Signal processing for determining water height in steam pipes with dynamic surface conditions

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ABSTRACT

An enhanced signal processing method based on the filtered Hilbert envelope of the auto-correlation function of the wave signal has been developed to monitor the height of condensed water through the steel wall of steam pipes with dynamic surface conditions. The developed signal processing algorithm can also be used to estimate the thickness of the pipe to determine the cut-off frequency for the low pass filter frequency of the Hilbert Envelope. Testing and analysis results by using the developed technique for dynamic surface conditions are presented. A multiple array of transducers setup and methodology are proposed for both the pulse-echo and pitch-catch signals to monitor the fluctuation of the water height due to disturbance, water flow, and other anomaly conditions.

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

1. Health Monitoring System

Health monitoring systems are used for many *in-situ* applications and this reported study covers the research and development that was conducted in support of measuring condensed water height in steam pipes. Such steam pipes are used in various major cities in the world and they are generally used to transfer steam from central power stations under city streets to support heating, cooling, or supply power to buildings and businesses. Health monitoring of steam pipes is critical to assure their safe operation. In previous studies, the authors sought to develop and demonstrate the feasibility of using an ultrasonic based technique of monitoring the condensate height that sustains the harsh environments of the steam pipe system (<250ºC). The developed technique was demonstrated with a good accuracy [Bar-Cohen et al., 2010a, 2010b, and 2010c, 2011]. A more recent development of the technique can be found in [Lih et al., 2013 and Lee et al 2014]. The developed nondestructive measurement is based on the Pulse-Echo method of using the time-of-flight of the wave reflections from the top surface of the water to calculate the water height (Figure 1). The numerous reflections that are received in the Pulse-Echo method require effective signal processing technique to distinguish the reflections from the top and the bottom surfaces of the condensed water. Generally, there are several issues that need to be taken into account including the strong ringing from the interfaces of the steel pipe, the effect of the pipe curvature that cause wave losses, and the associated attenuation. Also, for practical applications, the received signal may be unstable due to the disturbance of the water surface, external noise, temperature variation, turbulence of the water flow, scattering from potential sediments in the bottom of the pipe inner surface along the path of the wave, or presence of bubbles.

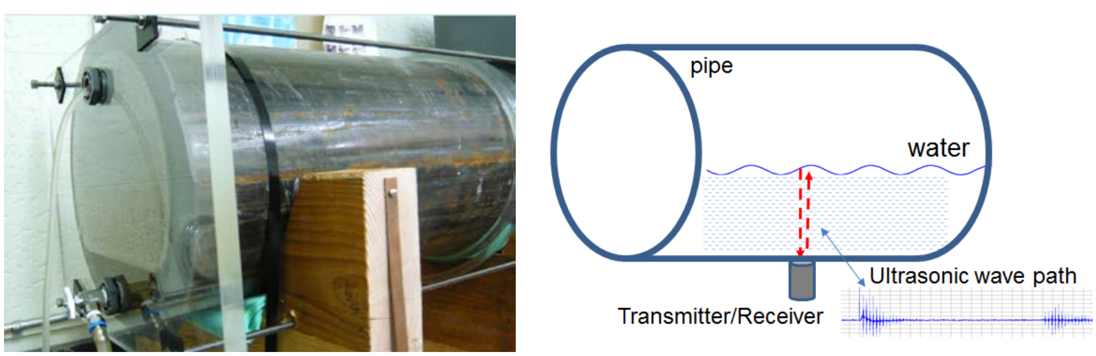

Figure 1. The test set up and a schematic diagram illustrating the pulse-echo method exhibiting ultrasonic probe mounted onto the steam pipe.

2. Signal Processing Methods

The measurement of the time-of-fight was developed based on the information signal processing theory such the autocorrelation, Hilbert Transformation, and the envelope determination techniques can be found in many early literatures such as [Bendat and Piersol, 2010]. However, the applications of the developed techniques need to be adjusted to be applicable to the different application fields such as medial, aerospace engineering, civil or mechanical engineering. To improve the capability and reliability for the in-situ measurement of liquid inside the pipe, it is necessary to have a cost-effective method to measure the time-of-flight from the reflected signals. For this purpose, different approaches including autocorrelation, Hilbert Transformation, and Shannon Energy Envelope methods were investigated. A systematic study of signal processing methods for the health monitoring of the water height in a steam pipe was presented by [Lih 2013]. These methods are summarized as follows.

Autocorrelation Method

A large number of reflections that are received from the pipe from a typical test are shown in the top of Figure 2. Therefore, it is difficult to determine of the height on simple time-of-flight measurements in real time and an auto-correction technique was developed by the authors. 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.

Hilbert Transform Method

From previous studies, it was understood that when the signals become unstable or the signals are overlapping it is hard to set a searching window for the autocorrelation in order to find the max value and the time-of-fight. It may lose the fidelity of the measurement under this circumstance. For this purpose, different approaches were 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 [Bendat and Piersol, 2010]. Hilbert transform of *s*(t) is defined as the Cauchy principal value of the integral:

$$H[s(t)] = \text{P.V.}\int_{-\infty}^{\infty} \frac{s(\tau)}{\pi(t-\tau)}d\tau \tag{2}$$

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. 2, and the envelope of the analytical signal can be obtained with the magnitude of the signal Z(t).

$$Z(t) = s(t) + jH[s(t)] = a(t)e^{-j\phi(t)} \tag{3}$$

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

As an alternative approach, Hilbert transform based signal processing has been developed to determine the time of flight. 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 with a high-pass filter. The filtered signals with their short time Fourier Transforms (STFT) are employed to determine the time of flight. The method has been demonstrated to be very effective in reducing the noise level to reconstruct the receiving signal.

Shannon Energy Envelope

The normalized average Shannon energy known as Shannon envelope is also one of the widely used signal processing method for envelope extraction of varies applications employing sound signals [Lih et al., 2013].
The Shannon energy $S_E(t)$ and average Shannon energy $E_s(t)$ can be defined as follows:

$$S_E(t) = -x_{norm}^2(t) log\, x_{norm}^2(t) \tag{4}$$

$$E_s(t) = \frac{1}{N}\sum_{i=1}^{N} x_{norm}^2(i)\log x_{norm}^2(i) \tag{5}$$

where $x_{norm}(t)$ is a normalized signal and *N* is the signal length, and *Es(t)* is the average Shannon energy for frame *t.*

The normalized average Shannon energy *N(t),* called as the Shannon envelope, is then calculated by as follows.

$$N(t) = \frac{E_s(t) - M(E_s(t))}{S(E_s(t))} \tag{6}$$

where S(Es(t)) is the standard deviation of Es(t), M(Es(t)) is the mean value of Es(t).

Note that this method emphasizes the medium intensity signal, which corresponds to the second maximum value, and attenuates the low and high intensity signals. Thus, the time of flight can be obtained by finding the maximum intensity signal. Another issue for the monitoring of steam pipe is the case of no water inside the pipe. Since there is no reflection from the water to be detected, the determination from the methods described before results in wrong TOF values. To further optimize and reduce the errors for the TOF determination, the Hilbert envelop energy algorithm was implemented in the data processing system as a guidance for the presence of water. The energy can be obtained by equation (7) through the integration of Hilbert envelop over the sampling period T.

$$E^* = \frac{1}{T}\int_0^T HT(t)dt \tag{7}$$

The water height can be determined through the correlated energy level.

3. Enhanced Signal Processing Method

To enhance the analysis of the data and obtain as much as possible reliable height values, a signal processing algorithms based on the Filtered Hilbert envelop of the auto correlation function of the pulse-echo time history was developed. An example as shown in Figure 2 is used to illustrate the method. On top of Figure 2 is the measured time history of the received signal. It shows the ringing high frequency reflections repeatedly from the pipe wall. These reflection signals usually generate many local peaks and valleys and make the determination of water height difficult by directly applying auto-correlation function or Hilbert envelope. The bottom of Figure 2 is the plot of the autocorrelation function, Hilbert envelope of the autocorrelation function, and filtered Hilbert envelope of the autocorrelation function from the measured signal data. Figure 3 is the zoomed part of the curves in bottom of Figure 2 at the region of the first wave group travels across the pipe wall. The wall thickness of the pipe can be estimated by the local Hilbert envelope of the autocorrelation function as the red curve shown in bottom of Figure 2. The low pass filter cut-off frequency can thus be estimated and used for as the low pass filtering frequency to filtered the original Hilbert Envelope (red line in the bottom of Figure 2) to obtain the filtered Hilbert envelope (green line in the bottom of Figure 2) . Then from the local peak of the filtered Hilbert envelop (blue circle line in the bottom of Figure 2) the time of flight and thus the water height can be determined.

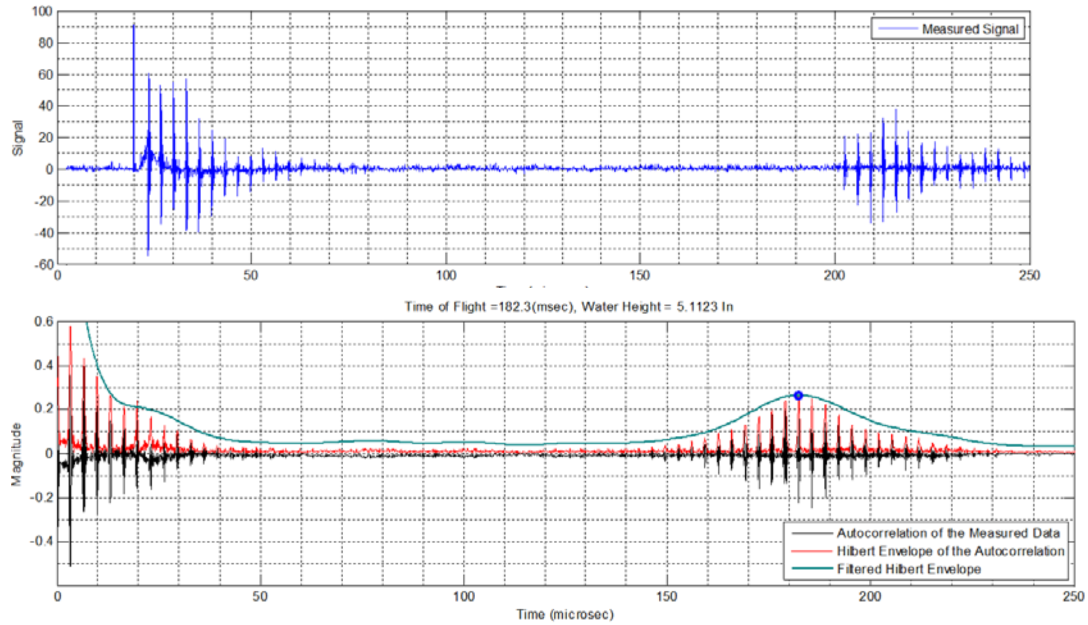

Figure 2: Top: The time history of the measured signal. Bottom: The autocorrelation, Hilbert envelope of the autocorrelation function, and filtered Hilbert envelope of the autocorrelation function from the measured signal data.

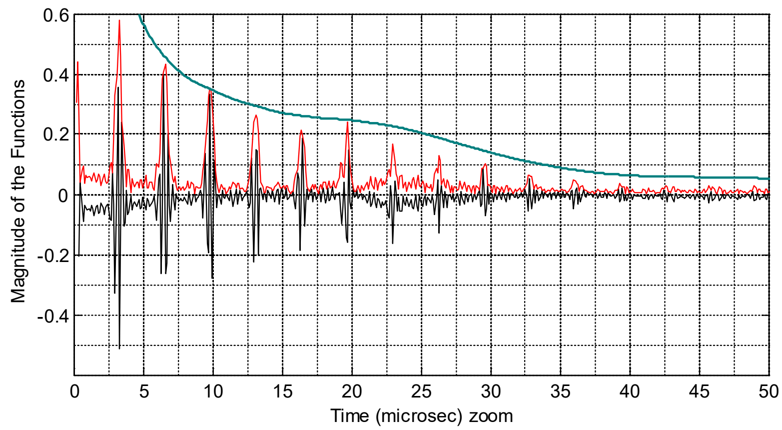

Figure 3: Zoomed time zone of the bottom of Figure 2 for the first wave group of the ultrasonic signal reflected from the pipe wall.

4. Experiment and Analysis for dynamic surface conditions

Using the developed enhanced algorithm for determining the height in real-time, the capability to handle surface and bulk interferences was tested. For this purpose, surface perturbations were introduced by shaking the surface, rocking the container, and by introducing bubbles into the path of the acoustic wave. The test setup consisted of a pipe segment that was covered from its two sides by welded plates to form a container shape that allows direct access from the top surface.

Surface perturbation due to tank shaking

The first dynamic testing was conducted by a light shaking of the pipe to generate sloshing effect between the pipe walls. The signal was recorded through a designated sampling interval. Then 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 as on the left of Figure 4. The tank was shaken in time frame of 1 to 2 minute. The mean and three standard deviations of the mean are shown on the right of Figure 4. It can be seen that the water height distribution is a Gaussian with a mean value 2.66 in and three standard deviations 0.145 in.

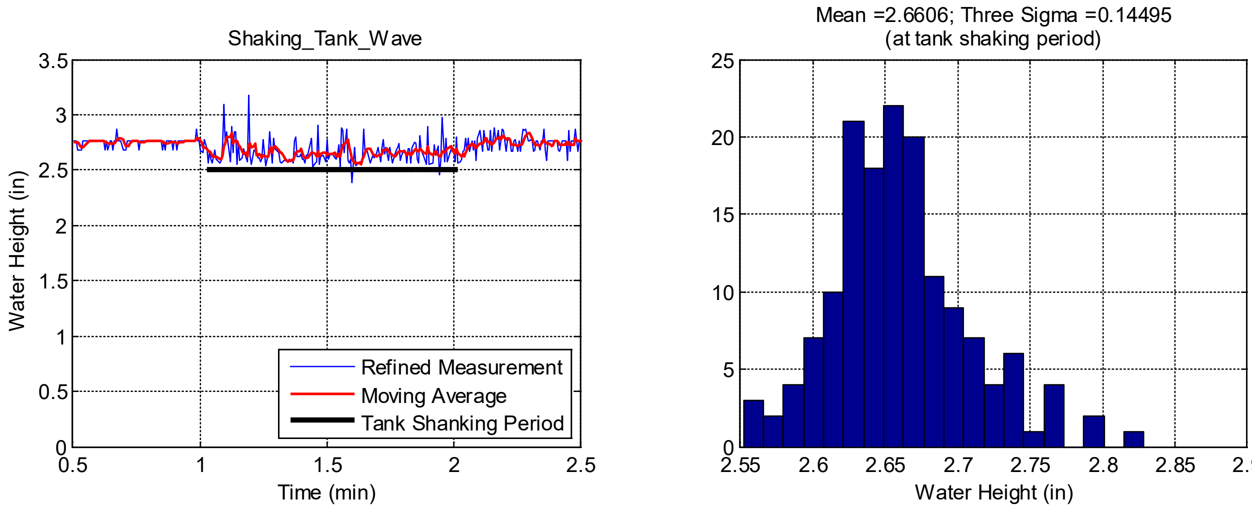

Figure 4: The refined measurement and filtered water height and its mean and three standard deviations of the mean with the tank shaking condition.

Bubble induced ripple surface condition

To further investigate the performance of the developed system under surface perturbation condition, a test setup with bubble generating device is used as shown on the left of Figure 5. Shown on the right of Figure 5 is an illustration of the experiment details. Each test consisted of one minute of water at "rest", one minute of perturbation (bubbling) and one minute of water at "rest" again. The data was acquired while calculating a moving average while excluding the outlier data. The bubbles were generated at the rate of ~3 bubbles per second and the surface wobbling was done at a rate of 2-3 Hz. The bubbles introduction consisted placing an air tube 0.5 inch from the bottom of the pipe surface and the example of generating bubbles at 1 inch away from the wave path is shown in Figures 6. 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. Figures 7 and 8 show the measured results by introducing the bubbles at 1 inch away from the wave path and right on the wave path, respectively. On the right of Figures 6-8 show the mean, and the three standard deviations of the mean of the measured heights. The results summarized in Table 1 indicated the measured values are very consistent and stable. The 99.73 percentile of the wave heights can thus be estimated through the mean and the three standard deviations of the mean values. The developed signal process method is demonstrated to be valid for measurement of the water height in dynamic water surface conditions.

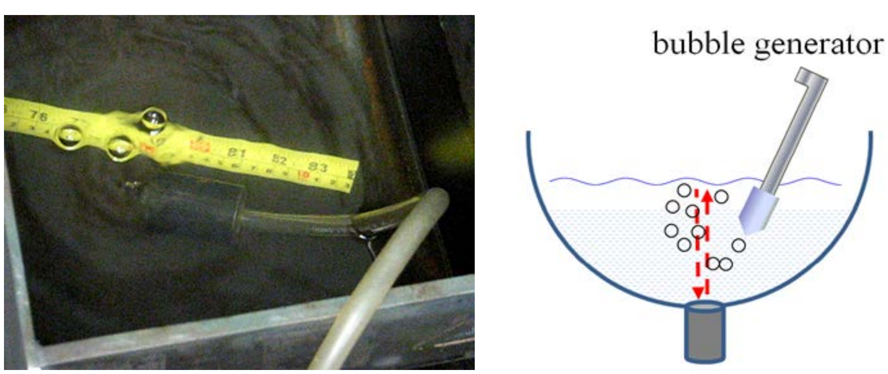

Figure 5: The illustration of the opened tank test setup (left) and the bubbles that were introduced into the water via the shown hose (right).

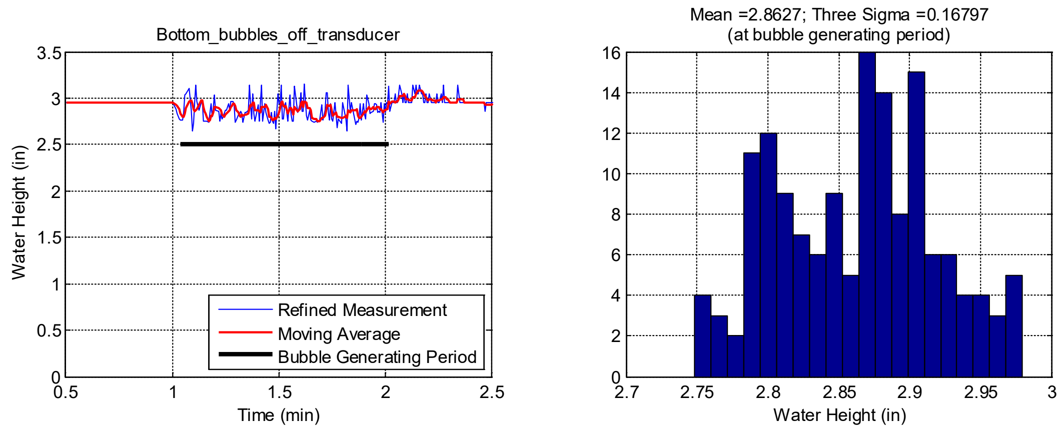

Figure 1: The refine measurement and filtered water height and its mean and three standard deviations of the mean with the bubble generating at the bottom in inch away from the transducer wave path.

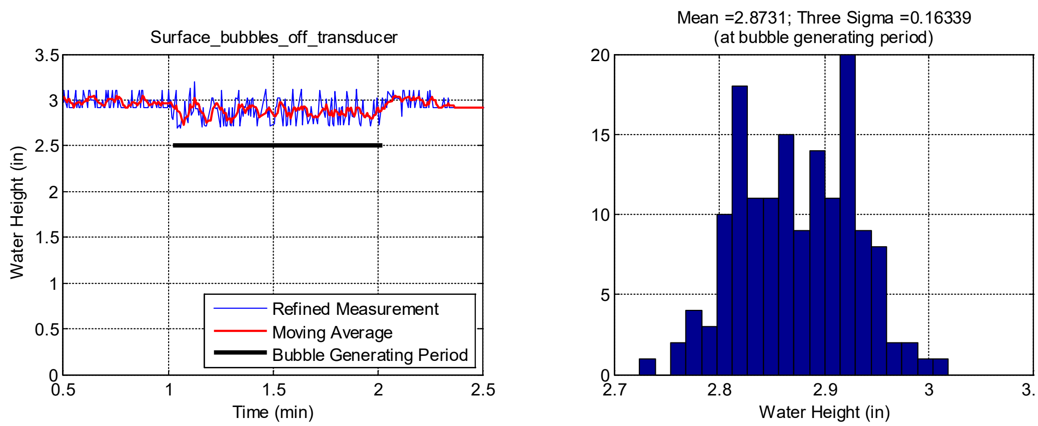

Figure 7: The refine measurement and filtered water height and its mean and three standard deviations of the mean with the bubble generating at the surface 1 inch away from the transducer wave path.

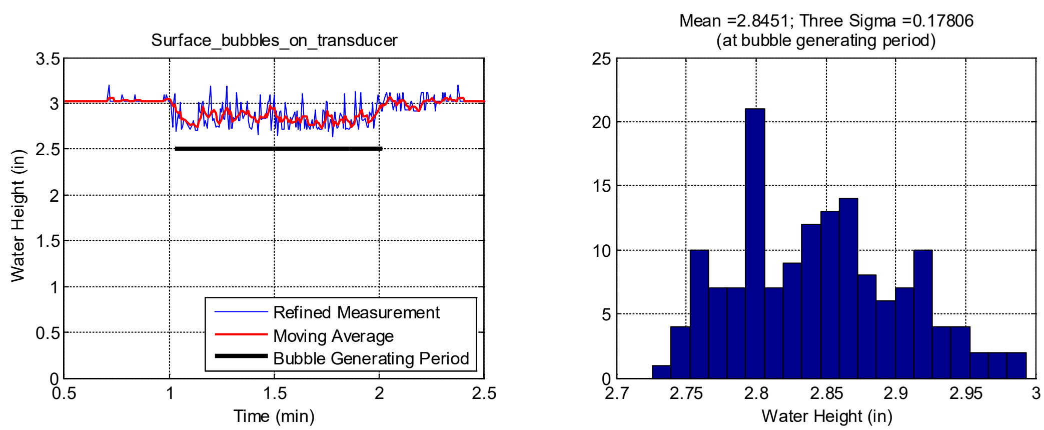

Figure 8: The refine measurement and filtered water height and its mean and three standard deviations of the mean with the bubble generating at surface of along the transducer wave path.

Table 1: The mean and three standard deviations of the mean for the filtered water height.

Bubble generating location	Mean height (inch)	3 standard deviations of the mean
At bottom away from the transducer	2.86	0.168
At the surface away from the transducer	2.87	0.163
At the surface along the transducer wave path	2.85	0.178

5. Multiple transducer array

Extended development of the research will use multiple transducers array and optimize their application. The possible approach for the implementation of multiple transducers on condensed water monitoring system is demonstrated in **Figure 9**. 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 is then achieved by the measurements from a series of scans with respect to time delay and multiple pitch-catch data with respect to refracted angle.

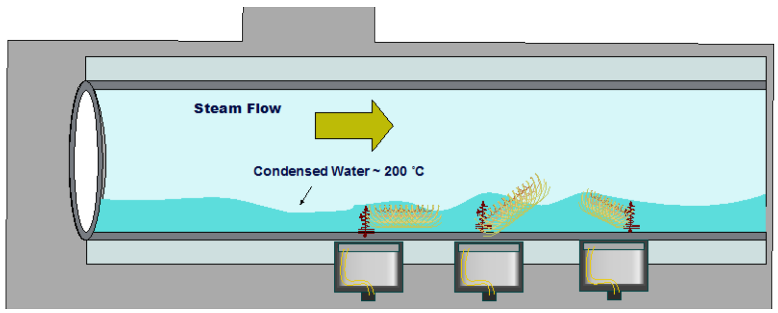

Figure 9: Schematic representation of multiplexed array transducers for health monitoring system.

A multiple array of transducers for both the pulse-echo and pitch-catch signals 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 $X_i(t)$ as shown in the Figure 10. The received signal $Y_{ij}(t)$ are then correlated with the input signals to obtained the cross correlation functions R_{XY} as

$$R_{X_iY_j}(\tau_j) = \frac{1}{T}\int_0^T X_i(t)Y_j(t+\tau_j)dt \tag{9}$$

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 will also allow determining effective location for the transmitting and receiving probes.

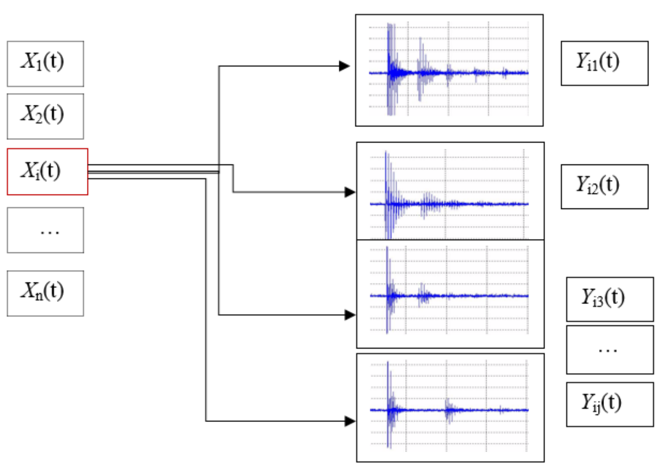

Figure 10. The illustration of the switching input and the output signals.

Conclusion

An enhanced signal processing methodology based on the filtered Hilbert envelope using an auto-correlated function was developed to monitor the height of condensed water thru the wall of a steel pipe in dynamic environments. Different algorithms including autocorrelation function, Hilbert Transform, and Shannon envelope methods were summarized in this paper. Testing and analysis results of the measured and processed water height in dynamic surface conditions by shaking the pipe and generating bubbles inside the pipe are presented. The results verified the consistency and stability of the developed signal processing for health monitoring the water height inside a steam pipe. A multiple array of transducers setup and methodology are proposed for both the pulse-echo and pitch-catch signals to monitor the fluctuation of the water height due to disturbance, water flow, and other anomaly conditions for the future study.

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