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Leak Localization by Using Time Delay Estimation of Negative Pressure Wave Signal

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Abstract. The aim of this paper is to investigate usability and accuracy of different time delay estimation techniques for purposes of pipeline leak localization. The generalized cross correlation with various weighting functions and time domain estimation techniques are compared. Limited measurements of pressure waves initiated by artificial leak are utilized for brief accuracy analysis of mentioned estimation techniques.

Introduction

Basic though of acoustic leak detection techniques is assumption that a leak is an acoustic source. Occurrence of a pipeline leak leads to local rarefaction and initiate a negative pressure wave propagated toward both ends of a pipeline. Using of a pair of sensors on both sides of the leak allow to sense a negative pressure wave. If a speed of sound wave propagated in the pipeline is known, time delay estimation calculated between two sensor signals can be used for leak localization.

This paper compares time delay estimation (*TDE*) techniques used for localization of the artificial leak on the experimental water-filled steel pipe. The negative pressure wave (*NPW*) initiated by the artificial leak is sensed by a pair of hydrophones placed on both sides of the leak. Subsequently, leak position is calculated by using of *TDE* techniques in time domain and the generalized cross-correlation in frequency domain. The basic cross-correlation (*BCC*), the average square difference function (*ASDF*), and the average magnitude difference function (*AMDF*) described by Jacovitti [1] and the generalized cross-correlation presented by Knapp [4] and reinterpreted by Gao [2] are investigated for the purpose of leak detection. In the first chapter are presented basic assumptions of sampled mutually delayed signals which represent inputs to the cross-correlation and TDE techniques. Equations of time domain techniques are introduced and various weighting functions obtained from listed literature for the GCC purposes are presented. The second chapter investigates performance of individual time domain techniques and GCC functions through variance of delay estimation. The third chapter shows use of most effective methods for delay estimation of negative pressure waves sensed through the experimental pipeline setup.

1 Theoretical development

Based on the assumption of two sensors placed on both sides of the pipeline leak, discretized signals x_1 and x_2 can be expressed as

$$x_1(k) = s_1(\mathrm{k}) + n_1(k)$$
$$x_2(k) = \alpha s_1(\mathrm{k}+\mathrm{D}) + n_2(k) \tag{1}$$

where *k* is number of samples, *D* is sample delay, s_1 is focused leak signal in the form of negative pressure wave and n_1, n_2 present additive noise.

Time domain techniques. Jacovitti [1] presents the direct cross-correlation method in time domain, also known as sliding dot product for sampled signal in the form

$$R_{x1x2}{}^{D}(\tau) = \frac{1}{N}\sum_{k=1}^{N} x_1(k)x_2(k+\tau) \tag{2}$$

where *T* is sampling interval and *N* is number of samples. Said author also specified the average magnitude difference function (*AMDF*) and the average square difference function (ASDF) in the following form.

$$R_{x1x2}{}^{M}(\tau) = \frac{1}{N}\sum_{k=1}^{N} |x_1(k) - x_2(k+\tau)| \tag{3}$$

$$R_{x1x2}{}^{S}(\tau) = \frac{1}{N}\sum_{k=1}^{N} [x_1(k) - x_2(k+\tau)]^2 \tag{4}$$

Delay estimation $\widehat{D}$ of true delay *D* is presented by Jacovitti [1] as argument of maxima or minimum for the specific function.

$$\widehat{D}^{D} = \mathrm{argmax}\left[R_{x1x2}{}^{D}(\tau)\right]$$
$$\widehat{D}^{M} = \mathrm{argmin}\left[R_{x1x2}{}^{M}(\tau)\right] \tag{5}$$
$$\widehat{D}^{S} = \mathrm{argmin}\left[R_{x1x2}{}^{S}(\tau)\right]$$

In respect to the computational time efficiency, the AMDF and the ASDF are more convenient than the direct correlation due to products of original and lagged signal are not required. The AMDF and the ASDF involves only subtracts, respectively their squares [1].

Frequency domain techniques. Gao [2] investigated using of the generalized cross-correlation (*GCC*) function for the purpose of leak detection on buried plastic pipes. He defines the GCC function as the inverse Fourier transform of the cross-spectral density in the following form.

$$R^{g}{}_{x1x2}(\tau) = F^{-1}\{\varphi^{g}(f)S_{x1x2}(f)\} \tag{6}$$

The function $\varphi^{g}(f)$is defined as $\varphi^{g}(f) = H_1(f)H_2(f)$. The weighting function $\varphi^{g}(f)$ introduces filters $H_1(f)$and $H_2(f)$ into calculation in order to facilitate estimation of time delay [4]. Gao [2] reinterpreted study by Knapp [4] for purpose of leak detection on plastic pipes. His study is focused on estimation of time delay by using the GCC with leak noise as input signal. Gao [2] compares five different forms of weighting functions (*PHAT, WIENER,* *SCOT, ML, ROTH*). Weighting functions stated by Knapp [4] and used in this study for purpose of negative pressure wave delay estimation are presented in the Table 1.

Table 1: Weighting functions

BCC	Roth	SCOT	PHAT	Eckart	HT
1	$\frac{1}{S_{x1x1}(f)}$	$\frac{1}{\sqrt{S_{x1x1}(f)S_{x2x2}(f)}}$	$\frac{1}{\lvert S_{x1x2}(f)\rvert}$	$\frac{S_{s1s1}(f)}{S_{n1n1}(f)S_{n2n2}(f)}$	$\frac{\frac{S_{s1s1}(f)}{S_{n1n1}(f)S_{n2n2}(f)}}{\frac{S_{s1s1}(f)}{S_{n1n1}(f)}+\frac{S_{s1s1}(f)}{S_{n2n2}(f)}+1}$

2 Variance of delay estimation

In accordance with Knapp [4] and Jacovitti [1] variance of delay estimation is introduced as representative value of the mentioned GCC and time domain techniques. In order to investigate usability of GCC functions for leak detection by delay estimation of negative pressure wave, artificially generated synthetic data are used. Generation of synthetic negative pressure waves is based on real measured negative pressure waves presented in previous work of the author [3]. Synthetic data presented on the Fig.1 are in accordance with the Eq.1. The signal $s_1$is represented by damped sine wave. Additive noises n_1, n_2 are introduced as white Gaussian noise with the specified S/N ratio. Signals x_1, x_2 with various S/N ratios in range (-10 dB, 50 dB) are used as inputs for each cross-correlator. The variance is calculated from 500 sample delay estimations for each S/N ratio step.

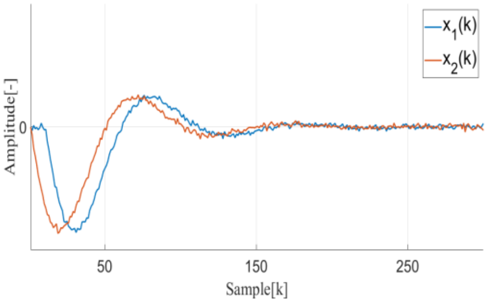

Fig. 1: Synthetic negative pressure wave
SNR=40 dB

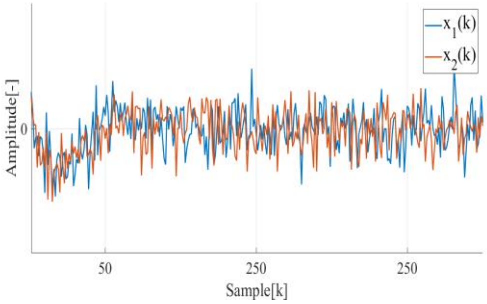

Fig. 2: Synthetic negative pressure wave
SNR=10 dB

Delay variance of time domain techniques. The Fig. 3 represents variance as a function of SNR for S/N ratio step 0.5 dB. In each step is calculated 500 time delay estimations using the BCC method, the average magnitude difference function and the average square difference function listed in the previous chapter. Despite of possibility of the calculation BCC in both frequency and time domain, all of figures show the basic cross-correlation method based on the Fourier transform which is computationally more efficient than the dot sliding product mentioned in previous chapter. Due to computational efficiency and simplicity the BCC serves as reference method for comparison with other time domain methods and GCC functions. Detailed variance of delay estimation at the interesting SNR range between 0 dB and 10 dB is presented on the Fig. 5. Although the Fig. 5 shows less variance of delay estimation for the AMDF and the ASDF for low S/N ratio (0 dB-3 dB), the BCC method provides with increasing S/N ratio faster ‘convergence’ to the theoretical zero variance. With increasing true delay between signals $x_1,\ x_2$ vanishes ‘convergence’ advantage of the BCC method in comparison with the AMDF and the ASDF (Fig. 7), (Fig. 9).

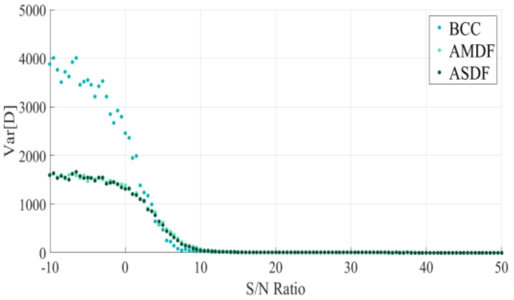

Fig. 3: Variance of delay estimation for time domain techniques (True Delay=0)

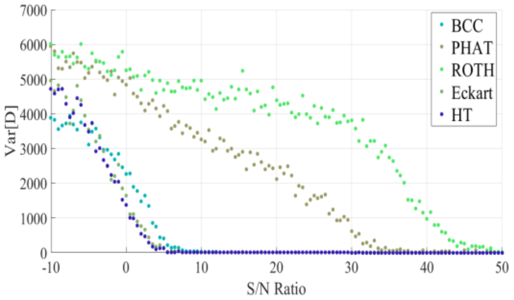

Fig. 4: Variance of delay estimation for GCC functions (True Delay=0)

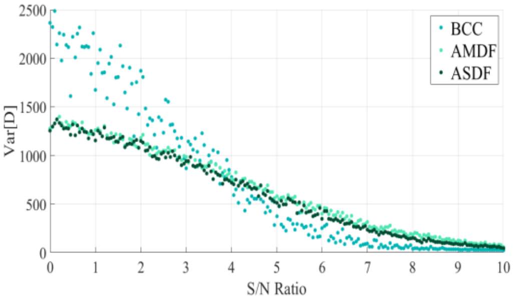

Fig. 5: Detailed variance (SNR= [0 dB,10 dB]) of delay estimation for time domain techniques (True Delay=0)

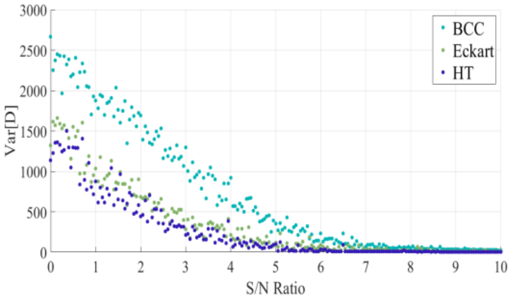

Fig. 6: Detailed variance of delay estimation for GCC functions (True Delay=0)

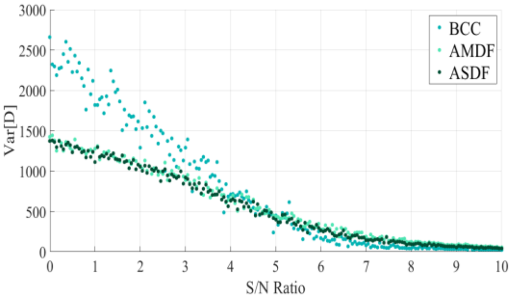

Fig. 7: Detailed variance of delay estimation for time domain techniques (True Delay=10)

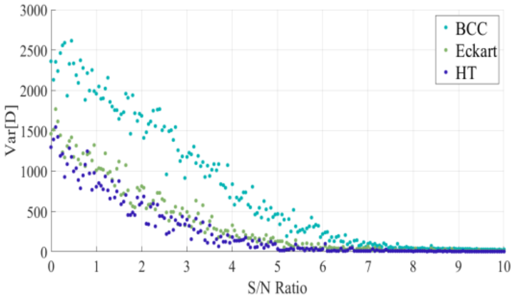

Fig. 8: Detailed variance of delay estimation for GCC functions (True Delay=10)

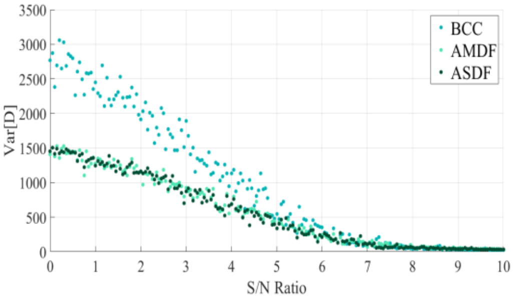

Fig. 9: Detailed variance of delay estimation for time domain techniques (True Delay=30)

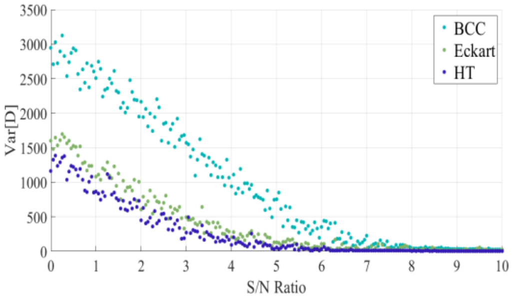

Fig. 10: Detailed variance of delay estimation for GCC functions (True Delay=30)

Delay variance of GCC methods. Fig. 4 shows variance of delay estimation for five GCC weighting functions mentioned in previous chapter, also presented by Knapp [4] and reinterpreted for purpose of leak detection by Gao [2]. If we assume variance od delay estimation as representative value of GCC methods performance, the BCC, the Eckart function and the HT (or ML) clearly outperform remaining GCC methods (Fig. 4). For this reason, only the Eckart and the HT are compared in the following analysis. The Eckart and the HT weighting functions provide better delay estimation performance than the BCC method (Fig. 6). It is caused by involving spectral densities of additive white noise into the weighting function (Tab.1). These methods suppress frequency bands of high noise [4]. With increasing value of true delay, the Eckart and the HT hold approximately equal ‘convergence’ to the zero variance, while the BCC worsen its delay estimation performance (Fig. 10). Of course, the PSD of noise signal can be easily obtained from artificially generated synthetic data. However, in real application, signal s_1 and noise n_1, n_2 are usually unknown and need to be estimated.

3 Experimental results and Discussion

The laboratory setup (Fig. 11) constructed for experimental investigation of leak detection and localization methods is presented in detail by Izold [3]. The setup consists by the water-filled steel pipe with welded branches where hydrophones are placed. The artificial leak (ball valve) is assumed as a source of the acoustic signal. The ball valve opening initiate a local rarefaction which is followed by a formation of the negative pressure wave propagated toward both hydrophones (Fig. 12).

Fig. 11: Experimental setup for sensing of negative pressure wave

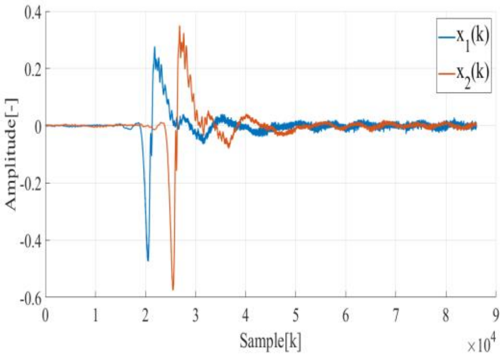

Fig. 12: Negative pressure wave sensed by pair of hydrophones

The Fig. 12 shows sensed negative pressure wave initiated by opening of the ball valve. Due to short length of the experimental setup and high speed of sound in water, real measured signals are artificially delayed for better illustration.

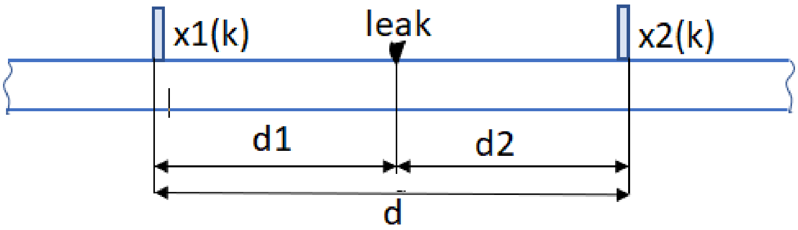

Fig. 13: Experimental setup scheme

Leak position estimation. If a pressure distribution is assumed as uniform across the cross-section of the pipe and a speed of sound wave is approximately constant across the pipe length, estimation of the leak position depends only on time (sample) delay estimation of pressure signals sensed by pair of hydrophones [5].

Leak position estimation in the form of distance from the Sensor No.1 is then defined by the following formula.

$$d_1 = \frac{d - c\widehat{D}}{2} \tag{7}$$

Where c[m/s] is speed of sound in water affected by pipeline calculated in accordance with Liu [6]. Based on the analysis stated in the previous chapter, five different techniques are used for leak position estimation. Negative pressure wave is actuated by valve opening for 10 times. Sensed pressure signals are used as inputs to the five estimation methods showed in Fig. 14. Aim of the calculation is to investigate delay estimation of two negative pressure waves actuated by valve open not delay estimation of leak noise. Therefore, for the calculation only segment of distinct negative pressure wave is selected. Noise spectra required for the Eckart and the HT weighting functions are estimated from segments of input signals where noise dominates.

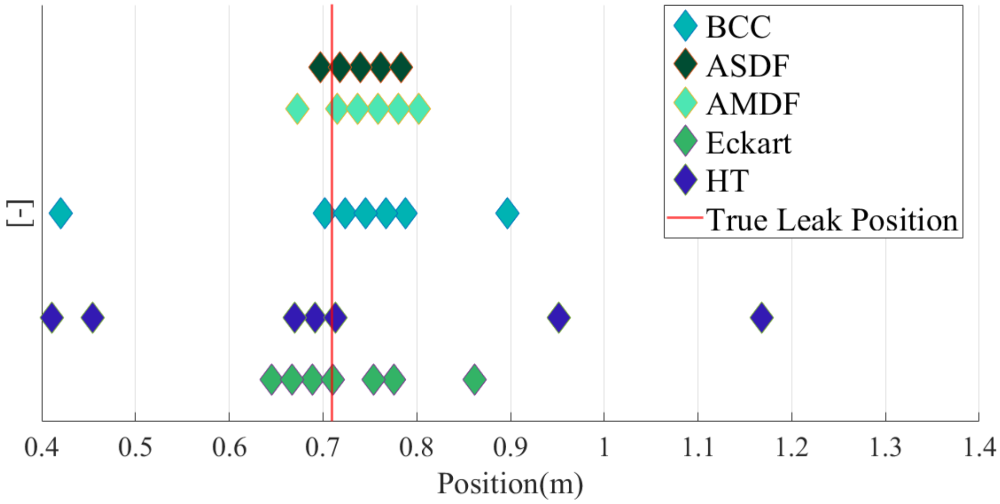

Fig. 14: Leak position estimation

The Fig. 14 surprisingly shows comparatively better estimation performance of time domain AMDF and ASDF techniques. Both provides better leak position estimate than the BCC and both GCC methods. The worsening of the Eckart and the HT weighting functions is probably caused by inaccurate estimation of the noise spectra. In addition, use of the GCC with the HT weighting function for experimental data provides in contrast with previous chapter less accuracy of leak position estimation than other compared methods. Mentioned results present only briefly suggestion of usability of listed techniques for experimental leak localization. For more relevant result, larger quantity of experimental data is required.

Conclusions

Investigation of significantly larger experimentally obtained data of negative pressure waves is necessary for relevant analysis of usability and accuracy of mentioned time estimation techniques for purpose of leak localization. Analysis with artificially generated inputs suggests more accurate delay estimation of the GCC with the HT and the Eckart functions only under the assumption of accurate noise spectra estimation. Analysis of experimentally obtained data approves using of mentioned TDE techniques.

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