AN ALGORITHM TO RECOVER THE ULTRASOUND PULSE SIGNAL BASED ON LASER HETERODYNE MEASUREMENT

Yang Ping
Division of Mechanics and Acoustics, National Institute of Metrology, Beijing, China

Zhu Haijiang
Information Science and Technology, Beijing University of Chemical Technology, Beijing, China

Xing Guangzhen, Feng Xiujuan and He Longbiao
Division of Mechanics and Acoustics, National Institute of Metrology, Beijing, China

e-mail: yangp@nim.ac.cn; zhuhj@mail.buct.edu.cn

Precise measurement of the pulse field from ultrasound equipments is vitally important for safety evaluation and precise therapy. High pressure pulse field from therapeutic ultrasound equipments, such as lithotripsy, should be measured by hydrophone with ideal flat wideband and linearity, which is not available till now. In this article, based on the original laser Doppler signal, an algorithm is developed to recover the pulse signal emitted from ultrasonic pulser. Inverse tangent quadrature demodulation signal, which is obtained from the original laser Doppler signal, is denoised by the wavelet denoising method based on Daubechies wavelet basis function. Experiments showed the recovered signal agrees well with the signal received by a membrane hydrophone, which has satisfactory flat bandwidth and linearity for low frequency and low pressure field. The algorithm provides a promising solution to measure the therapeutic pulse ultrasound field.

Keywords: lithotripsy, heterodyne interferometer, Daubechies wavelet, pulse recovery

1. Introduction

Precise measurements of the field from medical ultrasound equipments are vitally important for risk evaluation and precise therapy, especially with the increasing application of therapeutic ultrasound system such as HIFU and lithotripsy. Both diagnostic and therapeutic ultrasound field measurements have drawn intensive studies and resulted in many international standards [1-3].

Hydrophones for field measurement are calibrated by reciprocity or laser interferometry method in low pressure field, usually about or lower than 1 MPa, which is much lower for 10 MPa level ultrasound therapy [4-6].

Therapeutic ultrasound usually results in high pressure, rich harmonics, high temperature and cavitation, etc. Hydrophone requirements and calibration are far more demanding than those used in diagnostic field, where not only amplitude response, but robustness, linearity, directivity response, phase response should be considered. This is why there are no satisfactory hydrophones for therapeutic ultrasound field measurement. Although some experts have studied the deconvolution technique [7,8], there is still a need to development the calibration technique for the robust hydrophones.
Considering the laser heterodyne system has been adopted for the high frequency hydrophone calibration [6,9]. In this article, based on the laser Doppler signal caused by the pellicle displacement, an algorithm is developed to recover the ultrasound pressure pulse in water. In order to validate the algorithm, signal from broadband membrane hydrophone is compared with the signal recovered from laser signal. Good consistency suggests the laser direct measurement is a promising method to solve the problem.

2. General style parameters

The schematic diagram of the experimental system is shown in Figure 1. In the first configuration, the pressure pulse is emitted from 1 MHz focused ultrasound transducer (OLYMPUS V303-SU-F0.80 in) by an ultrasound pulser. The ultrasound will cause pellicle, which is mounted on the water surface, to vibrate with the ultrasound. The pellicle is made of 15 μm thick mylar coated with 40 nm aluminum on both sides, to ensure acoustically transparent and optically reflective. Laser heterodyne probe is positioned by a mechanical scanning system, with the laser beam 80 MHz shifted. Original laser Doppler signal is acquired by oscilloscope (TEK 4054) and transferred to computer.

In the second configuration, the pellicle and laser heterodyne probe is replaced with a membrane hydrophone (Precision Acoustics, UT1604-008), which has good wide bandwidth up to 20 MHz and good linearity for low pressure field. The sensitivity variation between 1 MHz ~ 10MHz frequency range is with ±5%. Ultrasound signal recovered from the original laser Doppler signal is compared with the signal from the membrane hydrophone, hereinafter called reference signal. RMSE (root mean square error) is adopted to evaluate the performance of the laser measurement system.

![Figure 1. Schematic Diagram of the Experiment System](image)

2.1 Laser Doppler Measurement Principle

The output signal of the laser interferometer is written by
\[ E = B + A \sin(2\pi(\Delta f + f_L)t + \varphi) \]  

where \( B \) is the DC output signal; \( A \) is the amplitude of the AC signal; \( f_L \) is the carrier frequency of the laser; \( \Delta f \) is the Doppler shift caused by the vibration of the pellicle; \( \varphi \) is the initial phase of the signal.

The cycles of the pellicle vibration during the short time \( \Delta t \) is estimated by

\[ \Delta n = \frac{2v\Delta t}{\lambda} \]  

where \( \lambda \) is the wavelength of the incident light; \( v \) is the velocity of the pellicle vibration; \( v\Delta t \) is the displacement of the pellicle.

Due to the constant characteristics of the speed of light, we can estimate the Doppler shift \( \Delta f \) between the frequency of the incident light and the reflected light.

\[ \Delta f = f - f_0 = \frac{\Delta n}{\Delta t} = \frac{2v}{\lambda} \]  

Therefore, the vibration speed can be computed by demodulating the frequency \( \Delta f \).

### 2.2 Signal Demodulation and Denoising Algorithm

In this algorithm, we obtain inverse tangent quadrature demodulation signal in terms of the original laser Doppler signal. Then it is denoised by the wavelet deonising method based on Daubechies wavelet basis function. Therefore, the recovered ultrasound pulse signal is compared with the reference signal from the membrane hydrophone.

Orthogonal demodulation is the one of the most commonly used method for demodulation, which has the advantages of dynamic measurement and high resolution. In this paper, orthogonal demodulation based on the arctangent function is selected, and the phase information of the original laser Doppler signal is extracted.

First, the tangent signal of the original laser Doppler signal equation (1) may be obtained by Hilbert transformation and it is expressed by

\[ T(t) = \tan(2\pi(\Delta f + f_L)t + \varphi) \]  

We can see that there is not amplitude term in the tangent signal. Next, the phase information is extracted by inverse tangent and phase unwrapping function and it is written by

\[ \Phi(t) = 2\pi\Delta ft + A \]  

Where \( A = 2\pi f_L t + \varphi \) is the high frequency signal. Then the signal \( A \) can by filtered out by a high pass filter.

Combining equations (3) and (5), we have

\[ \varphi(t) = 2\pi\Delta ft = \frac{4\pi vt}{\lambda} \]  

The relationship between the displacement and the sound pressure is written by

\[ P(t) = \rho cvt \]  

From equations (6) and (7), it can be derived that:

\[ P(t) = \rho c \frac{\lambda}{4\pi} \varphi(t) \]  

where \( \rho \) is the density of the media and \( c \) is sound velocity of the medium.

Finally, the sound pressure value \( P(t) \) at the reflective film may be measured from equation (8). Although the sound pressure can be demodulated, it is difficult to describe the original pulse signal due to lots of noises for the demodulation signal. Therefore, a deonising method based on Daubechies wavelet is proposed to filter the demodulation signal. The denoised process of the demodulation signal is summarized as follows: First, we select the suitable wavelet and wavelet decomposition layers to the signal and the wavelet coefficients may be computed. In this paper, the common “db4” wavelet is selected for processing the demodulation signal. Second, the threshold value of each layer is set according to the appropriate threshold selection principle. Then, the wavelet coefficients are modified by the threshold value. Finally, the signal is reconstructed by the modified wavelet coefficients. The reconstructed signal is the denoised signal.
After extracted the reconstructed pulse signal, we may estimate the RMSE between the standard pulse signal and the recovering pulse signal. The RMSE is defined by

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{n} (x_r(n) - x(n))^2}$$  \hspace{1cm} (9)

where $x(n)$ is the original pulse signal, $x_r(n)$ is the recovering pulse signal, and $N$ is the length of the signal.

3. Experimental equipments and results

3.1 Experimental equipments

Picture of the scanning system and arrangement are shown in Figure 2. It has 3 motorized axis, with the scanning area larger than (800×600×500) mm and resolution better than 5 μm.

![Figure 2. Experimental equipment](image)

The experimental equipment includes a 3D control system, high intensity ultrasonic probe, laser interferometer, translucent film. The motion device is controlled by the software in PC. Pure water removed from impurities and gases is placed in a sink, and high intensity ultrasonic probe is installed at the bottom of the tank. The translucent film is placed on the surface of water, and the level of the film is calibrated. There is no water on the surface of the translucent film and no bubble on the lower surface of the translucent film. The laser interferometer is perpendicular to the translucent film.

3.2 Signal Acquisition and Processing

![Figure 3. Doppler shift signal measured by an oscilloscope](image)

First, the collected data through an oscilloscope is an electrical signal with a Doppler shift and it is illustrated in Figure 3. Second, the demodulated signal is achieved using the orthogonal demodu-
lation and high pass filtering and it is displayed in Figure 4. We can see that the frequency change of the Doppler shift signal is not clear in Figure 3. The magnitudes between time $1 \times 10^{-5} (s)$ and time $1.05 \times 10^{-5}(s)$ of the signal have a little change. And we can find that the demodulated signal between time $1 \times 10^{-5}(s)$ and time $1.05 \times 10^{-5}(s)$ is a pulse signal in Figure 4. This result validated the inverse tangent demodulation method can filter the amplitude of the signal very well and the information of the frequency is only retained. However, there’s still a lot of noise in the demodulated signal. These noises may affect the measurement of the pulse signal.

![Figure 4. The demodulated signal](image)

Therefore, the demodulated signal is reduced noises through the deonising method based on Daubechies wavelet in section 2.2. Figure 5 is the comparison of the demodulated signal (marked by red line) with the reconstructed signal (marked by blue line). This result shows that the proposed method presents good performance on reducing the effects of noise.

![Figure 5. The demodulated signal (red line) and the reconstructed signal (blue line)](image)

Figure 6 displays the demodulated signal (left) and the deonisned signal (right), in which much noise is reduced in the right signal and the amplitude of the denoised signal has a few decreasing. The RMSE between the reconstructed pulse signal and the membrane is small which indicates the recovering pulse signal is closer to the original pulse signal. The remaining difference attributes to the phase response of the heterodyne interferometer together with the pellicle and the phase response of the hydrophone.
4. Conclusion

This work has described the ultrasound pulse signal reconstructed method based on laser heterodyne measurement. In this method, the Doppler shift signal is proceed by the orthogonal demodulation algorithm and the demodulated signal is obtained. And then the demodulated signal is denoised by the wavelet denoising algorithm. Lots of experimental results show that the clean pulse signal can be extracted well through the proposed method.

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