J. Marine Sci. Appl. (2013) 12: 122-125
DOI: 10.1007/s11804-013-1173-x

An Improved Water-filled Pulse Tube Method Using Time Domain Pulse Separation Method

Liang Sun* **and Hong Hou**

College of Marine, Northwestern Polytechnical University, Xi'an 710072, China

Abstract: Based on existing low-frequency water-filled impedance tube testing facilities, which is a part of the Low Frequency Facility of the Naval Undersea Warfare Center in Beijing, an improved water-filled pulse tube method is presented in this short paper. This proposed study is significantly different from the conventional pulse tube method because of the capability for a single plane damped sine pulse wave to generate in the water-filled pulse tube with a regular waveform and short duration time of about 1ms. During the generation process of the pulse, an inverse filter principle was adopted to compensate the transducer response. The effect of the characteristics of tube termination can be eliminated through the generation process of the pulse. Reflection coefficient from a water/air interface was measured to verify the proposed method. When compared with the expected theoretical values, a relatively good agreement can be obtained in the low frequency range of 500–2 000 Hz.

Keywords: pulse tube; damped sine pulse; water-air surface; water-filled pulse tube

Article ID: 1671-9433(2013)01-0122-04

1 Introduction

The low-frequency sound absorbing properties of underwater anechoic coating, which is usually fabricated with rubber material, is essential for its engineering use, such as the submarine stealth. However, determining how to measure its low frequency sound absorbing properties is still formidable (Zeqiri *et al*., 2010). In general, there are three different methods used mainly as a measuring device, which includes, the pulse tubes (Kuhl *et al*., 1947) (Sabin, 1966), two-sensor transfer function techniques (Corbett, 1983) (Dunlop, 1992), as well as active cancellation approaches (Kenny, 1997) (Piquette and Forsythe, 2001). Recently, the two-sensor-three-calibration technique has been adopted by Wilson *et al*. (2003), which can improve measurement accuracy and precision between 5 and 9 kHz. The low-frequency water-filled impedance tube testing facility, which is a part of the Low Frequency Facility of the Naval Undersea Warfare Center in Beijing, can operate between 200 Hz and 4 000 Hz, utilizing the traditional two-sensor transfer function methods as the measuring technique. Depending on this impedance tube instrument, a time domain pulse-separation method is conducted following the former work by Sun *et al*. (2009), Sun and Hou (2011). The preponderance of these studies has been performed in air; our purpose is to examine an alternative to the traditional underwater acoustic measuring methods.

2 Experimental setup

As shown in Fig. 1, the experimental setup includes a computer, an NI DAQ6062E data acquisition board, a BNC2029 adaptor, power amplifier (B&K 2703), signal conditioner (B&K 2692), and a water filled impedance tube system. A projector array consisting of seven pressure-compensated transducers is positioned on the bottom of the tube, which can generate a single frequency signal as low as 200 Hz. Both the transducers and four miniature hydrophones located on the tube wall are fabricated with the Poly Vinylidene Fluoride (PVDF) sheets. The stainless steel tube is 3.8 m in length, with an inner and outer diameter 0.208 m (responding to its first cutoff frequency 4 183 Hz), 0.42 m respectively. The distance between hydrophone 1 and the surface of the projector array is 0.1 m. The hydrophone 1, flush mounted into the tube wall, is used to generate the plane pulse wave, and hydrophone 2 is utilized to measure the sound pressures of incident and reflected pulses, with a distance of 0.9 m from the surface of the water-air. Two other hydrophones 3 and 4 are used to measure the acoustic pressures in the water-filled tube when transfer function method is implemented. The distance between hydrophone 2 and 3, and that between 3 and 4 are 0.35 m, 0.1 m respectively. However, only hydrophone 1 and 2 are utilized here as data sampling sensors to conduct the pulse separation method. The AI and AO channels of the NI DAQ 6062E board are programmed to be synchronized and have a sampling rate of 100 kHz.

3 Outline of the generation of sound pulse

According to the requirement of measurement of sound absorption coefficient, the sound pulse referred to as the damped sine pulse has been generated. Both principle and process of pulse generation are only summarized here (Sun *et al*., 2009; Sun and Hou, 2011).

To begin with, utilizing the impulse response of a digital

Received date: 2012-06-02.
Foundation item: Supported by the National Natural Science Foundation of China under Grant No. 11204242 and China Postdoctoral Foundation under Grant No. 2011M501477.
***Corresponding author Email:** slclh2005@hotmail.com

5th-order Butterworth filter with duration of 1ms as the excitation signal to drive the transducer-pipe system with open terminus, we recorded the response signal at hydrophone. $H_e(\omega)$ and $H_r(\omega)$ denote the Fourier transforms of excitation and response signals, respectively.

Then, the frequency response of the system is given by

$$H(\omega) = \frac{H_r(\omega)}{H_e(\omega)} \tag{1}$$

Secondly, the spectrum of the driving signal can be computed by the spectrums of the designed pulse $H_y(\omega)$ and the resolved frequency response $H(\omega)$.

$$H_x(\omega) = \frac{H_y(\omega)}{H(\omega)} \tag{2}$$

To avoid instabilities at the notches of $H(\omega)$, a positive constant, p, must be added to the denominator (regularization). Thus

$$H_x(\omega) = H_y(\omega)\frac{H^*(\omega)}{|H(\omega)|^2 + p^2} \tag{3}$$

where $H^*(\omega)$ stands for the conjugate of $H(\omega)$. In general, the small values of p (typically less than 5% of the transfer function peak) are usually enough to stabilize the method (Cobo, 1995).

Applying the inverse Fourier transform to Eq. (3), the driving signal of the transducer-tube system will be obtained.

Further, it should be noted that through this process, any deficiency in the frequency response of the sound generation system will be compensated, which would improve the signal-noise ratio in the measurement.

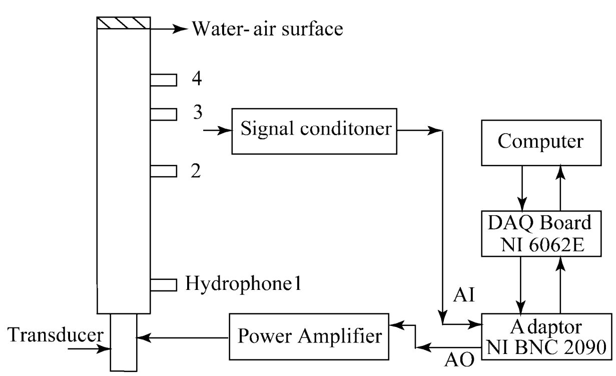
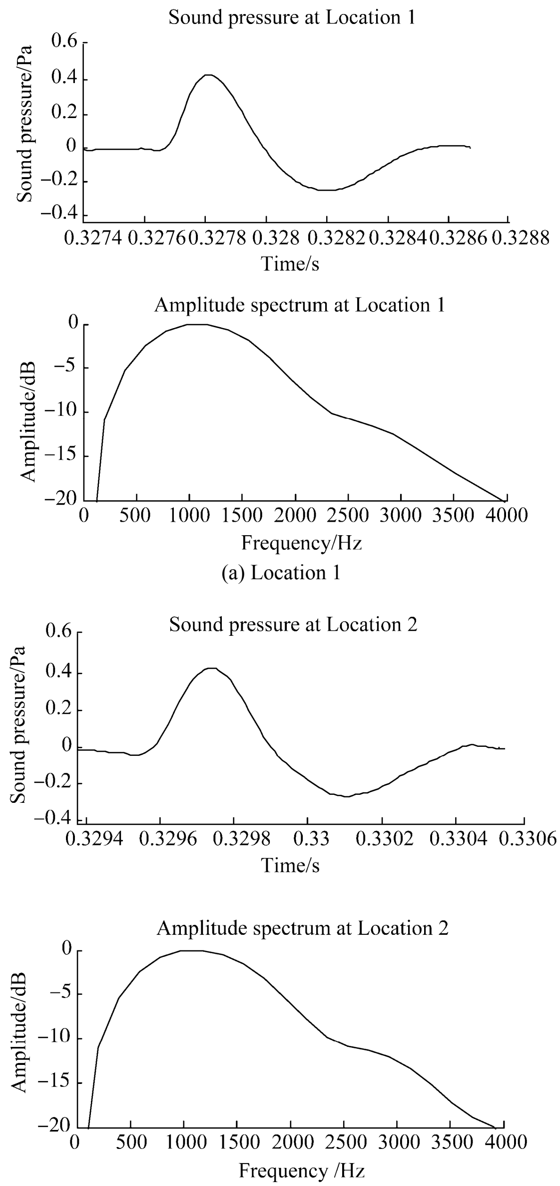


Fig. 1 The sound source configuration and the test equipment

4 Experimental results

4.1 Verification of plane pulse wave propagation in the tube

By using the generation procedure, the pulse is generated and picked up at location 1 (corresponding to hydrophone 1) as shown in Fig. 2(a), to verify whether a single plane pulse wave is propagating in the tube, the pulse signal is also sampled at location 2 (corresponding to hydrophone 2) as given in Fig. 2(b).



(a) Location 1

(b) Location 2

Fig. 2 Waveforms of the damped sine pulse

From Fig. 2, one can observe the impulse is propagating in the tube in a plane wave form as the amplitude of the impulse is constant either in time domain or in the frequency domain. Moreover, one should observe the starting time of each impulse at every location is in a good coincidence with the distance of these locations from each other.

Consequently, the impulse can be used for the measurement of reflection coefficient of the underwater acoustic material or structure as the plane pulse wave is propagating in the tube.

4.2 Calculation of reflection coefficient

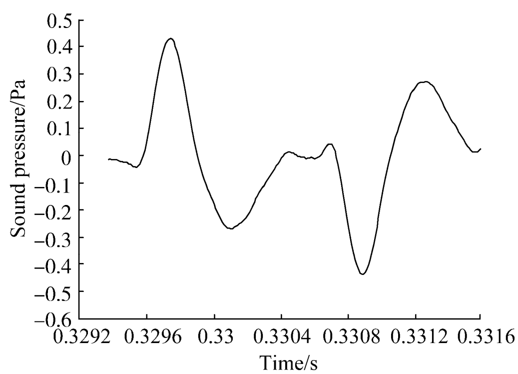
The reflection coefficient from the surface of water/air interface is calculated by the ratio of the reflected sound pressure to the incident sound pressure.

$$R(\omega) = \frac{p^-(\omega)}{p^+(\omega)} \tag{4}$$

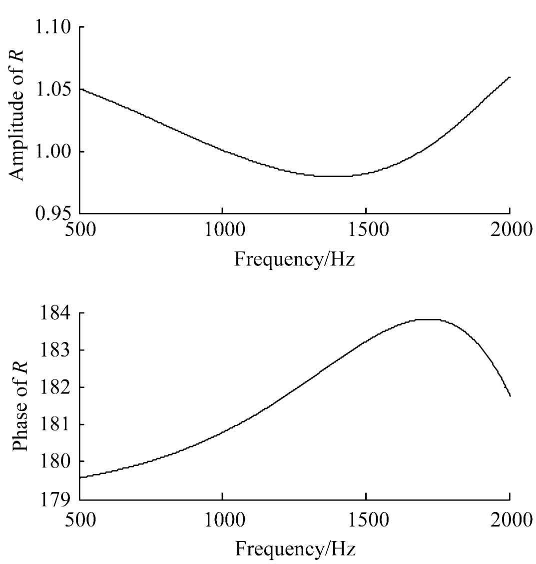
where $p^-(\omega)$ and $p^+(\omega)$ are the Fourier transforms of the reflected and incident sound pressures, respectively.

4.3 Measuring results

According to the above-cited measuring principle, the sound pulse was initially generated by using hydrophone 1, and then, hydrophone 2 to measure the incident and its reflected pulse from water-air interface. After which, a rectangular window was adopted to crop each pulse in the time domain. For each separated pulse, a 65536-point FFT was then performed and the reflection coefficient of water-air interface was calculated. The measuring results were provided in Fig. 3(a) and (b). In addition, errorbars of the reflection coefficient were also shown in Fig. 4 at 600, 800, 1 000, 1 200, 1 500, 1 800 Hz that were selected randomly. From Fig. 4, one can note the measuring results of reflection coefficient amplitude and phase deviate from the expected values by as low as 5% and 5º in the low frequency range of 500–2 000 Hz, respectively.

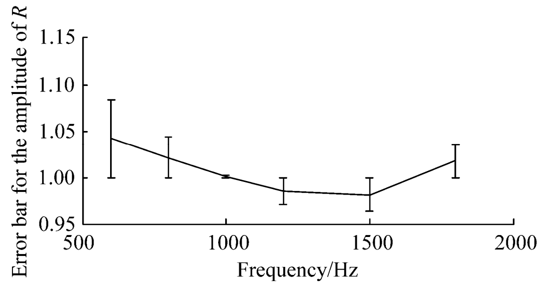


(a) Incident damped sine pulse and its reflection from water-air interface

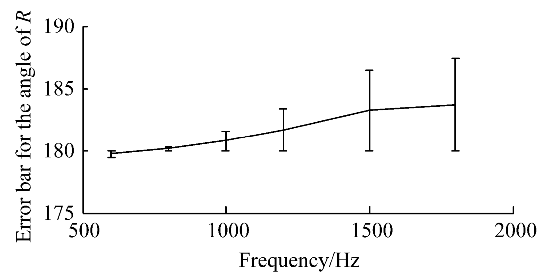


(b) Reflection coefficient R of water-air interface

Fig. 3 Time domain waveform of incident damped sine pulse and its reflection



(a) The amplitude of R



(b) The angle of R

Fig. 4 Error bars of reflection coefficient *R*

However, some deviations of the measuring results from the actual values are also present, which is probably due to the low signal-to-noise ratios at low frequencies. Nonetheless, the inverse filtering process can improve the frequency response of the source-tube system to some extent.

5 Conclusions

An improved water-filled pulse tube method utilizing the pulse separation technique in time domain is proposed in this paper. The measuring system consists of an impedance tube with a projector array located on the bottom of the tube and two hydrophones flush mounted into the tube wall. Based on the inverse filter principle, a single plane damped sine pulse wave can be attained in the tube. The validity of this technique is verified by measurement of reflection coefficient from a water/air interface.

In addition, it is worth emphasizing the careful designing of a short-duration pulse in order for the upper limit frequency to remain less than the cutoff frequency of the tube, for ensuring a plane pulse wave is propagating in the tube.

Acknowledgement

We greatly thank Prof. He Yuan'an and Mr. Huang Yongqiang for their assistance with the pulse generation and valuable discussions.

References

Cobo P (1995). Application of shaping deconvolution to the generation of arbitrary acoustic pulses with conventional sonar transducers. *Journal of Sound and Vibration*, **188**(3), 131-144.

Corbett III SS (1983). A two-hydrophone technique for measuring the complex reflectivity of materials in water-filled tubes. Master thesis, Pennsylvania State University, University Park, 22-30.

Dunlop JI (1992). Measurement of acoustic attenuation in marine sediments by impedance tube. *The Journal of the Acoustical Society of America*, **91**(1), 460-469.

Kenny DM (1997). A short water-filled pulse tube for the measurement of the acoustic properties of materials at low frequencies. Technical report No. NSWCCD-TR-97/029, Naval Surface Warfare Center Carderock Division, West Bethesda, MD, 122-130.

Kuhl W, Meyer E, Oberst H, Skudrzyk E, Tamm K (1947). *Sound Absorption and Sound Absorbers in Water*. Dept. of the Navy, Bureau of Ships, Washington DC, Vol. 1, Chap. IX, 381-453.

Piquette JC, Forsythe SE (2001). Low-frequency echo-reduction and insertion loss measurements from small passive-material samples under ocean environmental temperatures and hydrostatic pressures. *The Journal of the Acoustical Society of America*, **110**(2), 1998-2006.

Sabin GA (1966). Acoustic-impedance measurements at high hydrostatic pressures. *The Journal of the Acoustical Society of America*, **40**(6), 1345-1353.

Sun Liang, Hou Hong (2011). Transmission loss measurement of acoustic material using time-domain pulse-separation method. *The Journal of the Acoustical Society of America*, **129**(3), 1681-1684.

Sun Liang, Hou Hong, Dong Liying, Wan fangrong (2009). Measurement of characteristic impedance and wave number of porous material using pulse-tube and transfer-matrix methods. *The Journal of the Acoustical Society of America*, **126**(4), 3049-3056.

Wilson PS, Roy RA, Carey W M (2003). An improved water-filled impedance tube. *The Journal of the Acoustical Society of America*, **113**(4), 3245-3252.

Zeqiri B, Scholl W, Robinson SP (2010). Measurement and testing of the acoustic properties of materials: a review. *Metrologia*, **47**, 156-171.

Author biographies

Liang Sun is presently a post-doctor in underwater acoustic engineering in the school of Marine, Northwestern Polytechnic University. He has been granted with many foundations regarding the underwater acoustic materials measurement, such as the Postdoctoral Science Foundation, as well as the National Natural Science Fund. His activities are documented by an extensive publication record of scientific papers, technical reports, and papers at international conferences.

Hong Hou is presently a professor and PhD advisor in underwater acoustic engineering in the School of Marine, Northwestern Polytechnic University. He has been granted with many foundations regarding the underwater acoustic materials measurement, such as the Aviation Science Fund, as well as the National Natural Science Fund. His activities are documented by an extensive publication record of scientific papers, books, technical reports, and papers at international conferences. He received various prize awards for his overall research work and his scientific contributions to aeroacoustics and underwater acoustic materials measurement.