AN INVESTIGATION INTO THE EFFECTS OF SIGNAL DISTORTION ON THE ACCURACY OF TIME DELAY ESTIMATION FOR LEAK DETECTION IN BURIED PLASTIC WATER PIPES

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Abstract: *A major problem for water companies is leakage from underground pipes. For many years, acoustic techniques have been used to find leaks. One particular technique is the correlation of leak noise which is measured using sensors placed either side of a leak. Using the time difference of the arrival of the leak noise at the sensors, and knowledge of the speed at which the noise propagates in the pipe, the distance of the leak from one of the sensor positions can be estimated. In this paper, the effects on the time delay estimation of two types of leak noise signal distortion are studied. First, the effect of quantization noise caused by an analog/digital (A to D) converter is investigated. It is shown that a correlator with a small number of bits in its A to D converter can work as well as a system with a large number of bits. Second, the effect of clipping of the leak signal is studied. It is shown that this has a negligible effect on the estimated time delay and hence the location of the leak. Thus, it is postulated that simple and hence inexpensive hardware could be used for leak noise correlators, rather than the complex and expensive systems usually found in use today.***

Keywords*: leak detection, plastic water distribution pipes, acoustic methods, distortions in leak noise*

1. INTRODUCTION

Leaks are responsible for increasing energy by pumping more water, resulting in increased costs. There is also possible contamination of the water around the site where a leak is located. Furthermore, leakage damages roads and may endanger the foundations of buildings (Price and reed, 1989).

In 2014, 36.7 % of water was wasted from the treatment to the final consumer in Brazil (SNSA, 2016). In 2016, 19.8% of water was wasted due leakage in water pipe network and branches in São Paulo in comparison with the 16% of UK (SABESP, 2016).

Acoustic correlation methods for leak detection and location have been applied to metallic pipes successfully, being able to locate leaks in cast iron water pipes at large range (upwards of 1 km). However, this technique can be problematic in plastic pipes, due to a higher attenuation of the leak noise along the pipes (Hunaidi and Chu, 1999). The correlation method is used to determine the time difference (time delay) of the arrival of the leak noise at sensors placed either side of the leak. Using the estimated time delay, and knowledge of the speed at which the noise propagates in the pipe, the distance of the leak from one of the sensor positions can be estimated.

Physical measurements made in the course of leak detection, for example acceleration obtained from an accelerometer, velocity obtained from a geophone, pressure obtained from a hydrophone, etc. are represented digitally. For processing, conversion of these signals into digital form is necessary. In this conversion process, as result of the quantization, an error or noise is added to the signals. The errors due to the noise are controlled to some extent by using good resolution, increasing the processing time and storage space for the data collected. In order to establish a balance between accuracy and economy for the digitized signal, it is important to study the effects on the accuracy of the time delay estimate, which is determined using leak noise correlators.

Another issue is that leak signals from plastic pipes can suffer high attenuation as the noise propagates along the pipe, which means that background noise can mask these signals. The selection of an appropriate gain is important to preserve shape of these signals, and this gain is dependent upon local conditions. In some cases, the signals can become saturated (clipped).

This paper describes the effects of quantization and clipping on the estimation of the time delay using two leak noise signals. A quantization model is used to simulate these effects together with some measurements of leak noise carried out in a test rig located in Brazil under controlled conditions.

2. LEAK DETECTION USING CORRELATION

Figure 1 shows a typical situation in which leak noise is used to detect and locate its position. the leak position from the access point 2 is (Gao et al., 2004), $d_2 = (d - cT_0)/2$, where c is the speed of propagation of the leak noise, $d = d_1 + d_2$ is the total distance between the sensors, and $T_0 = (d_1 - d_2)/c$ is the difference in arrival times of the leak noise at the sensor positions (time delay).

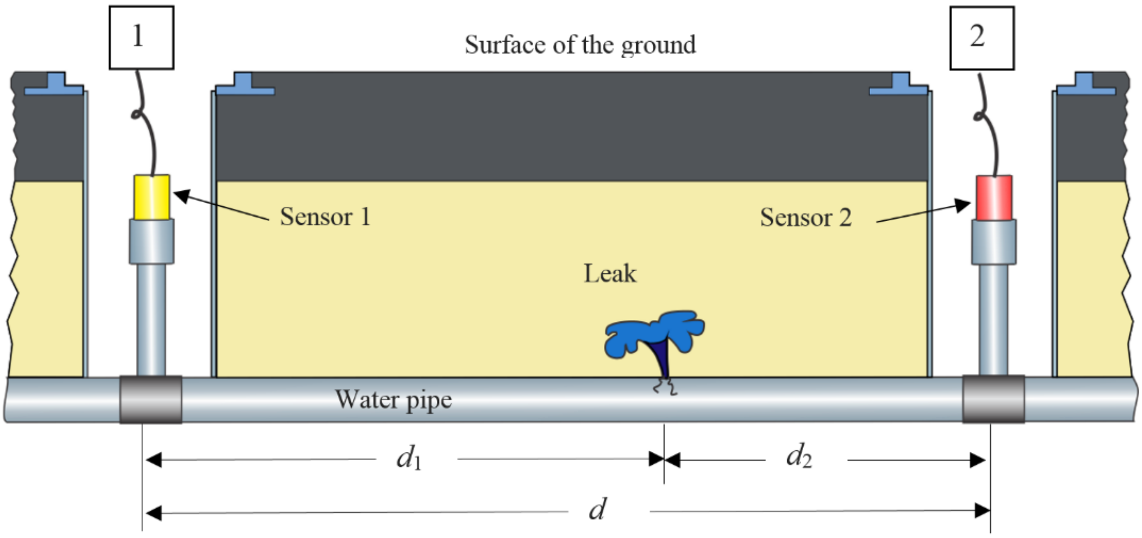

Figure 1. Typical diagram of leak detection and location in buried water pipe using acoustic signals with a leak between the two sensors.

The cross-correlation function can be derived from the inverse Fourier transform of $X_1(\omega)X_2^*(\omega)$, where * denotes conjugation, ω is circular frequency, $X_1(\omega)$ and $X_2(\omega)$ are the Fourier transform of the measured signals $x_1(t)$ and $x_2(t)$, respectively, (Gao et al., 2004).

The peak in the cross-correlation function gives the time delay estimate T_0 between the measured signals. Sometimes, it is useful to use the cross-correlation coefficient (CCC), which is the cross-correlation function in a normalized form with a scale of -1 to +1, is given by (Kihong and Hammond, 2008), $\rho(\tau) = R_{12}(\tau)/\sqrt{R_{11}(0)R_{22}(0)}$, where τ is the lag of time, and $R_{11}(0)$ and $R_{22}(0)$ are the values of the auto-correlation function at positions 1 and 2, when $\tau = 0$.

3. QUANTIZATION

The process of analog to digital (A to D) conversion is shown in Fig. 2. It can be seen that sampling occurs first, which is where the continuous-time signal is converted to discrete-time signal *x* by sampling at discrete time instants. If an analog signal is not correctly sampled, aliasing can occur (Kihong and Hammond, 2008). For aliasing not to occur, the sampling rate has to be at least twice that of the highest-frequency component of the analog signal. The second operation in the A to D converter is quantization. This is the conversion of each sample into a digital word, which has a value from a finite set of possible values. In binary format the bits take values of 0 and 1. A large number of bits is required for good resolution (Widrow and Kollar, 2008).

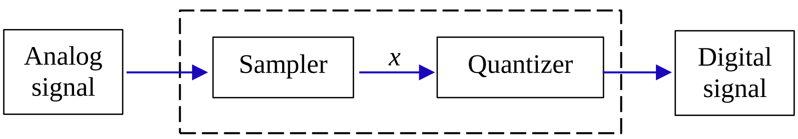

Figure 2 - Block diagram of the conversion of Analog signal to Digital signal (A/D)

In Fig. 3 is an example of the quantization of a signal using 2 bits. The dynamic range is also 2, which is the full-scale level of the converter. It has 2^N quantization levels where N is the number of bits (ISEN, 2008). The quantization levels are represented by the thin gray lines. The sampled sinusoidal signal is represented by the thick black line and the quantized signal is represented by the blue circles.

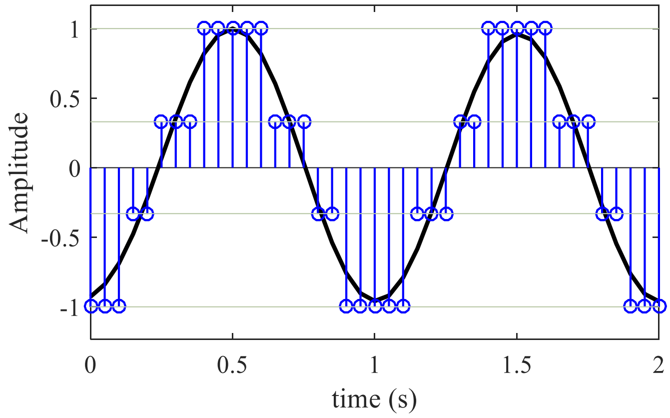

Figure 3 - a) Quantization of two bits for sampled sinusoidal signal, Thin gray line —, quantization level, thick black line —, sampled signal and blue circles marks —o, quantized signal

4. EXPERIMENTAL WORK

Data were collected in a test rig located in Brazil, as shown in Fig 1. The system was pressurized with a pump at 377 kPa. The material of the pipe is PVC (Polyvinyl Chloride) with outer diameter of 35.8 mm and thickness of 3.4 mm. The distances d_1 and d_2 are 5.46 m and 1.54 m respectively. Piezoelectric accelerometers with a sensivity of 100 mV/g were mounted with glue at the access points and used for vibration measurements. The signals from the sensors were transmitted through cables of approximately 20 m length to the data acquisition system. Leak signals were collected simultaneously for 2 minutes with a sampling frequency of 8192 Hz.

The processing of the signals is illustrated in Fig. 4. A band-pass filter is first applied to remove unwanted noise (bandwidth of 250-600Hz). Leak signals $x_1(t)$ and $x_2(t)$ were amplified and then quantized for 1, 2, 4 and 8 bits with a dynamic range equal to 1 volt. The Fourier transform is then applied to $x_{1q}(t)$ and $x_{2q}(t)$ to obtain $X_1(\omega)$ and $X_2(\omega)$, which are then processed to give the cross-spectrum $X_1(\omega)X_2^*(\omega)$, where * denote conjugation. Finally, the inverse Fourier transform is applied to give the cross-correlation function, $R_{12}(\tau)$.

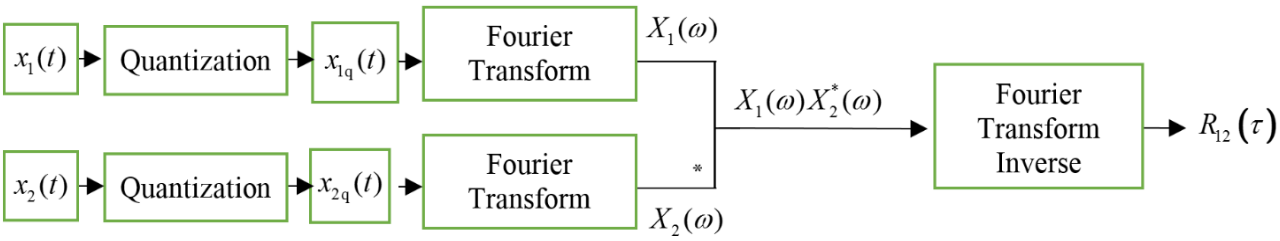

Figure 4. Schematic of the procedure to implement the quantization in the process to calculate the Cross-correlation function.

5. RESULTS

In Figure 5, sampled and quantized leak signals for 1, 2, 4 and 8 bits from the sensors placed at access points 1 and 2 are shown. The clipping effect is observed in all cases because the dynamic range is set at 1 volt. It can be seen that the level of quantization and the resolution increases when the number of bits increases. This resolution does not affect the analysis of the signals as is shown in the next section.

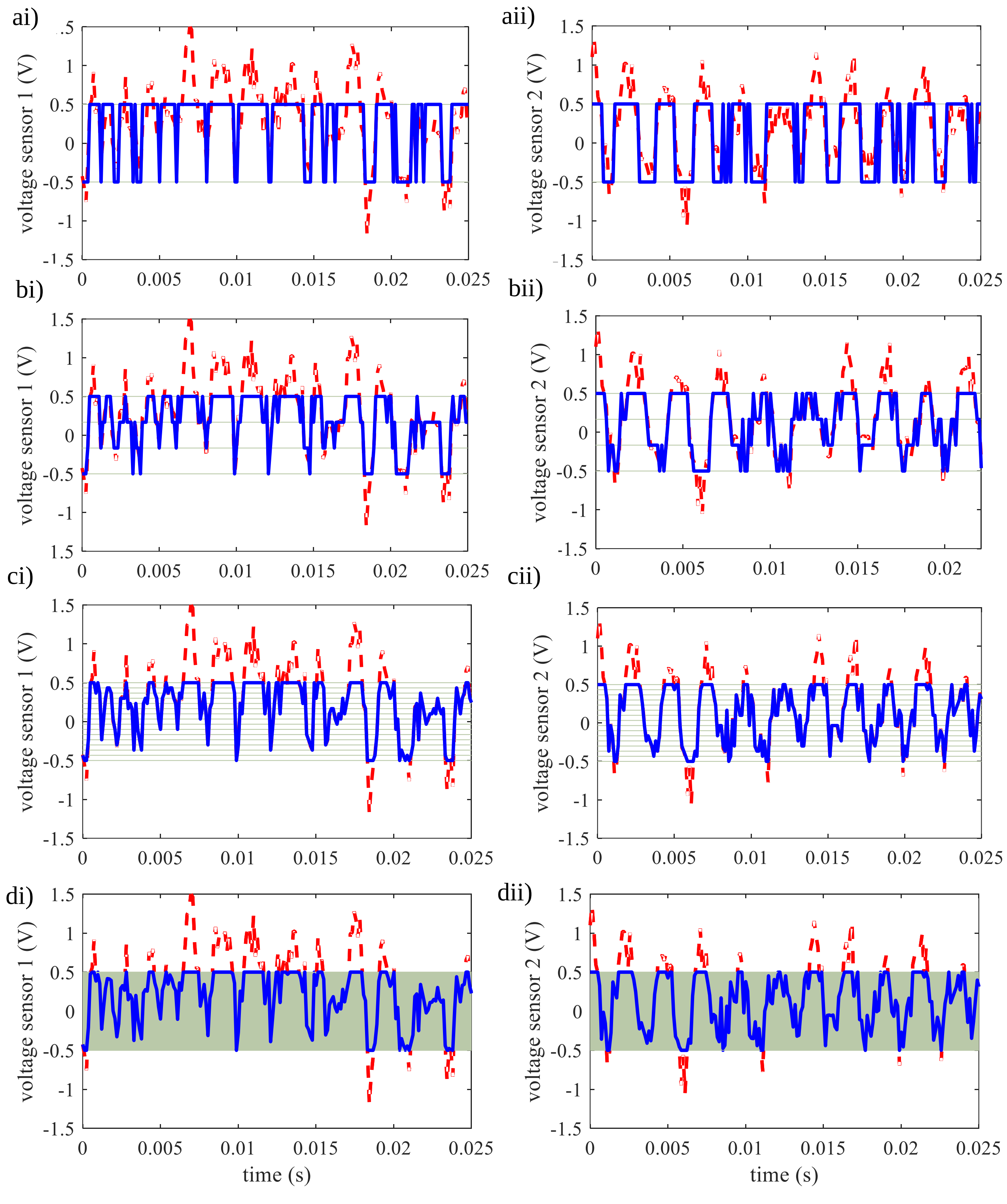

Figure 5- Quantization of leak signals from access points 1-2 with leak in bracket; ai) and aii) 1 bit; bi) and bii) 2 bits; ci), cii) 4 bits; di), dii) 8 bits. Gray lines —, quantization levels; red dashed-dotted line---, sampled signal; thick solid blue line —, quantized signal.

Figure 6 shows the power spectral density (PSD) normalized by the peak value, obtained from the quantized signals, the normalized modulus and phase of the cross-spectral density (CSD), the coherence and the cross-correlation coefficient, for 1, 2,4 and 8 bits. The sampled signals were first passed through a band pass fourth order Butterworth filter, with lower and upper limits of 250 Hz and 600 Hz respectively, before passing through the quantization process. This bandwidth contains the leak noise which is propagated to the sensors. The cross-correlation coefficient was computed using a 10240-point FFT, 5120 of overlap and a Hanning window.

It is observed that the tendency of the PSD and the modulus of the CSD obtained from the signals are similar for 1, 2, 4 and 8 bits for sensors 1 and 2 within the bandwidth of 250-600 Hz. The unwrapped phase of CSDs have the same slope for all cases. It can be seen that the coherence increases when the number of bits increases. From the cross-correlation function, the time delay (T_0) of 7.7 ms is obtained as shown in Fig. 6(f). Using this time delay a velocity of leak noise propagation is estimated to be 510m/s.

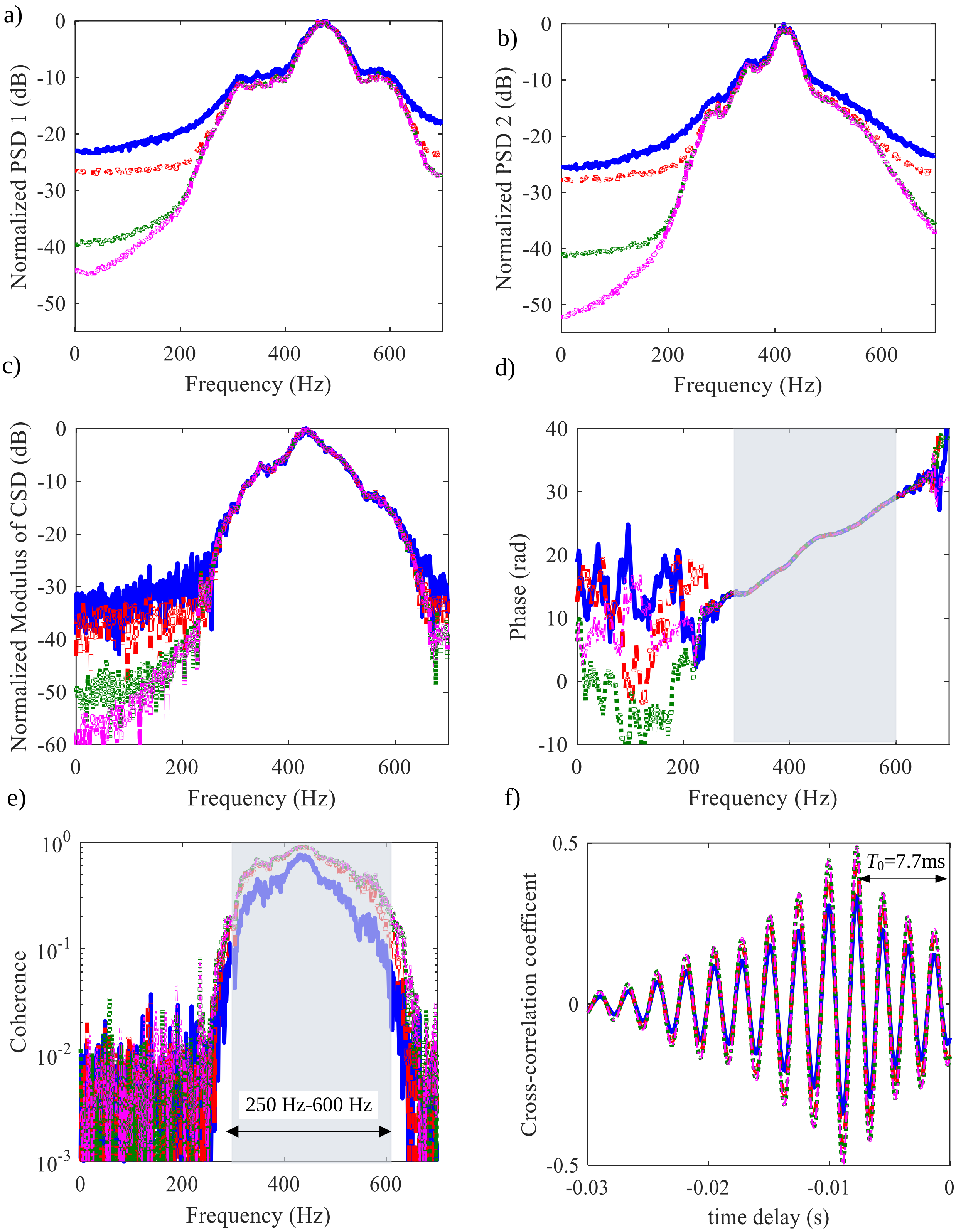

Figure 6 - a) Normalized PSD of signal from sensor 1 (b) Normalized PSD of signals from sensor 2 (c) Normalized Modulus of the CSD (d) Coherence (e) Phase spectrum (f) Cross-correlation coefficient. —1bit; ---2 bits; ….4 bits; −·− 8 bits. (Values in dB ref. V^2).

6. CONCLUSIONS

This paper has investigated the effects of quantization and clipping on the accuracy of the time delay between leak noise signals estimated using cross-correlation of the signals. Simulations using experimental data has shown that varying the number of bits in the A to D converter as well as the clipping on the signals, does not have an effect on the time delay estimation. Thus, it can be postulated that significant savings in the processing of leak noise could be made without compromising the efficacy of the device.

7. ACKNOWLEDGMENT

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9. RESPONSIBILITY NOTICE

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