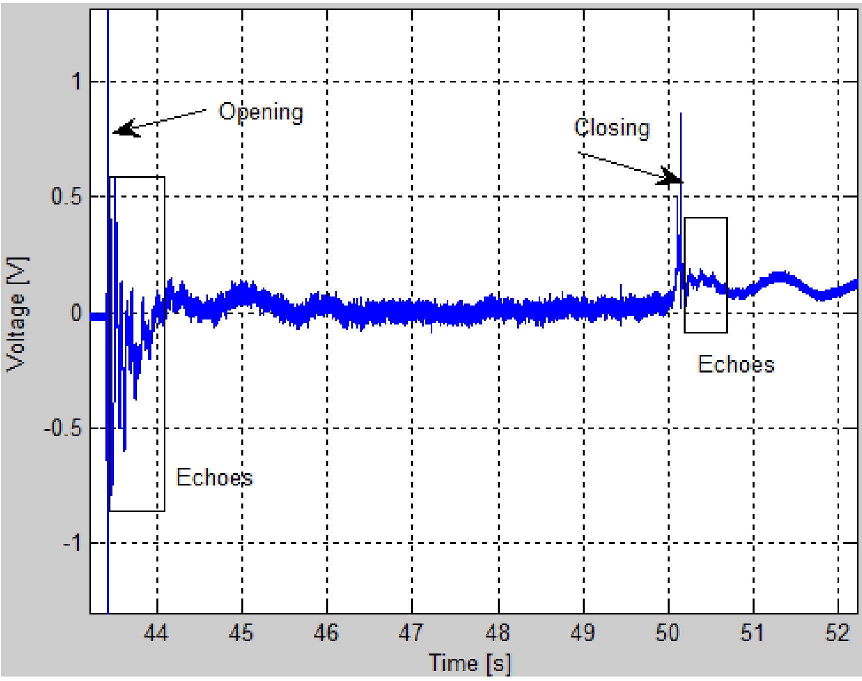

Figure 6. Resposne signal generated by solenoid valve

3 METHODS OF DIGITAL SIGNAL PROCESSING USED FOR LEAKAGE DETECTION IN WATER PIPELINES

Pipeline response signals can be used to identify reflections related to the geometry of the system and potential leakages. In a very basic approach time domain signals can be analysed to detect peaks corresponding to these reflections. In this approach the assumption is that the velocity of pressure waves in water pipeline systems is constant or can be averaged over desired time intervals. Thus a simple physical formula can be used to estimate distances from the transducer (i.e. measuring point) reflections points as

$$l = \frac{v}{2t} \tag{1}$$

where v is the average speed of pressure wave and t is the corresponding traveling time of the analysed wave. [7].

It is important to note that these calculations are strongly dependent on the average wave velocity. Estimation of this parameter is not easy in real operational conditions and thus additional transducers are needed to improve the accuracy. The experimental value of wave velocity in water pipeline systems is usually in the range between 200 and 1200 m/s [8-10].
Since response signals depend on various features of the system (e.g. length, geometry), external conditions and excitation signals, time domain signals are rarely used for leak detection. Various signal processing methods can be used to ease the identification of reflection-related pressure peaks. The work presented in this paper involved two different approaches, i.e. matched filtering and cepstral analysis. Low-pass filtering – with the cut-off frequency of 11 500 Hz – was used additionally in both approaches to eliminate high-frequency noise features.
The matched filtering method is based on the convolution equation that calculates correlation between the processed signal *x[k]* and the prototype pulse *h[k]* to be detected in the signal [11]

$$y[n] = \sum_{k=-\infty}^{\infty} x[k]h[n-k] \tag{2}$$

where *y[n]* is the filtered discrete signal, *x[k]* is the discrete input signal and *h[k]* are the discrete finite impulse response filter coefficients. Main objectives of the method are signal de-noising and signal shape tracing. From the mathematical point of view it is relatively easy to create matched filters for discrete signals. Coefficients of the filter need to be calculated directly from the input signal, by inversion of the signal in time, which results in maximization of the Signal-to-Noise Ratio (SNR). The reason behind the application of this filtration method for leakage detection and localization is that in many cases reflected waves exhibit similar shapes as the excitation signals (in terms of data peaks) but different (i.e. lower) amplitudes.
The second proposed method of signal processing is cepstral analysis. It is well known that the cepstrum can be defined as the inverse Fourier transform of the logarithm of the Fourier transform of the analysed signal [12]

$$y(t) = F^{-1}(\log(F(x)) \tag{3}$$

where *y(t)* is the input signal, F^{-1} is the inverse Fourier transform, *F* is the Fourier transform of the input signal *x(t).* There are two types of cepstral analysis employing the real and complex cepstra. The names come from the type of obtained information and applied type of the logarithm. The real cepstrum takes into account only the real part of the Fourier-transformed signal. The complex cepstrum also includes the imaginary part of the transformed signal, allowing for signal reconstruction and phase calculation. The application of cepstral analysis for leak detection is associated with certain obvious advantages, independently of the cepstral analysis type used. The processed signals are in the quefrency domain that is related to the time domain. Therefore peaks - corresponding to reflections/echoes – can be easily identified. The amplitude of processed signals is rescaled.

4 RESULT AND DISCUSSION

Pressure signal responses were acquired following the experimental procedure described in section 2. Figure 7 shows an example of the acquired pressure signal. Vertical lines mark eight consecutive reflections from the pipeline ends. It is important to note that leaks were not present in the system when this signal was acquired. Thus, pressure peaks related to leak-related echoes cannot be identified. Figure 9 shows the same response signal processed by the matched filter. The filter's coefficients were calculated using the sets of peaks appearing in the response signal. It is clear that this filtering led only to signal smoothing. The result of cepstral analysis was performed for this signal is shown in figure 9.

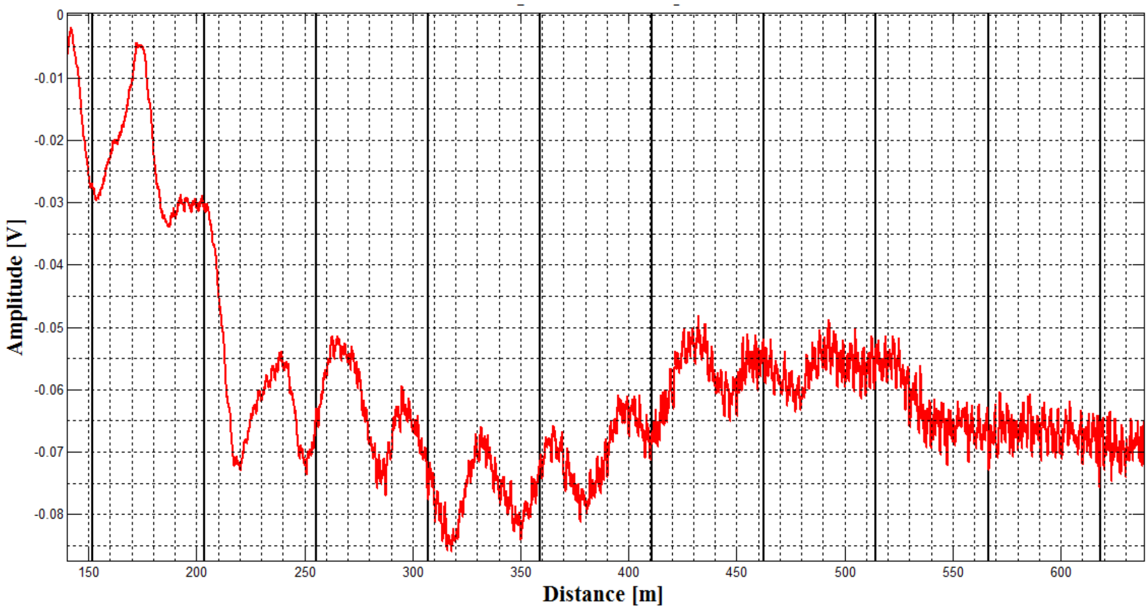

Figure 7. Pressure response signal.

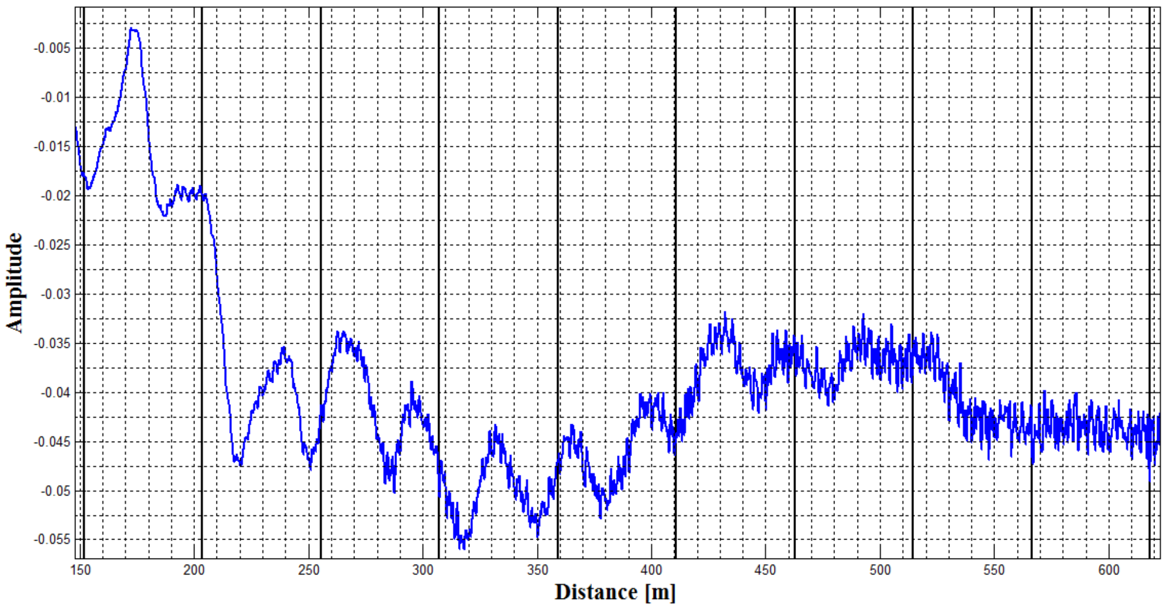

Figure 8. Pressure response signal after matched filtration.

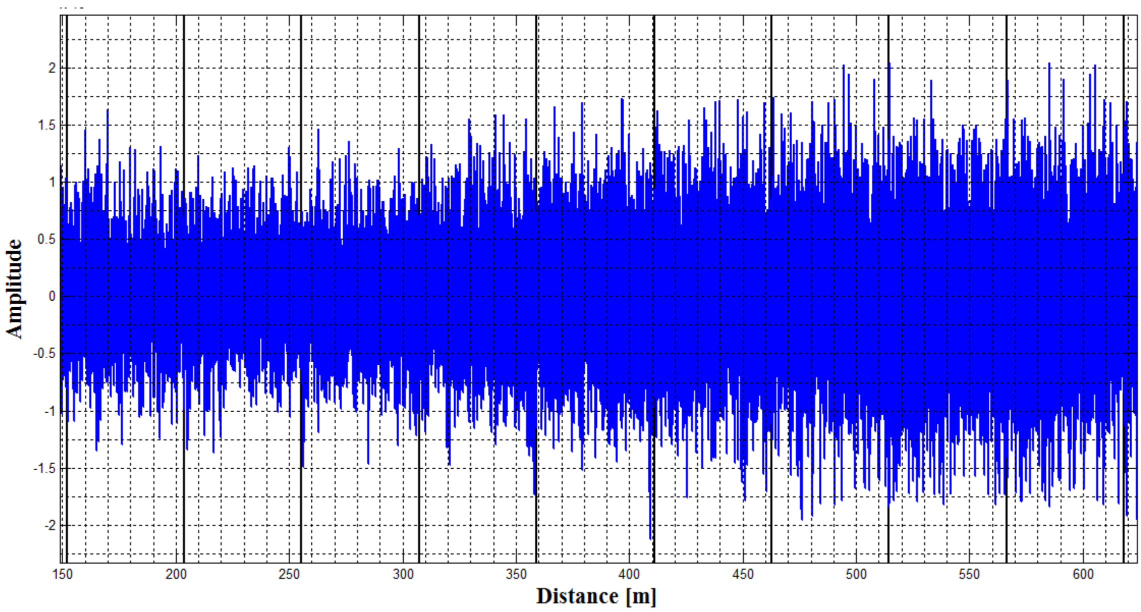

Figure 9. Cepstrum of the response signal.

In this case the results are also unsatisfactory since reflections from the geometrical features – indicated by vertical lines - cannot be clearly identified. In the next step matched filtering was combined with the cepstrum analysis, leading to the result presented in Figure 10 where the time peaks corresponding to the echoes can be clearly identified. The assumption is that once leakages are simulated in the analysed water pipeline system, leak detection and localisation will be possible, as demonstrated in [1].

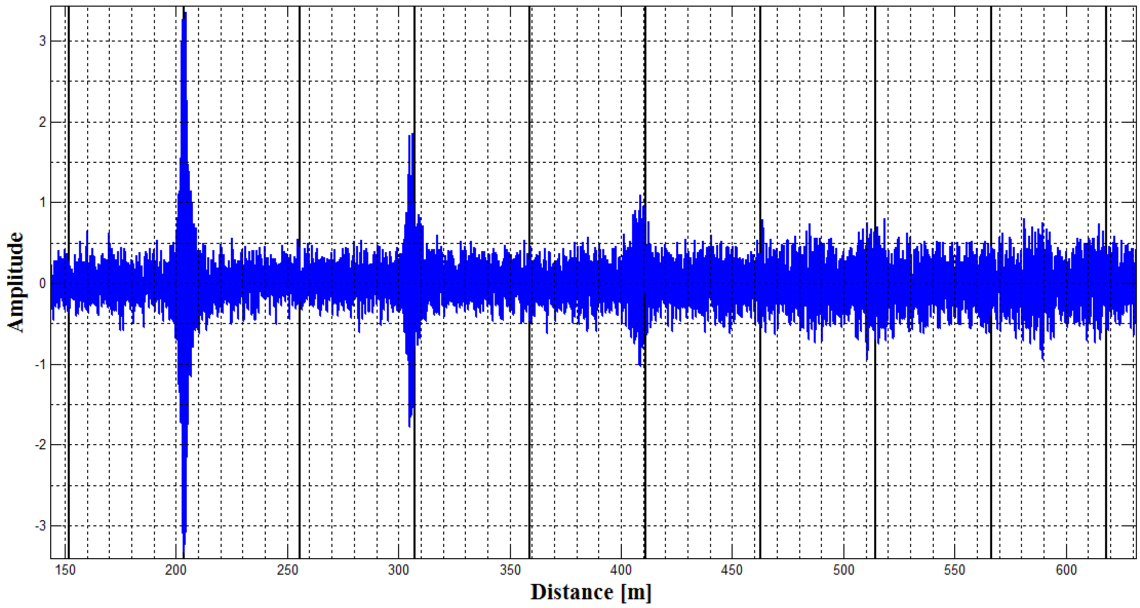

Figure 10. Cepstrum of the filtered response signal.

5 CONCLUSION

Artificially generated pressure waves in water pipeline systems were used for leak detection and localization. The major focus of the work presented was on the design and implementation aspects of the water pipeline network and the detection system that could be used for the experimental leak detection tests. Two different signal processing methods were also investigated, i.e. matched filtering and cepstral analysis. The results show that when both methods are combined peaks in pressure waves corresponding to reflections can be clearly identified. It was shown that when the two analysed signal processing approaches are used separately, echo detection and localization was not possible. It is anticipated that this combined approach can facilitate leak detection and localization in real water pipeline systems. Further research work is required with respect to the excitation. It is clear that short pulse, broadband excitation will be required to reliably detect reflections related to leaks. Future work will also concentrate on experimental simulations of various types of leaks and leak detection scenarios.

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