In-situ measurement of the height of condensed water in steam pipes with dynamic flow

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ABSTRACT

A method based on the use of enhanced filtered Hilbert envelope of the wave signal was developed in order to monitor the height of condensed water through the wall of steam pipes having dynamic flow conditions. A prototype testbed was designed and fabricated in this study to simulate the dynamic flow conditions including the air stream flowing above the water and bubble induced disturbance. A dual-transducer was used to perform the test as a basis for the multiple transducers system to facilitate the detectability and reliability for long term monitoring of the condensed water height in dynamic conditions. The results demonstrated that the method of measuring the water height using multiple-transducer system employing the developed novel signal processing technique is an efficient and accurate tool for practical applications

Keywords: Health monitoring, water level in pipe, dynamic surface conditions, Hilbert Transform, signal processing.

1. Introduction

This paper reviews and reports the progress in developing signal-processing techniques for water height monitoring through the wall of steam pipes. The developed health monitoring system is critical to ensuring the pipes operation safety. This reported study is part of an ongoing series of research and development investigations with the goal of developing a monitor system that can be operated at temperatures as high as 250 ºC [Bar-Cohen et al., 2010-2011, and Lee et al., 2014]. Details of the signal processing techniques used in the measuring system were reported in [Lih et al., 2013 and Lih et al., 2015].

The developed system is based on the ultrasonic Pulse-Echo nondestructive evaluation (NDE) technique using transducers that send and receive pulses through the pipe wall and the condensed water. The time-of-flight of the wave reflections from the top surface of the water is used to calculate the water height (**Figure 1**). The reflected signals that received require effective signal processing to analysis and distinguish the group of waveforms in the time history. Usually, there are several issues that need to be taken into account including the strong ringing of the signal that are reflected from the interfaces of the steel pipe, the effect of the pipe curvature that cause wave losses, and the related attenuation. In the previous studies, the authors developed for this purpose signal-processing techniques for a single transducer system. The results obtained in the lab and the field demonstrated the feasibility and efficiency of the system. However, in practical operation, the received signal would become unstable due to the dynamic environments that are involved, including vibration of the support structures, ripples of the water surface induced by the fast blown steam, temperature variation, presence of bubbles, potential water hammer effect, etc. These effects cause disturbance of the water surface and make it difficult to obtain accurate measurement of the water height inside the water based on a single transducer system. To overcome the difficulties involved with dynamical environments, we are investigating the use of multiple transducers as illustrated in **Figure 2**. To expand the reception angles, additional transducing probes can be installed around the pipe, which can act as both transmitters and receivers. A two-dimensional cross-sectional profile of condensed water can be determined using measurements from a series of scans with respect to the time delay and multiple pitch-catch data related to the refracted angle. A newly developed dual pulse/echo transducers system and test results are presented in this paper building the framework of the testing system, data acquisition module, and signal processing codes. Further development of the system based on the use of dual transducers system will be straightforward expansion to transduce array. The use of transducer array is expected to be part of studies where both the pulse-echo and pitch-catch signals will be used to monitor the fluctuation of the water height due to disturbance, water flow, and other anomaly conditions via the switching the input from the transmitters in the array.

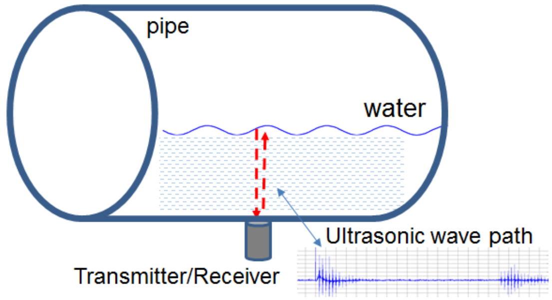

Figure 1. A schematic illustration of the pulse-echo test method using a single probe mounted on the steam pipe.

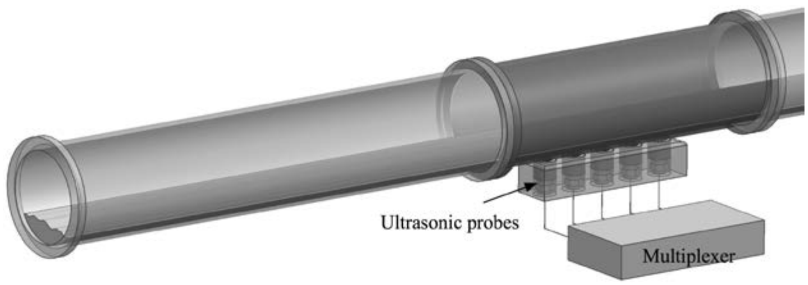

Figure 2. Schematic illustration of the use of transducer array for the health monitoring system.

2. The Experimental Setup

Previously, the authors developed a health monitoring system that is based on a single ultrasonic transducer which transmits ultrasonic pulses and receives the reflections from the pipe. There are limitations that need attention including limited depth of focus and no multiple-angle refections detection. In this reported study, we addressed the possibility that the water surface has various shapes including circumferential around the internal surface of the pipe. For this purpose, we use multiple probes and seeking to select optimal number and positions for them. Using more than one probe provides statistical correlations between probes with regard to potentially suspicious measurements that may result from such causes as degradation of the interface with the probe or internal corrosion, as well as allows for dealing with two dimensional cross-sectional profile of the condensed water. For this purpose, the setup was modified to include dual ultrasonic transducers that are driven by a multiplexer. The test setup also includes a pipe segment that is covered from its two sides by welded plates to form a container shape that allows direct access from the top surface as shown in **Figure 3**. Two disturbing water conditions were introduced by blowing air (simulating flowing steam) over the water surface and by introducing bubbles into the path of the acoustic wave as shown in the left and right of **Figure 3**, respectively.

For multiplexer, we used an eight channel multiplexer (USB-UT350MT, US Ultratek, Inc.). This multiplexer consists of a combination of a tone burst pulser/receiver and an analog-to-digital, and it is capable of processing data at high speeds (in real-time) suitable for the analyses of multiple signals. A Labview based *in-situ* GUI code was developed for the signal processing and the data acquisition to allow for varying the control parameters such as filtering frequency range, data buffer length, sampling rate, trigger, etc.

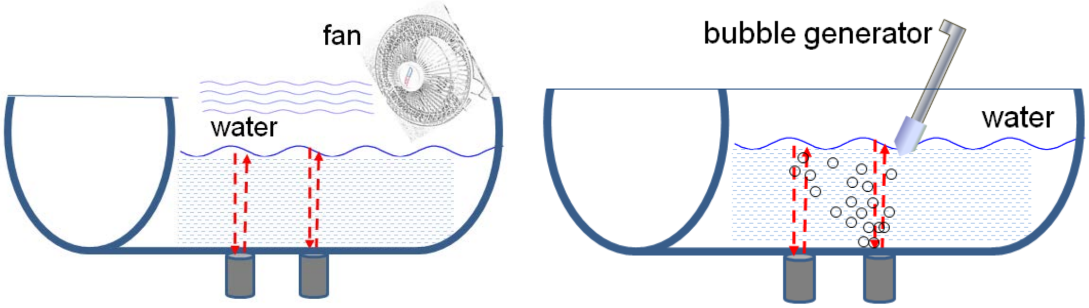

Figure 3. The test setup for the dynamic disturbing conditions of the pipe by blowing air stream over the water (left) and by generating bubbles (right).

3. The Signal Processing

The measurement of the time-of-fight was done based on the signal processing theory such as the autocorrelation, Hilbert Transformation, and the envelope determination techniques [Bendat and Piersol, 2010]. However, the application of these techniques requires adjustment to the specific application, such as medial, aerospace engineering, civil or mechanical engineering. A systematic study of the signal processing methods for the health monitoring of the water height in a steam pipe was presented in [Lih et al, 2013; and 2015]. An enhanced implementation of the signal processing procedure for a dynamical environment was discussed in [Lih et al, 2015]. The methods based on autocorrelation and Hilbert transform methods are summarized as follows.

Autocorrelation Method

Auto-correction is one of the most widely used signal processing methods to find repeated patterns or time-of-arrival in the presence of noise. The autocorrelation function can be defined as follow:

$$R_{xx}(\tau) = \frac{1}{T}\int_0^T x(t)x(t+\tau)dt \tag{1}$$

Where, T is the total sampling time and τ is the time separation variable. The time of flight (TOF) is then determined using a predetermined search window for the second maximum auto-correlation group from the calculated value of the auto-correlation.

A transducer array is assumed to performs pulse-echo and pitch-catch to monitor the fluctuation of the water height due to disturbance, water flow, and other anomaly conditions via the switching the input from the transmitters array X_i(t). The received signals Y_{ij}(t) are then correlated with the input signals to obtained the cross correlation functions R_{XY} as

$$R_{X_iY_j}(\tau_j) = \frac{1}{T}\int_0^T X_i(t)Y_j(t+\tau_j)dt \tag{2}$$

Through the analysis of the cross correlations function and its spectrum of various simulated disturbance conditions, a systematic monitor system to gauge the water level and anomaly conditions can be established. The enhanced capability also allows determining effective location for the transmitting and receiving probes.

Hilbert Transform Method

Another approach was introduced to characterize time-of-flight by such as a widely used signal-processing method for the TOF estimation that is an envelope extraction based on the Hilbert transform technique. Hilbert transform of s(t) is defined as the Cauchy principal value of the integral:

$$H[s(t)] = \text{P.V.}\int_{-\infty}^{\infty} \frac{s(\tau)}{\pi(t-\tau)}d\tau \tag{3}$$

The Hilbert transform yields another time series that has been phase shifted by 90° via its integral definition. The analytical signal Z(t) of the echo s(t) is defined in Eq. 3, and the envelope of the analytical signal can be obtained with the magnitude of the signal Z(t).

$$Z(t) = s(t) + jH[s(t)] = a(t)e^{-j\phi(t)} \tag{4}$$

where *a(t)* is the envelop, $\phi(t)$ is phase, $j = \sqrt{-1}$.

It should be noted that the echoes generally interfere with the noise, which causes the distortion of the frequency spectrum. To overcome this problem, the signal needs to be filtered by a high-pass filter. The method has been demonstrated to be very effective in reducing the noise level to reconstruct the receiving signal.

4. Experiment and results of the dynamic surface conditions

Using the developed algorithm for determining the height in real-time, the capability to handle surface and bulk interferences was tested. Two disturbing water conditions (as mentioned in **Figure 3** earlier) were introduced by blowing air stream over the water surface and by introducing bubbles into the path of the acoustic wave.

Surface disturbance due to air stream

The first dynamic testing was conducted by a fan generated air stream above the water as shown in the left of **Figure 4**. The test setup of blowing air stream over the water and the transducers locations are shown in **Figure 4** left and right respectively. The transducers' location is marked as "ch1" and the "ch2" for their connecting channels in the data acquisition system. Two data acquisition channels were used to receive the signals and processing the data to find the time of flight and determine the height in real time where the airflow started at ~ 15sec of the right-hand graphs shown in **Figure 5**. The first and second rows of the graphics represent the results from the two channels and the first and second columns indicate the low-pass filtered signal, the Hilbert envelop at a certain time, respectively. The third column shows plots of the log of the measured water height. The red lines on column one and two mark the value of the time of flight (TOF). It can be seen from the third column of **Figure 5** that there exists void measurements due to the unclear received signal, which needs to be filtered out. The statistical correlation between the heights measured from channel 1 and channel 2 is plotted in **Figure 6**. It shows that the data from the two channels has a weak correlation with a value of -0.11543. The statistical correlation can be used to gauge the strength of the disturbance, the changing of the water height, and other dynamic conditions for practical applications.

Next, the measured water height was refined by outliers' removal process. The refined measurement and filtered water height was done by moving average results is shown **Figure 7** on the left and the mean and three standard deviations of the mean on the right of for channel 1. Same result for channel 2 is shown in **Figure 8**. It can be seen that the water height has a mean value of 2.37" with three standard deviations of 0.22" for channel 1 and a mean of 2.19" with three standard deviations of 0.12" for channel 2, respectively. It indicates that within the selected interval the average water heights are measurable with an empirical filtering and moving average criteria under the air stream over the water condition. Besides, the value can be used to evaluate the degree of water height perturbation under air stream condition. However, further investigation is needed to learn the effect of the air stream to the water height measurement.

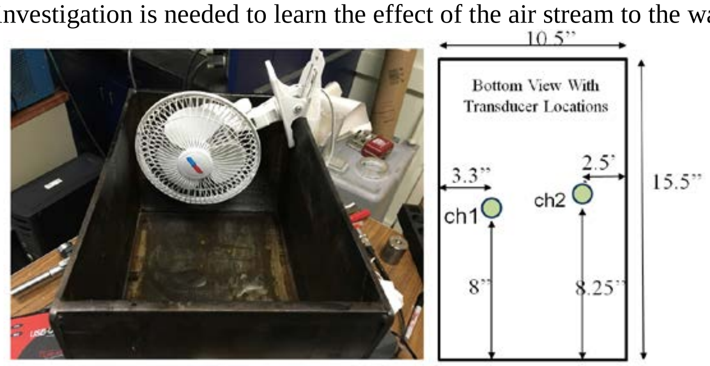

Figure 4. The test setup of blowing air over the water (left) and by the transducers locations (right).

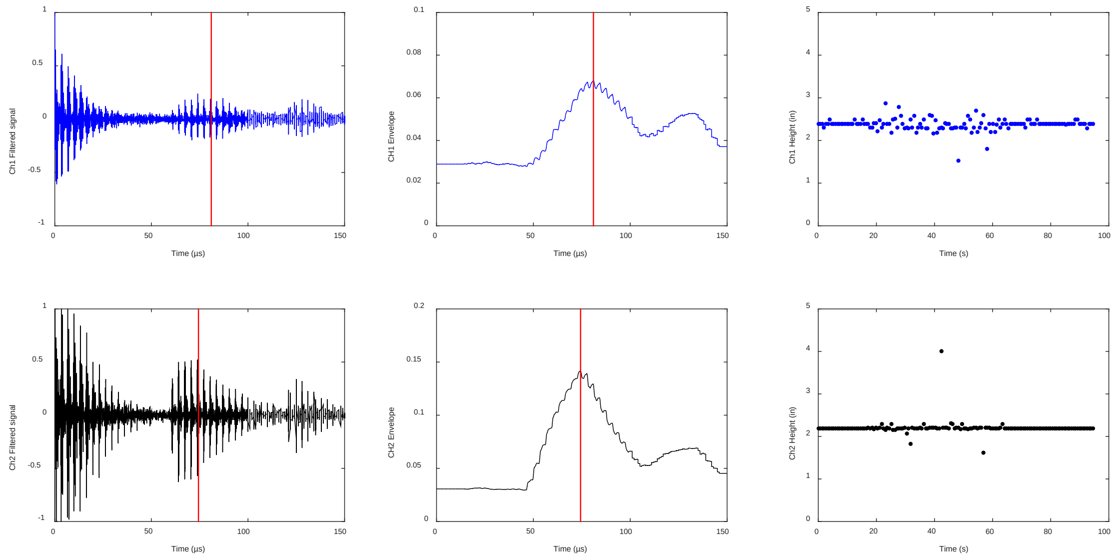

Figure 5. The in-situ data processing of a dual channel measurement system results due to due to the air stream.

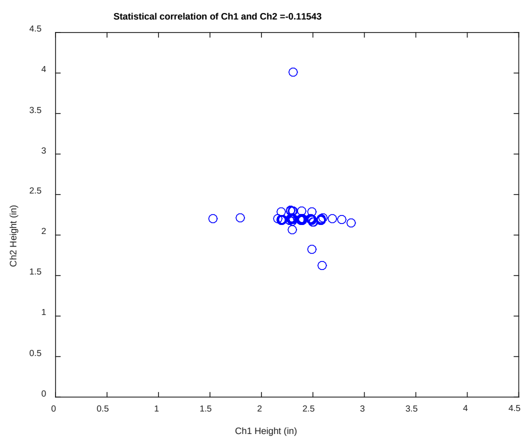

Figure 6. The statistical correlation of the measured water height of the two channels to due to the air stream.

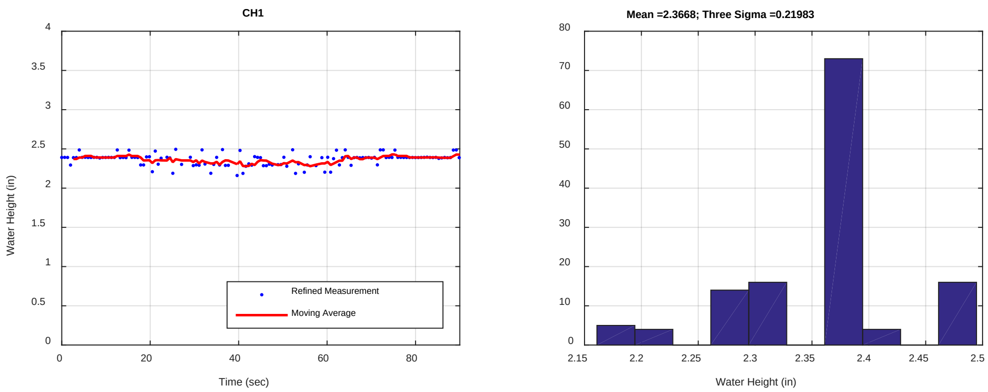

Figure 7. The refined measurement and filtered water height and its mean and three standard deviations of the mean of channel 1 due to the air stream.

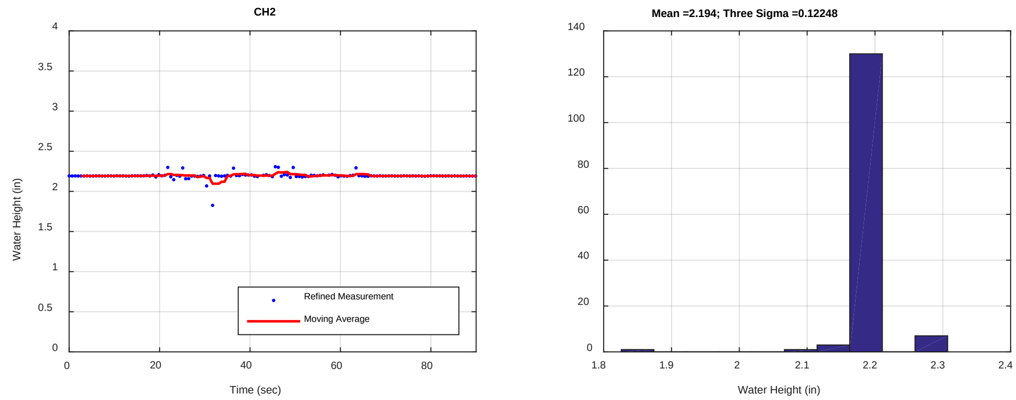

Figure 8. The refined measurement and filtered water height and its mean and three standard deviations of the mean of channel 2 due to the air stream.

Bubble induced ripple surface condition

The performance of the developed system was investigated further under surface perturbation condition, a test setup with bubble generating device was used as shown on the right of **Figure 3**. The head of the bubble generator is placed near the corner of the tank close to channel 1. A noisy data was acquired in the window of time that the perturbation was introduced but the moving average provided a reasonable accuracy of the water height measurement. The transducers are placed the same locations as the air-stream testing shown in **Figure 4**. It can be seen from the third column of **Figure 9**, which used the same definition as the air stream **Figure 5** that there exists fewer void measurements compared to the air stream testing. It indicated the mild disturbing surface condition along the wave path of the transducers of this case. The statistical correlation between the heights measured from channel 1 and channel 2 is plotted in **Figure 10**. It shows that the data of the two channels has even weaker correlation with a value of 0.074 compared to the air stream case. The statistical correlation indicated that the bubbles spreading is random and the two channels received uncorrelated signals.

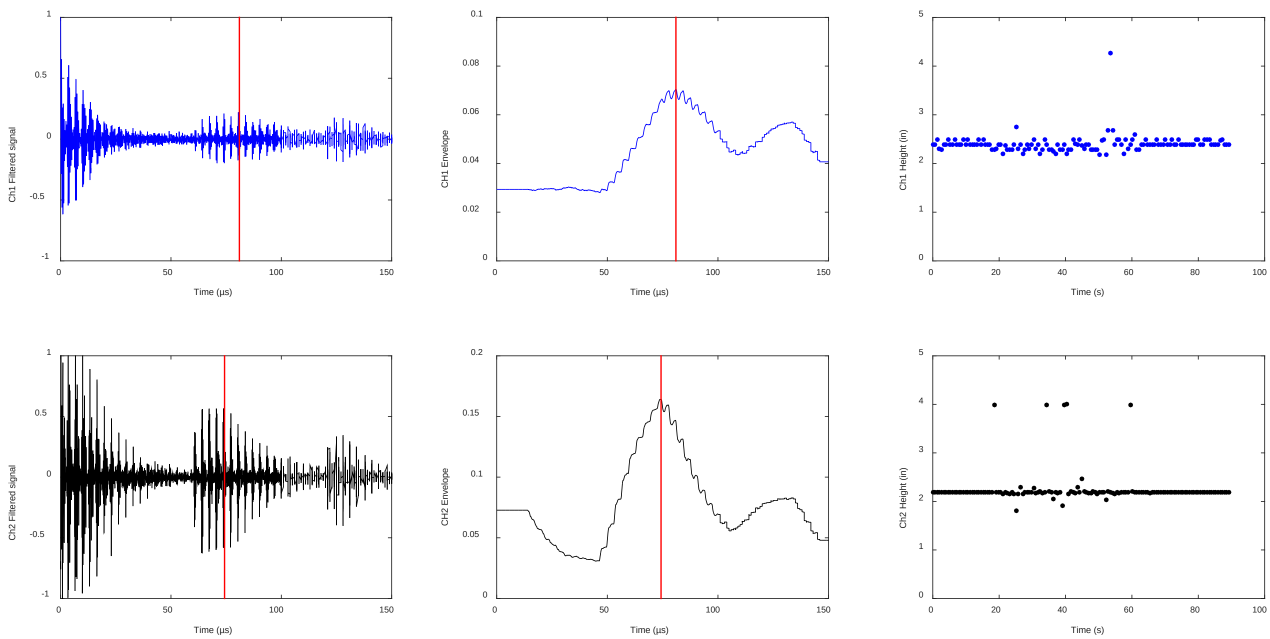

Figure 9. The in-situ data processing of a dual channel measurement system results due to due to the bubbles.

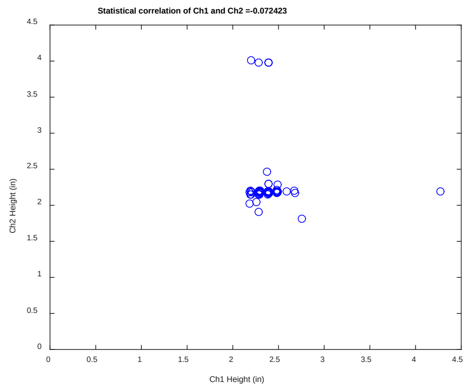

Figure 10. The statistical correlation of the measured water height of the two channels to due to the bubbles.

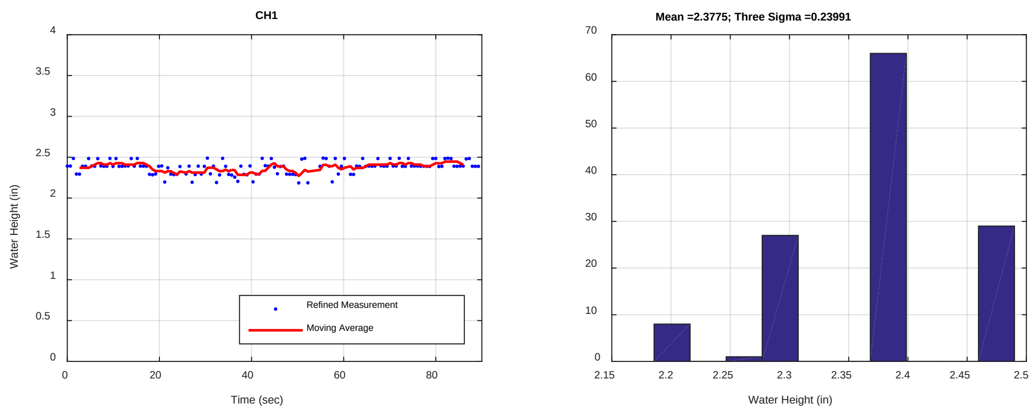

Figure 11. The refined measurement and filtered water height and its mean and three standard deviations of the mean of channel 1 due to the bubbles.

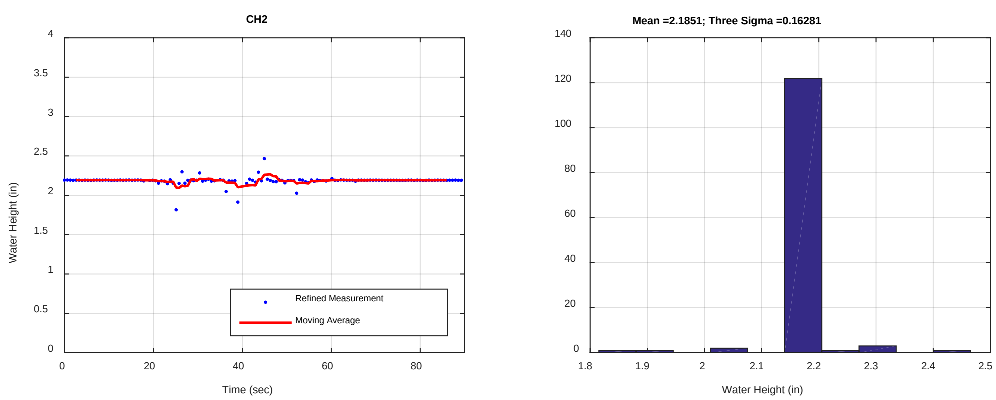

Figure 12. The refined measurement and filtered water height and its mean and three standard deviations of the mean of channel 2 due to the bubbles.

Similar to the air stream case, the measured water height was refined by an outliers removing process. The refined measurement and filtered water height by the moving average results is shown on the left and the mean and three standard deviations of the mean is on the right of **Figure 11** and **Figure 12** for channel 1 and channel 2, respectively. The water height has a mean of 2.38" with three standard deviations of 0.24" for channel 1 and a mean of 2.19" with three standard deviations of 0.16" for channel 2, respectively. The result is reasonable form observation and is consistent with the case of air stream.

Conclusion

An enhanced signal processing methodology based on the Hilbert envelope and auto-correlated function was developed using multiple transducers to monitor the height of condensed water measured thru the wall of a steel pipe with dynamic environments. Tests and analytical results are presented for measured using two transducers and processed water height in dynamic surface conditions subjected to air stream and bubbles inside the pipe. The results verified the consistency and stability of the developed signal processing for health monitoring the water height inside a steam pipe. The framework for transducer array based system is established to monitor the fluctuation of the water height due to disturbance, water flow, and other anomaly conditions for the practical application. Further experiments and studies are required to investigate the effect of various dynamic conditions such as real air stream in a pipe, the effect of turbulence flow, bubble formations, etc. to the water height measurement.

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