Proceedings of the SPIE Smart Structures and Materials/NDE Symposium, San Diego, CA, March, 2013

Advanced Signal Processing for High Temperatures Health Monitoring of Condensed Water Height in Steam Pipes

Shyh-Shiuh Lih, Yoseph Bar-Cohen, Hyeong Jae Lee, Nobuyuki Takano, and Xiaoqi Bao
Jet Propulsion Laboratory/California Institute of Technology, MS 67-119, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, 818-354-0784, lih@jpl.nasa.gov, Web: http://ndeaa.jpl.nasa.gov

Abstract

An advanced signal processing methodology is being developed to monitor the height of condensed water thru the wall of a steel pipe while operating at temperatures as high as 250°C. Using existing techniques, previous study indicated that, when the water height is low or there is disturbance in the environment, the predicted water height may not be accurate. In recent years, the use of the autocorrelation and envelope techniques in the signal processing has been demonstrated to be a very useful tool for practical applications. In this paper, various signal processing techniques including the auto correlation, Hilbert transform, and the Shannon Energy Envelope methods were studied and implemented to determine the water height in the steam pipe. The results have shown that the developed method provides a good capability for monitoring the height in the regular conditions. An alternative solution for shallow water or no water conditions based on a developed hybrid method based on Hilbert transform (HT) with a high pass filter and using the optimized windowing technique is suggested. Further development of the reported methods would provide a powerful tool for the identification of the disturbances of water height inside the pipe.

Keywords: High Temperatures (HT), Fluid height monitoring, health monitoring, monitoring steam condensation, Hilbert Transform.

1. INTRODUCTION

A metropolitan steam system is a district heating system which takes steam produced by steam generating stations and carries it under the streets to heat, cool, or supply energy to factories, buildings, and businesses. It is critical to monitor such systems to assure the safe operation. One of the major issues of the steam system is the accumulation of the condensed water inside the pipe system. Excessive rise in the height of water in the pipe is a source of concern due to the possible excitation of water hammer effects that may lead to serious consequences including damaged vents, traps, regulators and piping. The water hammer effect is caused by accumulation of condensed water that is trapped in horizontal portions of the steam pipes. 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 (<250°C). 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]. 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**). Typical Pulse-Echo reflection signals from the reflections of the water inside the pipe are shown in **Figure 2**. 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. In

Figure 3, the left figure shows reflections from a steady surface whereas on the right the water surface reflections are shown to vanish when extremely high waviness is introduced. These issues will cause the loss of fidelity of received signals and make the estimation of the water height difficult. Characteristic of this condition is the variability in the amplitude of the surface reflections. Thus, a reliable signal processing code is needed that consists of windowing, tracking and filtering the reflected signals to obtain stable readings.

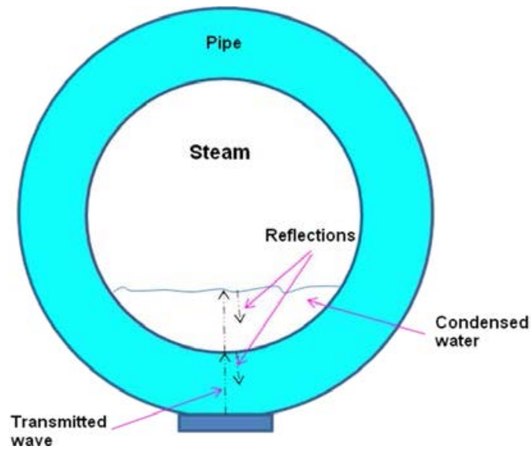

Figure 1: Illustration of the condensed water height monitoring using time-of-flight measurements of reflected ultrasonic waves.

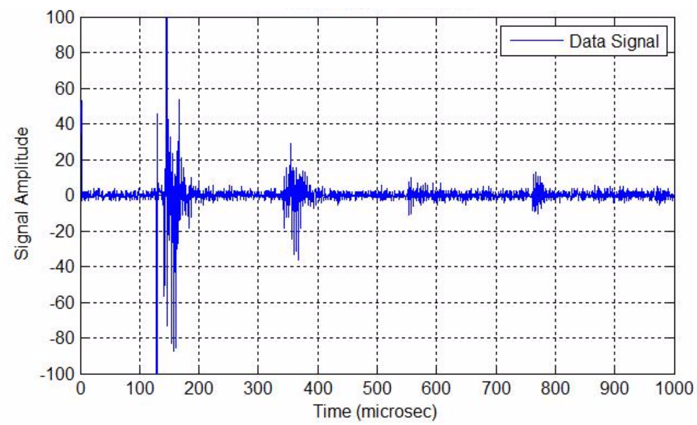

Figure 2: A typical reflection signal from the pulse-echo system.

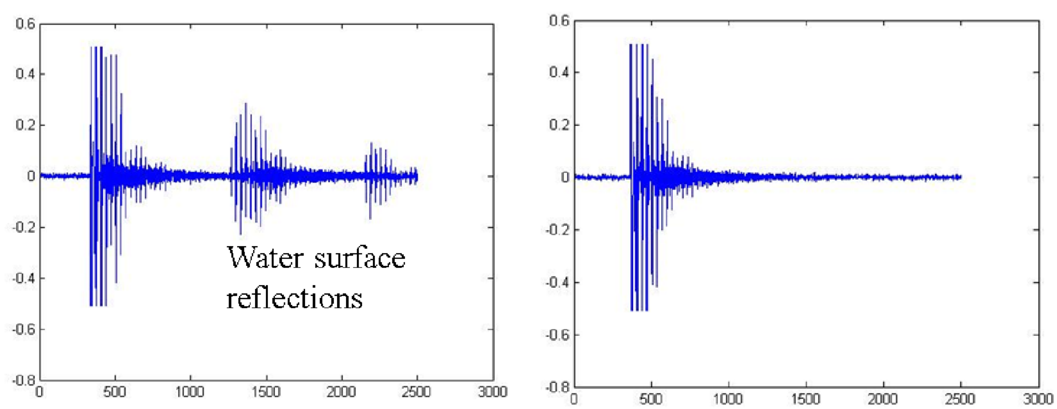

Figure 3: The reflected signals from the water surface when the surface is steady (left) and when wavy (right).

2. THE SIGNAL PROCESSING METHODS

Characterization of the time-of-fight

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 [Middleton, 1996]. 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.

Autocorrelation Method

A large number of reflections that are received from the pipe from a typical test are shown in **Figure 6**. 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 [Bracewell et al., 1978, Cutard et al., 1994]. The autocorrelation function can be defined as follow:

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

where T is the total sampling time and τ is the time separation variable.

An example of the autocorrelation technique was studied by the authors [Bar-Cohen 2011] and is summarized here. The time history of the pulse-echoed signal for testing the water height inside the pipe is shown in **Figure 4**. Note that a significant number of reflections are received from pipe wall (the first set of reflections) and they are becoming further complicated by the multiple reflections within the water itself. This large number of reflections makes it difficult to base the determination of the height on simple time-of-flight measurements. An auto-correction of the signal, where the autocorrelation leads to a first maximum group (the blue line) in the initial time stage at t = 0 then decay out at a certain period of time is shown on the left of **Figure 4**. These group f max autocorrelation is associated with the ringing signal from the pipe wall. While the second max group of the signal (the red line) after a certain period of time we obtained a local max at time t = τ , when the backscattered echoes are separated by a time delay. The time, τ , thus, corresponds to a time delay between two successive echoes, corresponding to the time of flight of the ultrasonic waves through the pipe and water. Thus, the time of flight is then determined using a predetermined search window for the second maximum auto-correlation group from the calculated value of the auto-correlation.

However, 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 [see Middleton, 1960 or Bendat and Piersol, 2010].

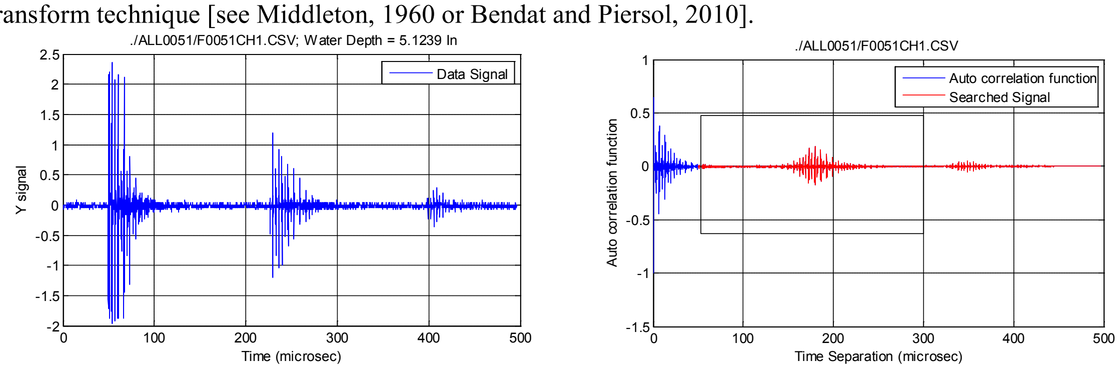

Figure 4: The time of flight (left) showing the first arrival time difference of 179.0 μsec and the calculated auto-correlation time difference of 179.6 μsec.

Hilbert Transform Method

Hilbert transform was originally developed to solve integral equations. The Hilbert transform yields another time series that has been phase shifted by 90° via its integral definition. Recently, the Hilbert transform technique has become widely used for the TOF estimation by using the envelope extraction method. Hilbert transform has been applied to obtain an analytical signal (complex envelope) from a real signal to determine instantaneous frequency and envelop estimation [Boashash et al., 1992, Chen et al., 2005, Oruklu et al., 2009]. 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).

$$Z(t) = s(t) + jH[s(t)] = a(t)e^{-j\phi(t)} \tag{2}$$

where a(t) is the envelop, $\phi(t)$ is phase, $j = \sqrt{-1}$, and H[s(t)] is Hilbert transform of s(t), defined as the Cauchy principal value of the integral:

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

As an alternative approach, Hilbert transform based signal processing has been developed to determine the TOF. 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. The effect of a high-pass filter is demonstrated in **Figure 5**, where the received and the filtered signals with their short time Fourier Transforms (STFT) are presented. It can be seen from the figures that the noise in the reconstructed signal has been greatly reduced and the echoes are clearly visible due to a high-pass filter.

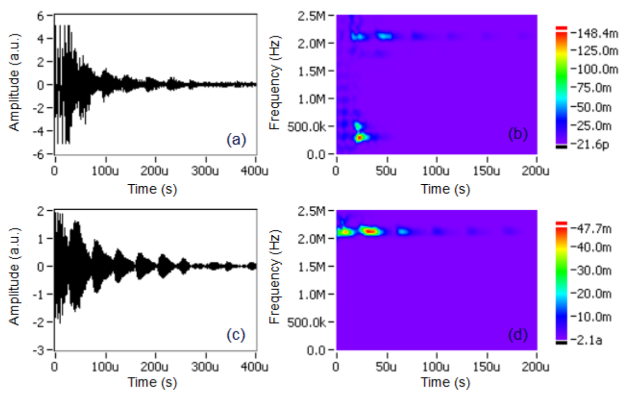

Figure 5: The effect of a high-pass filter (a) The received signal, (b) The time-frequency spectrum of the (a) signal using short-time Fourier transform (STFT), (c) The received signal subjected to a high-pass filter, and (d) The time-frequency spectrum of the (c) signal using STFT.

One method to determine the TOF values from the Hilbert envelop is to find the peak and threshold time of the first echo from the pipe wall, which are defined as To and T_1, respectively. Then, the time T_m of at the local maximum of the second signal group can be found by searching above the threshold time T_1. The TOF can thus be found by the time difference T_m- To as shown in **Figure 6.**

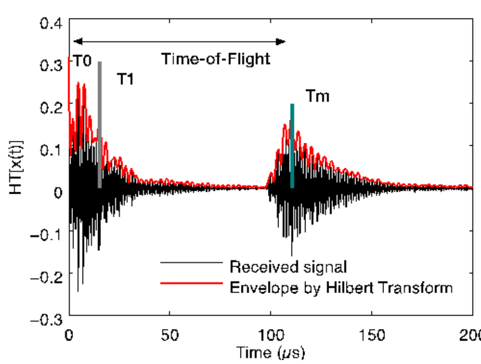

Figure 6: Received signal and the signal envelope obtained from Hilbert transform. T_0, T_1 and T_m are the peak time from the pipe wall, threshold time and the peak time from the water, respectively.

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 cardiac sound signals [Liang et al., 1997, Choi et al., 2008, Liu et al., 2012]. The Shannon energy SE(t) and average Shannon energy $E_s(t)$ can be defined as follows:

$$S_E(t) = -x_n^2(t) log\ x_n^2(t) \tag{4}$$

$$E_s(t) = \frac{1}{N}\sum_{j=1}^{n} x_n^2 \log x_n^2 \tag{5}$$

where x_n is a normalized signal, n is the length of data, and N is signal length. Es(t) is the average Shannon energy for frame t, M(Es(t)) is the mean value of Es(t), and S(Es(t)) is the standard deviation of Es(t). The normalized average Shannon energy N(t), called as the Shannon envelope, is then calculated by as follows.

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

An example of Shannon energy and Shannon envelope, where normalized original signal, Shannon energy and normalized average Shannon energy are shown **Figure 7**. 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. The performance comparison of the discussed methods is shown in **Figure 8** for the determination of TO, where the left plots show the original and processed signals when TOF value was around 110 us (approximately 7.5 cm of water height), while the right figures are those of around 40 us, corresponding to 2.5 cm of water height. It can be seen that all processing methods provide a reasonable accuracy for the detection of TOF, which is indicated by the small arrows. However, the drawback of this method is that the TOF value is generally overestimated compared to the values determined by autocorrelation and Hilbert envelop methods. The signal processing results obtained from a case of shallow water that is less than 1 inch are shown in **Figure 9**. The limitation of the signal processing methods for low water height is evident as these methods cannot resolve the overlapping echoes. The problem of the autocorrelation method arises from the fact that the noises in the received signals are not only from the ambient noise (white Gaussian noise). They also result from backscattered periodical ringing from the top and bottom of pipe wall. The consequence is the values of autocorrelation for the received echoes from pipe wall become higher than those of actual echoes from the water surface, making it difficult to determine the TOF when the target water height becomes lower, as shown in **Figure 9**. For the case of Hilbert envelope, due to the overlapping signals from the pipe wall and water surface, it may not be able find the TOF value directly. Also, in the case of Shannon envelope, the envelope was found to be flat arising from the fact that the intensity of the reflected echoes are similar at low water height water height, so the Shannon envelope method attenuates all signals. The results conclude that none of the above methods can be used for the low water height conditions.

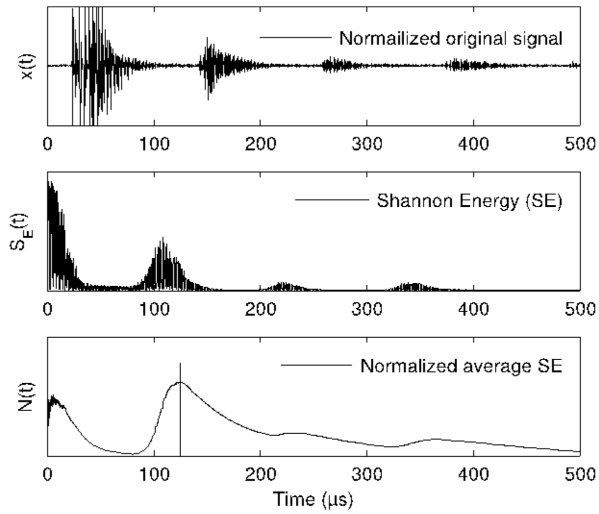

Figure 7: The normalized original signal, Shannon energy and normalized average Shannon energy.

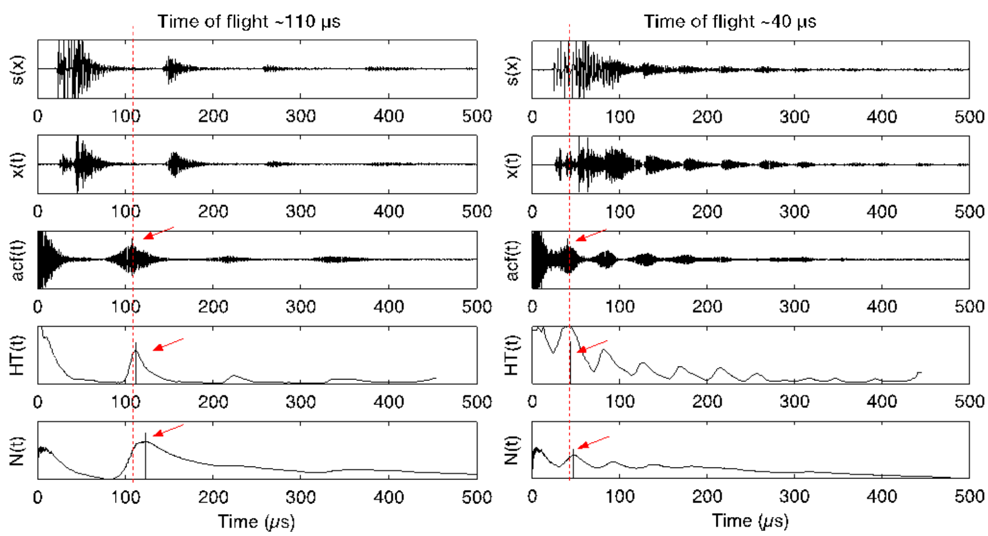

Figure 8: Signal processing results from received signals in high (left figures) and low (right figures) oil heights. From the top down, they are original signal s(t), filtered signal x(t), autocorrelation of signal acf(t), Hilbert transform envelope HT(t), and Shannon energy envelope N(t).

In order to improve the accuracy and expand the range of the ultrasonic water height determination, a hybrid frequency analysis method was developed. This hybrid method is based on Hilbert transform (HT) with a high-pass filter and followed by the fast Fourier transform (FFT) through an optimized windowing technique.

An example of the frequency-domain signal by taking the fast Fourier transform (FFT) of a Hilbert envelope is shown in **Figure 10**. It can be seen that the peak frequency occurred at 9.07 kHz, whose inverse is the period of a signal envelope which equals to 110 µs. This value is close to the value physically measured height level. Note that one major issue of the FFT of Hilbert envelope method is that the accuracy of echo frequency strongly depends on the search window length with respect to echo repetition period. Thus, the FFT of Hilbert envelope method was implemented only for low height of the target, with a narrow search window by cutting the signal in parts and only analyzing a small portion in time. Since the time interval between echoes is short in the low height condition, the analysis of the small part is sufficient to determine the frequency of echo repetition.

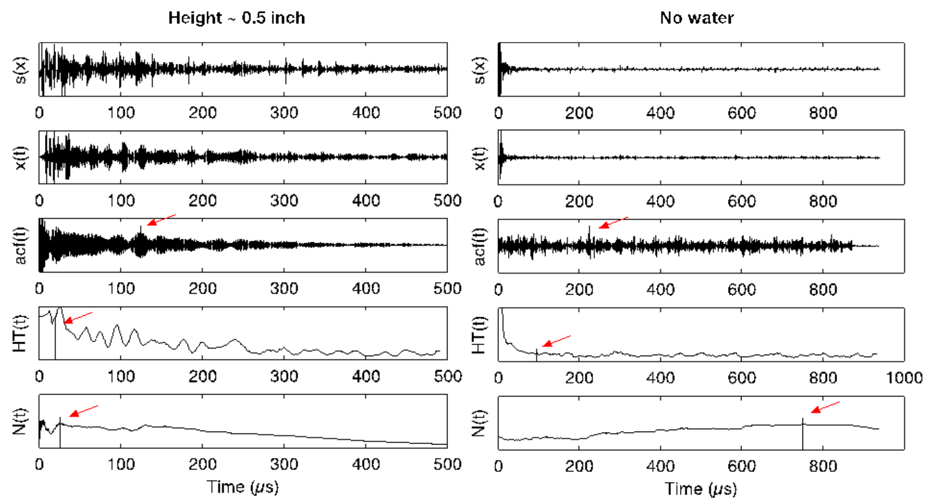

Figure 9: Signal processing results from received signals in shallow oil. From the top down, they are original signal s(t), filtered signal x(t), autocorrelation of signal acf(t), Hilbert transform envelope HT(t), and Shannon energy envelope N(t).

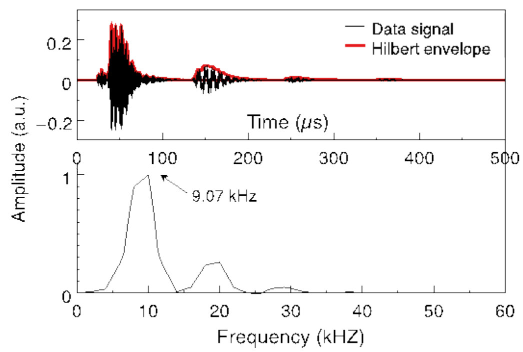

Figure 10: Reflected signal and Hilbert envelop (top). The bottom figure shows the fast Fourier transform of a Hilbert envelope.

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 (8) through the integration of Hilbert envelop over the sampling period T.

$$E^* = \frac{1}{T}\int_0^T HT(t)dt \tag{8}$$

The correlation of energy level with water heights is shown in **Figure 11**. In this figure, the left of the subplots are the received signals of varies water heights numbered from height to low. It can be seen in the right of the figure that when there is no water or almost no reflections the energy becomes a very low value. Thus, the coherence between the energy level of the echoes and the obtained time of flight can be used to verify the TOF value determined to ensure the measured water height is correct.

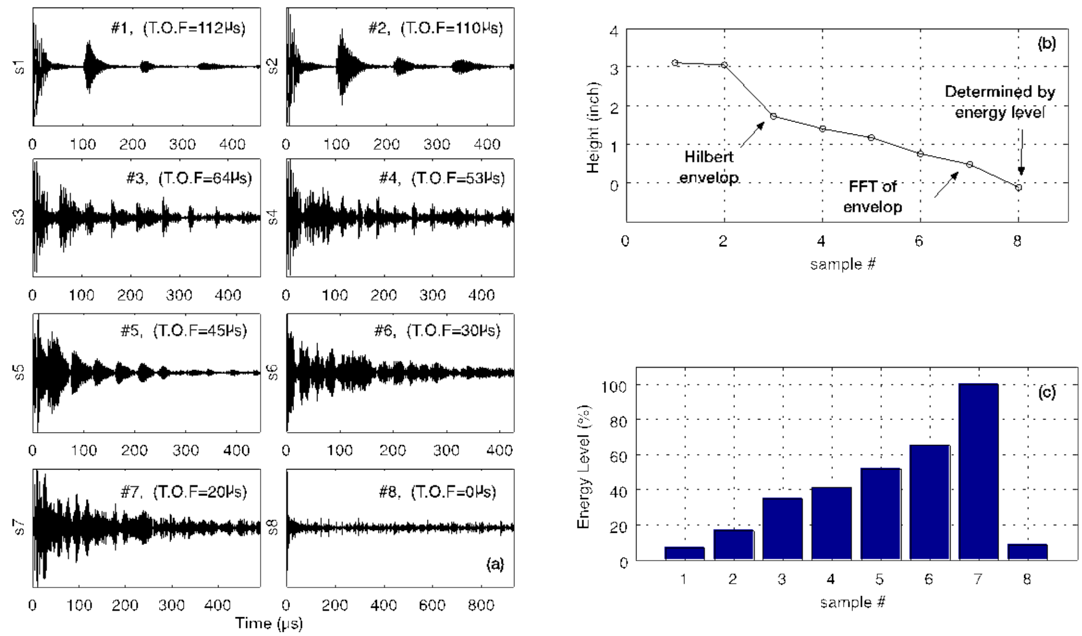

Figure 11: (a) Received signals from varies water height level, (b) the determined height level and (c) the integrated energy level.

3. HILBERT-HUANG TRANSFORMATION METHOD

The methods mentioned in section 2 are based fundamentally on the decomposition of the signals through a high/low-pass or band limit filters, or break the signals into harmonic components through the phase shift, or time to frequency domain transformations such as Hilbert of Fourier Transforms. All these methods are based on the assumption that the stationary. However, when the disturbance happened in the operation, the signal is usually not stationary and not band limited. Hence, a method using Empirical mode decomposition (EMD) was proposed [Huang et al. 1998]. The method uses a sifting process that decomposes a wide class of signals into a set of band-limited functions (Intrinsic Mode Functions, IMFs). It has been shown that the method is viable to extract instantaneous information from the signal. A preliminary result of the Pulse-Echo signals using the IMFs decomposition is shown in **Figure 12**. In the figure, it can be see the each mode of the IMFs has the unique constituents and this can be used for the identification of the disturbances caused by turbulence flow, bubbles gendering, cavitations, shock and vibrations or shallow water conditions in a harsh environment. The details or the results will be presented in the fore coming papers by the authors.

4. CONCLUSION

An advanced signal processing methodology is being developed to monitor the height of condensed water thru the wall of a steel pipe while operating at temperatures as high as 250^{o}C. The validity of different algorithms including autocorrelation function, Hilbert Transform, and Shannon envelope methods were studied and reported in the paper. While these methods provide good accuracy in determining the water height, they are effective only under the stationary normal operating conditions when the water level is relative high. Alternative solutions for shallow water or no water are suggested. Further development of the described techniques including the enhancing the signal analysis by the Hilbert-Huang Transformation would provide a viable tool for the health monitoring of the water level inside a pipe or other forms of containers under irregular conditions including turbulence flow, bubbles gendering, cavitation, shock and vibrations or shallow water conditions.

5. ACKNOWLEDGEMENT

The research reported in this paper was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics and Space Administration (NASA). The authors would like to thank Edward Ecock, Josephine Aromando, and David Y. Low for their support of this task and for the inputs, comments and helpful suggestions regarding the health monitoring of the height of condensed water in steam pipes.

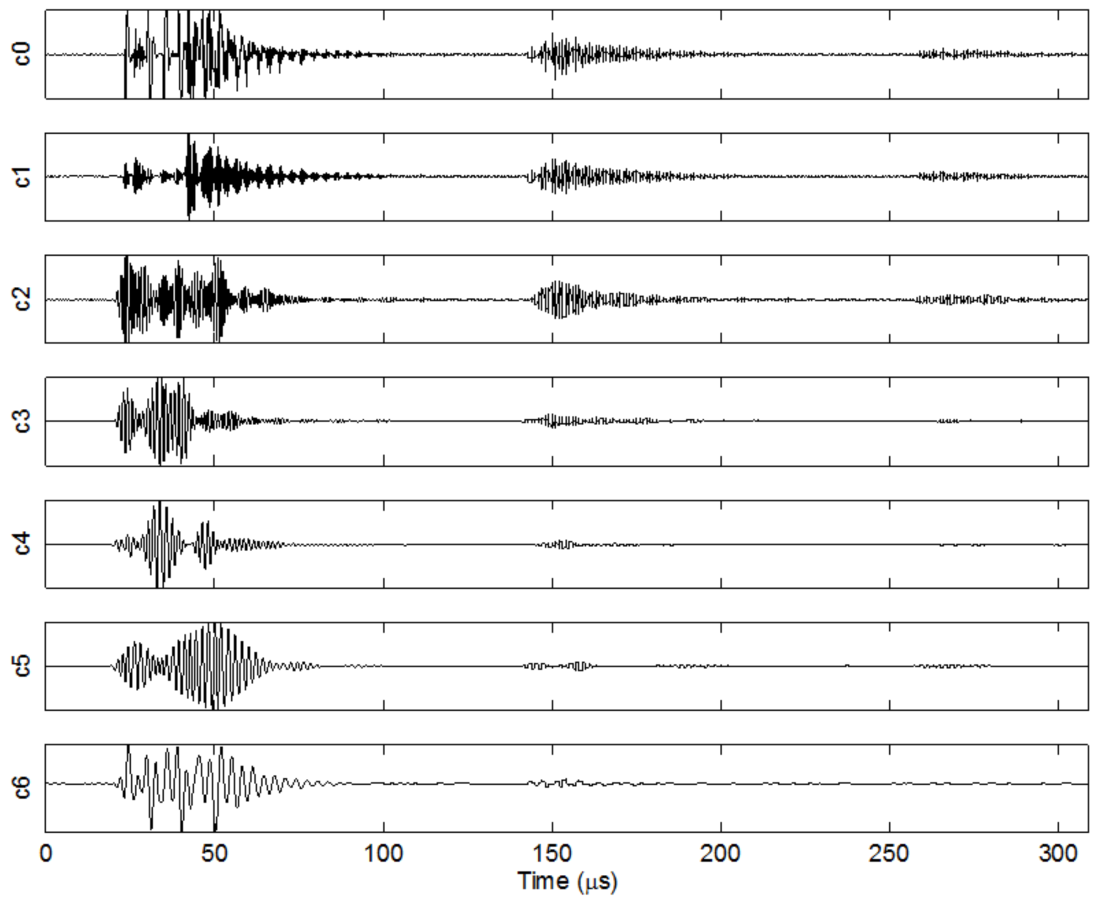

Figure 12: Pulse-Echo signals using the Empirical mode decomposition (EMD) with IMFs c0-6.

6. REFERENCE

Bar-Cohen Y., S. Lih, M. Badescu, X. Bao, S. Sherrit, S. Widholm and J. Blosiu, "In-service monitoring of steam pipe systems at high temperatures" SPIE Health Monitoring of Structural and Biological Systems IV Conference, Smart Structures and Materials Symposium, Paper 7650-26, San Diego, CA, March 8-11, 2010a

Bar-Cohen Y., S. Lih, M. Badescu, X. Bao, S. Sherrit, S. Widholm, J. Scott, J. Blosiu, "In-service monitoring of steam pipe systems at high temperatures," NTR Docket No. 47518, Submitted on January 28, 2010. Provisional Application No. 61/312,164 filed by Caltech, Patent File No. CIT-5563-P submitted on March 9, 2010b.

Bar-Cohen Y., S. Lih, M. Badescu, S. Widholm, X. Bao, S. Sherrit, and Z. Chang, "Task A: Development of a system for measuring condensed water levels", in Y. Bar-Cohen, J. Blosiu, "Advanced Health Monitoring of Steam Pipe Systems," Final Report of the "Phase I: Feasibility Study and Proof-Of-Principle Demonstration" Contract with Con-Edison, JPL Task Plan No. 82- 12986, JPL Report No. D-68772 (May 4, 2010c)

Bar-Cohen Y., X. Bao, J. Scott, S. Sherrit, S. Widholm, M. Badescu, T. Shrout, and B. Jones, "Drilling at high temperatures using ultrasonic/sonic actuated mechanism," Invited Paper, ASCE's Earth and Space 2010 conference, Honolulu, HI (March 14-17, 2010d).

Bar-Cohen Y., S. Lih, M., Badescu, X. Bao, S. Sherrit, S. Widholm, P. Ostlund, and J. Blosiu, "High temperature monitoring the height of condensed water in steam pipes ," Proceedings of the SPIE Proceedings of the SPIE Smart Structures and Materials/NDE Symposium, San Diego, CA, Vol. 7984, pp. 798423-798423-6 (March, 2011).

Bendat J. S. and A. G. Piersol, *Random Data: Analysis and Measurement Procedures,* Wiley; 4 edition (February 8, 2010).

Boashash B., "Estimating and interpreting the instantaneous frequency of a signal- Part 1: Fundamentals," Proceedings of the IEEE 80, 520–538 (1992).

Chen T.-L., P.-w. Que, Q. Zhang, and Q.-k. Liu, "Ultrasonic signal identification by empirical mode decomposition and Hilbert transform," Review of Scientific Instruments 76, 085109 (2005).

Cutard T., D. Fargeot, C. Gault, and M. Huger, "Time delay and phase shift measurements for ultrasonic pulses using autocorrelation methods," Journal of Applied Physics 75, 1909– 1913 (1994).

Choi S. and Z. Jiang, "Comparison of envelope extraction algorithms for cardiac sound signal segmentation," Expert Systems with Applications, Vol. 34, Issue 2, Pages 1056–1069 (February 2008).

Huang N. E, Z. Shen, S. Long, M. Wu, H. Shih, Q. Zheng, N. Yen, C. Tung, and H. Liu, "The Empirical Mode Decomposition and the Hilbert Spectrum for Nonlinear and Non-tationary Time Series Analysis," Proceedings of the Royal Society of London, Number A454, P903-995 (1998).

Liang H., S. Lukkarinen, and I. Hartimo, "Heart sound segmentation algorithm based on heart sound envelogram," Computers in Cardiology 24, pp. 105–108, (1997).

Lih, S.-S., Y. Bar-Cohen, H. J. Lee, M. Badescu, X. Bao, S. Sherrit, N. Takano, P. Ostlund, and J. Blosiu "High temperatures health monitoring of the condensed water height in steam pipe systems," Proceedings of the SPIE Smart Structures and Materials/NDE Symposium, San Diego, CA (accepted, March, 2013).

Liu J., W. Liu, H. Wang, T. Tao, and J. Zhang, "A novel envelope extraction method for multichannel heart sounds signal detection," (2012) pp. 630 – 638.

Middleton D., *An Introduction to Statistical Communication Theory*, Wiley-IEEE Press, (1960, reprinted 1996).

Oruklu E., Y. Lu, and J. Saniie, "Hilbert transform pitfalls and solutions for ultrasonic NDE applications," in Ultrasonics Symposium (IUS), 2009 IEEE International (2009) pp. 2004 –2007.