24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

EFFECTS OF DEMODULATION METHODS ON THE REPRODUCTION OF UNDERWATER ACOUSTIC PRESSURE BY OPTICAL HETERODYNE INTERFEROMETRY

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Underwater acoustic pressure is typically measured by hydrophones, which should be calibrated periodically to ensure its measurement accuracy. An alternative way to reproduce the pressure of underwater acoustic fields is the optical method. It has the potential to provide a direct traceability to the acoustic pascal. The optical heterodyne interferometry has been a well-known method to reproduce the underwater acoustic pressure, for instance in middle frequency range 25 to 500 kHz, by measuring the acoustic displacement. During the above process, demodulation technique has to be applied to extract the acoustic displacement, which is directly related to the pressure under reproduction. In this paper, two demodulation methods, namely zero-crossing demodulation and arctan demodulation, are discussed and compared to evaluate the effects on calculating the acoustic pressure. We find that the zero-crossing method is affected by the determination of the arrival time of acoustic, while the arctan method is significantly affected by the low frequency vibration. By properly designed, the two demodulation methods could obtain the approximate pressure. A related experimental system is also established. And the experimental data show that the pressure sensitivities calculated by the two demodulation methods are close to that of a reference hydrophone within $1\mathrm{dB}$.

Keywords: Underwater acoustic pressure, optical heterodyne interferometry, demodulation methods, hydrophone

1. Introduction

As a nonperturbing way of measurement, optical methods have attracted considerable attention to reproduce the pressure of underwater acoustic fields in recent years [1–5]. They could achieve higher accuracy than the traditional measurement method by hydrophones, since the hydrophones should be submerged in the underwater acoustic field, which would cause unavoidably perturbation to the acoustic field under measurement. What's more, in the perspective of hydrophone calibration, optical methods do not rely on the availability of a transducer being reciprocal or on the assumption of the acoustic field being spherical-wave propagated, and they could potentially provide accurate measurement of acoustic pressure with direct traceability to the wavelength of laser light [6–10]. Consequently, optical methods have been identified as the next generation of primary standards for the calibration of devices in underwater acoustics [11].

The principle of reproducing the underwater acoustic pressure by optical methods is measuring the acoustic displacement or particle velocity via an interferometry system, and then the acoustic pressure at that point could be calculated directly. The reproduced acoustic pressure can be used to calibrate hydrophone by putting it at the above exact point, recording the output voltage and calculating its sensitivity. During the process of reproducing the acoustic pressure, demodulation techniques have to be applied to extract the acoustic displacement or particle velocity from the received laser Doppler signals. So the accuracy of the reproduced acoustic pressure is directly affected by different demodulation methods, such as zero-crossing demodulation and arctan demodulation. Actually, Theobald had realised the hydrophone calibration in the frequency range 10 to 600 kHz using a commercial heterodyne interferometer [6, 7]. However, he didn't introduce how the acoustic particle velocity is demodulated. Later Koukoulas presented the zero-crossing demodulation method to extract the particle velocity and hence the acoustic pressure [8, 9], but the effects of this demodulation method and some others on the reproduced acoustic pressure still need further discussion.

In this paper, we present two demodulation methods, namely zero-crossing demodulation and arctan demodulation, to calculate the acoustic particle velocity or displacement due to acoustic pressure by optical technique. A related experimental system is also established to reproduce the acoustic pressure in the frequency range 25 to 500 kHz with a self-built laser heterodyne interferometer. The effects of these two demodulation methods on the reproduced acoustic pressure are discussed and compared by calibrating a reference hydrophone.

2. Measurement principle and signal demodulation

Under the assumption of plane-wave propagation, the acoustic pressure can be directly related to acoustic particle velocity or displacement by

$$p(t) = \rho c v(t) = \rho c \omega s(t), \tag{1}$$

where ρ is the density, c is the speed of sound in the medium (water here), and $v(t) = \omega s(t)$ denotes the particle velocity with ω and $s(t)$ being the angular frequency and the acoustic displacement, respectively.

The acoustic displacement in (1) can be measured by optical heterodyne interferometry. Firstly, a membrane is placed in the underwater acoustic field to represent the vibration of the water particles. This membrane should be thin enough in contrast with the acoustic wavelength and matched to the impedance of water as well, so that it could follow the motion of the water particles totally. Then two laser beams, i.e. a measurement beam and a reference beam, are generated by a heterodyne interferometer. The measurement beam can be expressed as

$$e_m(t) = E_m \cos(2\pi f_0 t + \phi_m), \tag{2}$$

where E_m is the amplitude, f_0 is the frequency of the laser beam, and ϕ_m is the initial phase. While the reference beam has a frequency shift of f_c and is given by

$$e_r(t) = E_r \cos\left[2\pi(f_0 + f_\mathrm{c})t + \phi_r\right]. \tag{3}$$

The interferometer is adjusted to make sure that its transmitted measurement beam is perpendicular to the membrane, so the reflected beam can return to the interferometer through a reversible optical path. Due to the vibration of the membrane, the reflected beam will be added a phase shift of $\psi(t) = \frac{4\pi}{\lambda} s(t)$, where λ is the laser wavelength. Without loss of generality, the measurement beam and the reference beam are assumed to share the same initial phase, i.e. $\phi_m = \phi_r$. Then the interferometer mixes the reflected measurement beam with the reference beam, and the output becomes

$$y(t) = A \cos\left[2\pi f_\mathrm{c} t + \frac{4\pi}{\lambda} s(t)\right]. \tag{4}$$

In (4), A denotes the amplitude and the DC offset has been omitted. It is seen that $y(t)$ is a phase-modulated signal with carrier frequency f_c. The acoustic displacement $s(t)$ can be extracted by demodulation techniques. Two efficient demodulation methods are presented as follows.

2.1 Zero-crossing demodulation

Zero-crossing method demodulates the acoustic particle velocity and hence the acoustic pressure. It is reasonable here because equation (4) can also be expressed as frequency modulation by the relationship of

$$\Delta f = \frac{1}{2\pi} \times \frac{d\psi(t)}{dt} = \frac{1}{2\pi} \times \frac{4\pi}{\lambda} \times \frac{ds(t)}{dt} = \frac{2v(t)}{\lambda}, \tag{5}$$

where Δf is the Doppler frequency shift.

The output continuous signal of (4) is captured by an oscilloscope with high sampling rate. The captured sequence may not contain all the negative-to-positive zero-crossing points of the original signal. So a point-by-point searching should be made to find all the pair of adjacent points y_i and y_{i+1}, which satisfy $y_i < 0$ and $y_{i+1} > 0$. Then an interpolation is conducted to determine the zero-crossing point between them.

Denoting the time of occurrence of the ith zeros crossing of the sequence by t_i $(i = 1, 2, \ldots, n)$, we could calculate two subsequent time series as [9]

$$t_i^* = t_i + \frac{t_{i(n+1)} - t_{i(n)}}{2} \tag{6}$$

and

$$\Delta t_i^* = t_{i(n+1)}^* - t_{i(n)}^*. \tag{7}$$

Then a series of Doppler frequency shift can be calculated by

$$\Delta f(t_i^*) = \frac{1}{\Delta t_i^*}. \tag{8}$$

Using equations (5) and (1), we can respectively obtain the acoustic particle velocity and pressure as

$$v(t_i^*) = \frac{\lambda}{2} \Delta f(t_i^*) \tag{9}$$

and

$$p(t_i^*) = \rho c v(t_i^*). \tag{10}$$

It should be noted that, the above method is regarded as a good way of demodulation in a perspective of metrology since it does not require software calibrations [8]. But the interpolation may affect the accuracy of the demodulated acoustic pressure unavoidably. Moreover, we will also see that the demodulated result is greatly affected by the determination of the arrival time of acoustic wave.

2.2 Arctan demodulation

Unlike the zero-crossing method, the arctan method demodulates the acoustic displacement directly. The key technique is to produce a pair of ideal quadrature signals, namely the in-phase signal and the quadrature signal, which are formulated by

$$\begin{cases} u_{\mathrm{i}}(t) = U_{\mathrm{i}} \cos \phi(t) \\ u_{\mathrm{q}}(t) = U_{\mathrm{q}} \sin \phi(t). \end{cases} \tag{11}$$

This quadrature signal pair could be obtained by a down-mixing process as shown in Fig. 1, where $y(t)$ in (4) is used as the original carrier signal and $\phi(t)$ is given by

$$\phi(t) = 2\pi(f_{\mathrm{c}} - f_{\mathrm{d}})t + \psi(t) = 2\pi(f_{\mathrm{c}} - f_{\mathrm{d}})t + \frac{4\pi}{\lambda} s(t). \tag{12}$$

The frequency of the down-mixed signal becomes $(f_{\mathrm{c}} - f_{\mathrm{d}})$.

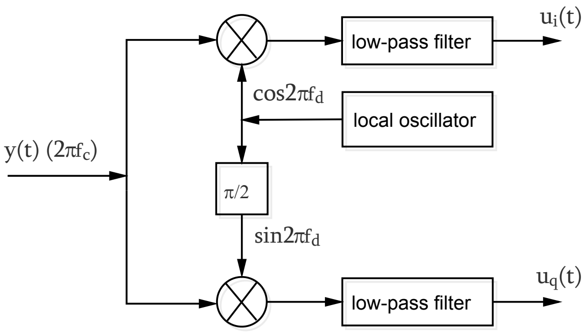


Figure 1: Down-mixing process of the heterodyne carrier to a pair of quadrature signals.

Then the two quadrature signals are sampled by AD converters, and the phase of the carrier signal $y(t)$ at sample time t_n can be calculated by

$$\psi(t_n) = \arctan \frac{u_{\mathrm{q}}(t_n)}{u_{\mathrm{i}}(t_n)} + m\pi, \quad m = 0, 1, 2, \ldots. \tag{13}$$

In this equation, a high-pass filter should be applied firstly to remove the DC offset $2\pi(f_{\mathrm{c}} - f_{\mathrm{d}})t$ in $\arctan \frac{u_{\mathrm{q}}(t_n)}{u_{\mathrm{i}}(t_n)}$. Then since the arctan function is not continuous with relatively large acoustic displacement, a proper integer number m should be chosen to avoid the discontinuities of $\{\psi(t_n)\}$, which can be referred to [12]. Once the phase $\psi(t_n)$ is determined, the acoustic displacement and pressure can be obtained easily by $s(t_n) = \frac{\lambda}{4\pi}\psi(t_n)$ and $p(t_n) = \rho c\omega s(t_n)$.

It is noteworthy that the accuracy of this demodulated result is affected by the down-mixing process and the synchronization of sampling the two quadrature signals. What's more, it is shown in the experiment that the demodulated displacement is also severely influenced by low frequency vibrations of surroundings. Thus a subsequent digital filter is needed to be properly designed to reduce this influence.

3. Measurement system

The experimental system for measuring the underwater acoustic pressure by optical heterodyne interferometry is shown in Fig. 2.

A water tank with dimensions of $1.5\mathrm{m} \times 0.9\mathrm{m} \times 0.6\mathrm{m}$ is used to undertake the measurements. The tank has two positioning arms to position and fix devices, and each positioning arm has five degree

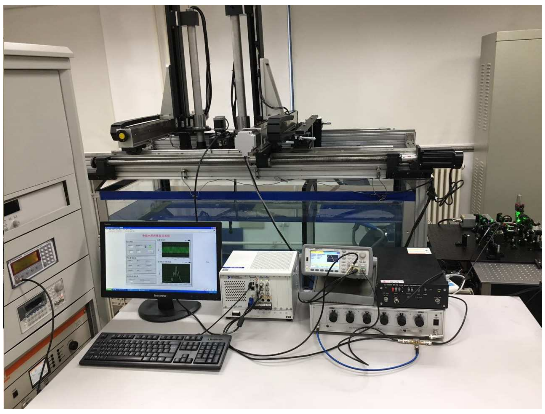


Figure 2: Measurement system of underwater acoustic pressure by optical heterodyne interferometry.

of freedom. Two transducers are used to provide stable underwater acoustic fields with different frequency ranges. To discriminate reflections, burst signals are generated to excite the transducers. A circular membrane with thickness of $15\mu\text{m}$ is suspended in the water by mounting on a ring frame, and it is thinly coated with aluminium to reflect the measurement laser beam better. The distance between the transducer and the membrane is set as 0.45m to satisfy the assumption of plane-wave propagation.

Outside the water tank, a self-built laser heterodyne interferometer is well adjusted to generate the laser beams for measurements. A Torus 532 laser device is used to generate a laser beam with the wavelength of 532 nm and the optical power of 100 mW. The transmitted laser beam passes a collimating beam expander to reduce spread. Then the collimated beam enters a Bragg cell to produce diffraction beams, each shifted by $f_c = 80$ MHz. The zero-order or unshifted beam is used as the measurement beam, and the first-order or 80 MHz shifted beam is used as the reference beam. The measurement beam is transmitted into the tank through an optical window to detect the vibration of the membrane, while the reference beam is kept in the interferometer to be re-combined with the reflected measurement beam. The mixed beam is converted to electric signal by a photodetector and then demodulated by the following demodulation systems. It is worth pointing out that, the laser heterodyne interferometer used in this system is self-built instead of a commercial one. This makes the uncertainty of each part be more measurable and controllable.

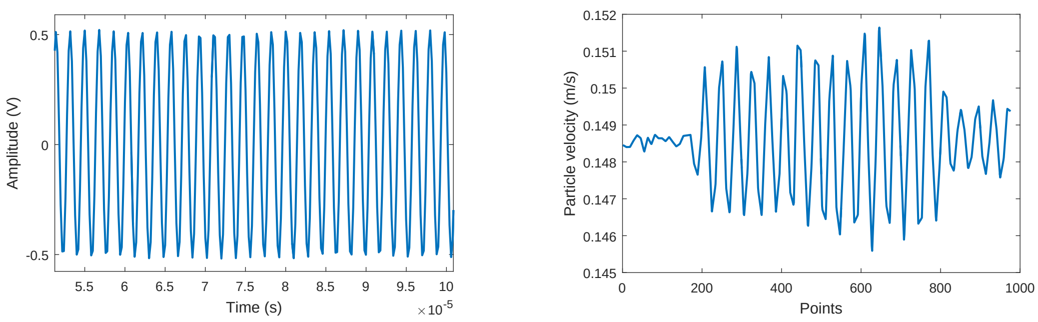
For the zero-crossing demodulation, the signal detected by the photodetector is captured by a Tektronix DPO4054B oscilloscope which has a bandwidth of 500 MHz and a maximum sample rate of 2.5 GS/s. Then the captured data file is processed by the aforementioned demodulation method in Matlab. While for the arctan demodulation, the output signal of the photodetector is down-mixed with a 79.4 MHz local oscillator signal produced by an Agilent 33600A function generator. The down-mixed signals enter FV-628B filters to eliminate the high-frequency components. Finally, the filtered quadrature signals are sampled by NI PXI-5124 and saved to a local computer, where the arctan demodulation is conducted by LabVIEW.

Once the acoustic pressure is reproduced by the demodulated particle velocity or displacement, a B&K 8103 reference hydrophone is placed at the exact measurement point and its output voltage is recorded. Then the pressure sensitivities are calculated and compared with the nominal values at different frequencies, to validate the measurement system and the two demodulation methods.

4. Results and discussions

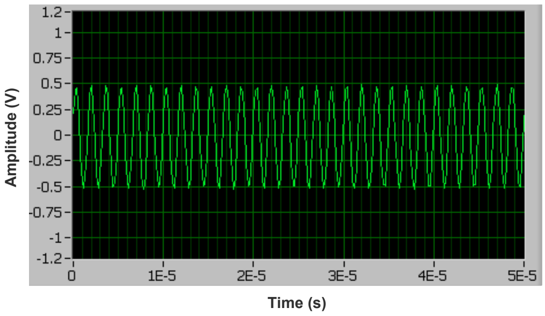
In this section, some experimental results are shown to validate the two demodulation methods by calibrating a reference hydrophone.

The frequency of the exciting burst signal is set to be 125.1 kHz first. For the zero-crossing de-

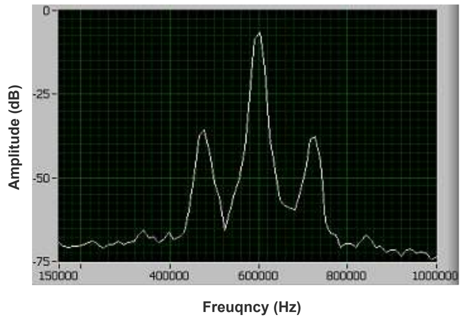


(a) (b)

Figure 3: (a) The signal captured by the oscilloscope for zero-crossing demodulation. (b) The demodulated particle velocity.



(a)



(b)

Figure 4: (a) The phase-modulated signal after down-mixing for arctan demodulation. (b) The spectrum of (a).

modulation, we also down-mix the output signal of the photodetector to make the subsequent process more convenient before the signal is captured by the oscilloscope. The captured signal and the demodulated particle velocity are shown in Fig. 3. They are somewhat not smooth because the sample rate of the oscilloscope is compromised to be relatively low. While the phase-modulated signal after down-mixing for arctan demodulation and its spectrum are shown in Fig. 4. The components of the 125.1 kHz burst signal are seen clearly besides the highest peak. The acoustic pressures reproduced are then used to calibrate a B&K 8103 hydrophone with the ID of 3008108. The pressure sensitivities calculated by the zero-crossing demodulation and the arctan demodulation are -212.36 dB[1] and -212.01 dB, respectively. They are both approximate to the nominal value -211.7 dB obtained from the certificate, and the deviations between these results are less than 1 dB.

Then, the calibrated results of the two methods at more different frequencies are given in Tab. 1 with comparisons to the nominal values. It is seen that the pressure sensitivities calculated by the zero-crossing method (M_{zer}) match well with the ones obtained by the arctan method (M_{arc}), and the differences between them at different frequencies are within 1 dB, or even 0.7 dB in Column 5. The last column shows the maximum difference of $|M_{\text{zer}} - M_{\text{nom}}|$ and $|M_{\text{arc}} - M_{\text{nom}}|$, where M_{nom} represents the nominal sensitivity. We see that the maximum differences are less than 1 dB as well. Noting that the results for 300 kHz and 500 kHz in the last column are not given since the related nominal values are not available in certificate, but the two demodulation methods still have been validated for each other, as seen in Column 5.

Table 1: Comparisons of the calibrated pressure sensitivity between the two demodulation methods and the nominal values in certificate.

Frequency (kHz)	M_{zer} (dB)	M_{arc} (dB)	M_{nom} (dB)	$\lvert M_{\text{zer}} - M_{\text{arc}}\rvert$ (dB)	$\max\{\lvert M_{\text{zer}} - M_{\text{nom}}\rvert, \lvert M_{\text{arc}} - M_{\text{nom}}\rvert\}$(dB)
25	-212.95	-212.26	-212.60	0.69	0.35
50	-214.81	-215.36	-215.20	0.55	0.39
100	-212.34	-212.17	-212.50	0.17	0.33
200	-222.57	-222.80	-223.10	0.23	0.53
300	-207.22	-207.55	-	0.33	-
500	-225.65	-226.12	-	0.47	-

During the experiments, we find that it is important to determine the arrival time of acoustic wave for zero-crossing demodulation since we have used burst signals to reduce reflections. Large deviations or incorrect results may be obtained regardless of this point. In addition, for the arctan

[1] [dB re 1V/μPa]

demodulation, a high-pass digital filter is needed to reduce the effect of low frequency vibration, which appears to be comparable to the acoustic displacement under measurement.

5. Conclusion

In conclusion, two demodulation methods are presented to extract the underwater acoustic pressure reproduced by a self-built laser heterodyne interferometer system. The extracted pressure is further used to calibrate a reference hydrophone. Experimental results have shown that, the pressure sensitivities obtained by the two methods are approximate to each other, and they also both match well with the nominal values with the differences being less than $1\ \mathrm{dB}$. In addition, The effects of the two demodulation methods on the pressure are pointed out and discussed. Specifically, the zero-crossing demodulation needs to determine the arrival time of acoustic correctly, while the arctan demodulation should reduce the effect of low frequency vibration. Since this paper mainly provides a preliminary study on the reproduction of underwater acoustic pressure by optical methods, a detailed uncertainty assessment is need and it would be one of our main future research tracks.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China under Grants 51505453 and 51575502.

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