An Active Stabilization Technique Of A Homodyne Interferometer Based On PTDC For High Frequency Hydrophone Calibration

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Abstract. Under plane wave conditions, the ultrasonic pressure could be derived by the detected displacement with a stabilized homodyne interferometer, and then compare with the voltage output of the hydrophone, it could calibrate the hydrophone. Generally, what is noteworthy is that the disfigurement of the homodyne interferometer easily influenced by the low frequency noise in environment such as acoustic noise and water surface agitation. As a result, signal faded. Based on direct current phase tracking, an active stabilization technique was devised to maintain the quadrature working point for the interferometer. While the interferometer stabilization was maintained, most of environmental noises could be effectively compensated, and the ultrasonic signal fading problem could be figured out. An active stabilization technique of a homodyne type Michelson interferometer for calibrating the high frequency hydrophone is described in this article.

Introduction

The miniature high-frequency hydrophone is used in the normal detection of the acoustic output from medical ultrasonic equipment. To provide the absolute measurement, the sensitivity of the hydrophone must be calibrated precisely. By using optical interferometer, many techniques have been developed for the calibration of hydrophone [1,2,3]. Optical interferometer can determine the acoustic pressure of interest and is directly traceable to the measurement of displacement. In addition, it is independent of transducer properties generating the acoustic field. In view of the advantages of optical methods over other techniques, a Michelson interferometer used to detect the acoustic field and calibrate the hydrophone can be a good method. However, the phase shift between the measurement beam and reference beam causing by low frequency noises in environment, such as acoustic noise, water surface agitation and random pressure fluctuation, can make signal fading, or lead to distortion of the signal under normal operating conditions.

In a practical hydrophone calibration, it is essential to maintain the phase shift continuously at $\pi/2$. To deal with the signal fading in the homodyne interferometry, some effective methods have been proposed. By means of the Pockels cell, introducing equal phase changes to the reference beam can compensate for the drift of the phase shift [4], yet the Pockels cell always release some poisonous gas. Introducing significant phase modulation by modulating the light source or through the use PZT as the modulator effecting on the reference arm, homodyne demodulation using phase generated carrier (PGC) can put the impact of external interference into effect on the modulated signal, and low-frequency external interference can be separated from the signal [5,6]. Also, with complex system architecture, alternating current phase tracking (PTAC) can produce phase compensation to keep the interference at quadrature by feedback control [7]. Especially, considering of simple structure, less Electrical complexity, small signal distortion, linear working status, direct current phase tracking (PTDC) can be a better compensation method [8].

In this paper, an active stabilization technique based on PTDC is described. This method is applicable to a homodyne interferometer for high frequency hydrophone Calibration. As a result, the interferometer can maintain the maximum sensitivity, and then, under plane wave conditions, the ultrasonic pressure could be derived by the detected displacement with a stabilized homodyne interferometer, and the hydrophone could then be calibrated. Experimental results verify the validities of the method. Measurement results indicated that the hydrophone calibration system based on the active stabilization technique of homodyne interferometry was sound in theory and feasible in practice.

The principle of the measurement device

The Michelson interferometer measurement device. A homodyne interferometer based on Michelson arrangement is used as shown in Fig. 1.PBS is the polarizing beam splitter, PZT is the piezoelectric ceramic transducer. In this device, the displacement of the pellicle in a water tank, which represents the sound pressure of the sound field, is detected by the Michelson interferometer device

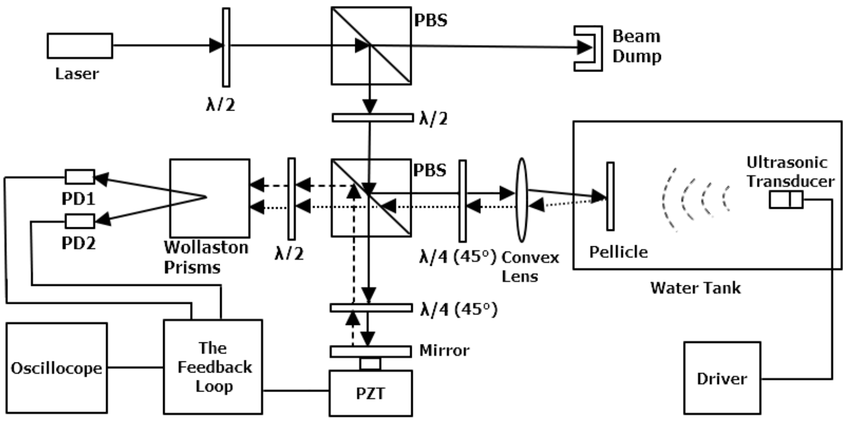

Fig. 1 The Michelson interferometer measurement device

To get stable laser light power, a green light laser (Model: G4 +200; MaxOutput: 450mW; Laser Wavelength: 532nm), as a light source in the interferometer, is lay on a metal radiator. The half-wave plate are used to rotate the polarizing state of the light, together with the polarizing beam splitter, the power with different polarizing state can be controlled. A beam dump is used to collect the stray light and prevent the light reflects back to the optical system. The quarter-wave plates are placed to the optical beam to change the polarization state and ensure the light is reflected by the polarization beam splitter.

Under the stabilizing driving, the ultrasonic transducer produces an acoustic field. To avoid the disturbance of sound, the ultrasonic wave is incident from the one side of tank, meanwhile, the laser beam comes from the other side.After passing the convex lens, the light in the measurement arm is focused on the pellicle, the air-backed side of which is covered with an Au layer to improve the optical reflectivity. Whereas the signal beam is reflected from the pellicle which follows the motion of the ultrasonic wave, the reference beam is turned back on its original path by use of the mirror mounted on the PZT (PI Namiway:E-509.S1N). To make interference between the measure beam and the reference beam, a Wollaston prism is placed in front of two photodiodes. After the Wollaston prism, the two interference signals differ in phase by π.

With the phase difference of 180 degrees, the two interference signals is detected by a photodetector equipped with two photodiodes (photodiode1 and photodiode2 in Fig. 2) for a differential detection scheme. As a result, the two interferometric signals is processed by the feedback loop system. The new signals generated from the feedback loop system are used as the compensative signal to drive the PZT in the reference arm. By means of this, the displacement of the PZT in the reference arm working by the mirror can keep the interferometer at a quadrature position. In another word, the differential phase drifts in the two arms are effectively eliminated, and the interferometer is stabilized. With a high Signal to Noise Ratio, the detected signal was sampled with a high frequency digital oscilloscope (DPO 7104, Tektronix) and then transferred to the computer through LAN connection for demodulation.

The feedback loop device. The feedback loop device is shown in Fig. 2. Photodiode1 and photodiode2 (C30902;Spectral response range: 400 to 1000nm)are Silicon Avalanche Photodiodes with high responsivity between 400 and 1000 nm as well as extremely fast rise and fall times at all wavelengths. To get high responsivity, the reverse DC voltage of photodiode1 and photodiode2 is set up close to 250V, less than the breakdown voltage of Silicon Avalanche Photodiodes. The currents i_1 and i_2, detected by photodiode1 and photodiode2, have the following forms:

$$i_1 = K_1 i_o[1 - k\cos(\Phi_d + \Phi_s)] \tag{1}$$

$$i_2 = K_2 i_o[1 + k\cos(\Phi_d + \Phi_s)] \tag{2}$$

Where K_1,K_2 are linear to the power of two interference signals,i_0 is decided by the input laser power, k is related to interferometric fringe visibility, Φ_d is the differential phase between the measurement arm and the reference beam, and Φ_s is uncertain phase effected by environmental disturbances.

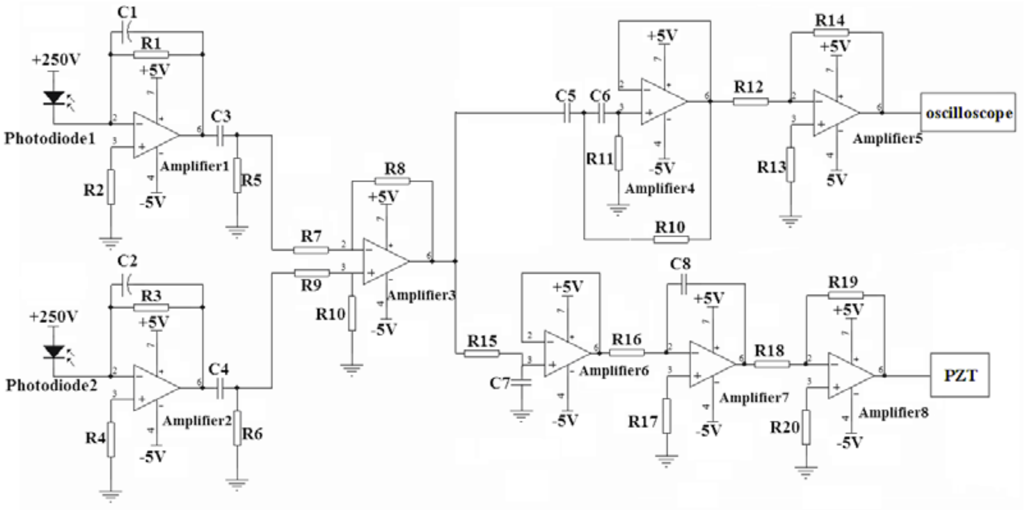

Fig. 2 The feedback loop device

Photodiode1 and photodiode2 are connected to two current-to-voltage converters amplifiter1 and amplifiter2.After passing converters, the two signals have the following forms:

$$u_1 = K_1' u_o - k_1' u_o \cos(\Phi_d + \Phi_s)] \tag{3}$$

$$u_2 = K_2' u_o + k_2' u_o \cos(\Phi_d + \Phi_s)] \tag{4}$$

Before amplifiter3 (the differential amplifier: R7=R8=R9=R10), C3 R5 and C4 R6 make up two high-pass filters to remove the two DC voltage$K_1' u_o$,$K_2' u_o$. Two photodiodes (photodiode1 and photodiode2 in Fig. 2) for a differential detection scheme can reduce dark current noise. The differential amplifier produces an output:

$$U_1 = K\cos(\Phi_d + \Phi_s) \tag{5}$$

Where K is conversion gain of two interference signals from photodiode1 and photodiode2 to amplifiter3. After high-pass filter (Amplifiter4) and voltage amplifier (Amplifiter5), the signal can be showed on the oscilloscope, which represents the displacement of the pellicle when the interferometer is on the quadrature state.

Amplifiter6 is a high-pass filters to filter out high frequency circuit noise. After passing the electronic integrator Amplifiter7, the output of Amplifiter7 have the following form:

$$U_2 = K' \sin(\Phi_d + \Phi_s - \pi/2) \tag{6}$$

As the interferometer is in a quadrature state, there is:

$$\Phi_d + \Phi_s = \pi/2 \tag{7}$$

that is， $U_2 = 0$.

Also when the interferometer is close to the quadrature state, $\Delta\Phi$ ($\Delta\Phi = \Phi_d + \Phi_s - \pi/2$) is approximately equal to zero, and U_2can be described as:

$$U_2 = K^{'} \Delta\Phi \tag{8}$$

Whereas U_2 is linear to the deviation between the interferometer state and the quadrature state, the signal of Amplifiter7 which amplifies U_2 is used as the compensative signal to drive the PZT. At the same time, the compensative signal driving the PZT is also input to the reset circuit showed in Fig. 3.

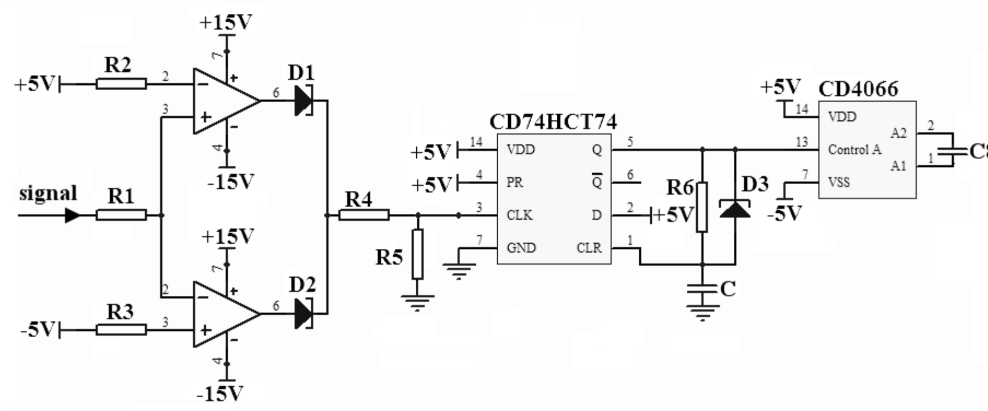

Fig. 3 The reset circuit

According to the instructions of the PZT, the voltage applied on the PZT must be limited between -5V and +5V. Once the voltage applied on the PZT is out of the limitation, the reset circuit can shortly set the voltage to zero. In the reset circuit, the compensative signal is connected to the voltage comparator consisted of two amplifiers. If the compensative signal is out of the limitation, one of two diodes D1,D2 is opened, and the output voltage of the voltage comparator is closely up to 15V. After the voltage division by R4 and R5 (R4:R5=2:1), CD74HCT74 gets a useful rising edge. Then the pin Q of the CD74HCT74 outputs a high-level signal for a time $t_{reset}(t_{reset} = C \cdot R6)$. With high-level signal effects on CD4066, the switch A of CD4066 closes, namely pin A1 and pin A2 discharge the capacitor C8 (also in the Fig.2). As a result, the compensative signal is reset to zero.

The phase feedback loop device model show in Fig.4. φ is the phase difference between the measurement arm and the reference arm, k_d is the phase-voltage coefficient for photodiodes which depends on the conversion gain of the avalanche photodiode, current-voltage conversion(Amplifiter1 and Amplifiter2) and the quality of optical interference. *a* is the open loop gain, introduced by the differential amplifier(Amplifiter3). I(s) depicts the transfer function of the integrator(Amplifiter7). $I(s) = 1/RCs$, which is influenced by the integration time constant *RC*, *R* and *C* are the resistance and capacitance of the integrator respectively. *b* is the gain of Low-pass filter(Amplifiter6), and low frequency signal amplifier(Amplifiter8). k_p is the voltage-phase coefficient for PZT.

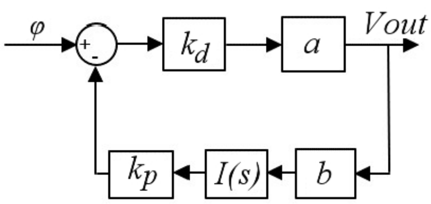

Fig. 4 The feedback loop device model

From Fig. 4, it can be deduced that the transfer function of the closed feedback loop is

$$H(s) = \frac{V_{out}}{\varphi} = \frac{aK_d s}{s + abK_d K_p / RC} \tag{9}$$

Let $s = j\bar{\omega}$,

$$|H(j\bar{\omega})| = \frac{aK_d}{\sqrt{1+\left(\frac{\bar{\omega}_0}{\bar{\omega}}\right)^2}} \quad (10)$$

Where $\bar{\omega}_0 = a * b * K_d * K_p / RC$. Thus it can be deduced that the feedback system can be regarded as a high pass filter, where the cut off angular frequency is $\bar{\omega}_0$. In order to optimize the feedback compensation performance, *a,b,R,C* should be well designed to change the frequency.

The experiments and discussion

Determination of the PTDC parameters. In order to stabilize the interferometer at the quadrature state, first of all, k_p and k_d should be ascertained by measuring. Fig. 5 shows the photodiode1 and photodiode2 received signal when PZT is driven by a triangular wave, channel 1 shows the triangular wave signal while channel 2 and channel 3 shows the photodiode1 and photodiode2 received signal. As triangular wave signal changes 1.69V, the phase change is about 20π, thus k_p is 37.1 rad/V. In the same way, k_d for photodiodes can also be determined while the interferometer is close to the quadrature state. The photodiodes output signal changes 1.43V when the optical phase change is about π/2, thus k_d is about 0.91 V/rad. These values just represent the calculation method, actually k_p and k_d should be measured repeatedly for average value to reduce measurement error, also with little adjustment according to the result of experiments.

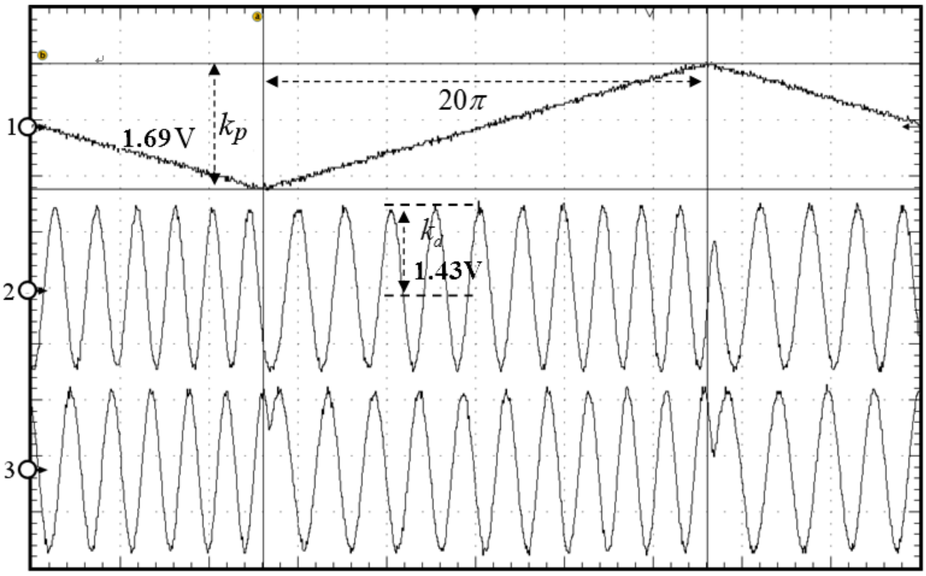

Fig. 5 The photodiodes received signal while the PZT is driven by triangle wave

Fig. 6 shows the signal before phase tracking and Fig. 7 shows the signal after phase tracking. From Fig. 6, it can be seen that owing to the low frequency interference in environment and water surface agitation in the water tank, the output of homodyne interferometer drifts periodically without ultrasonic wave effecting on the pellicle, certainly leading to the ultrasonic signal's fading in normal experiments. When the feedback loop device is at work, the output of the interferometry is stabilized, shown in Fig. 7.

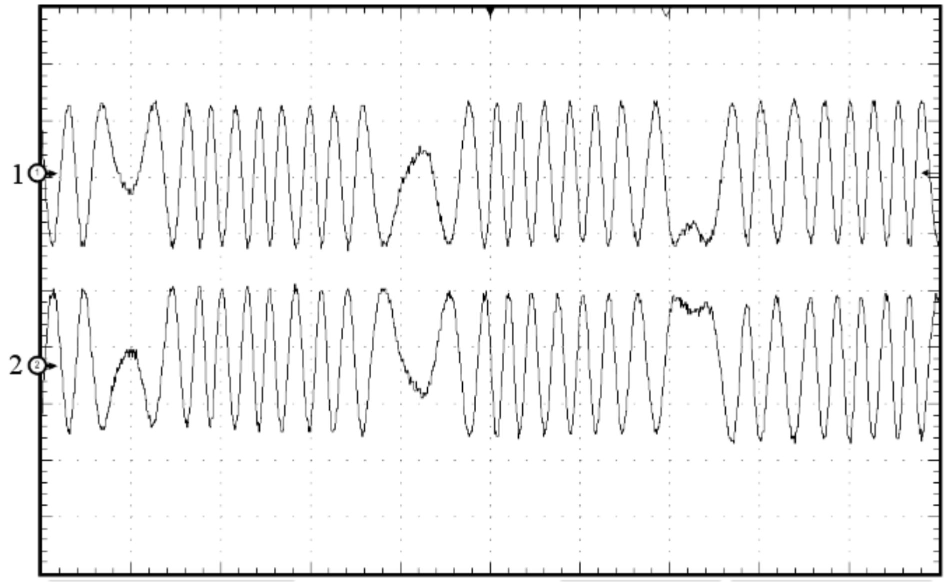

Fig. 6 The output of the homodyne interferometer with environmental noises

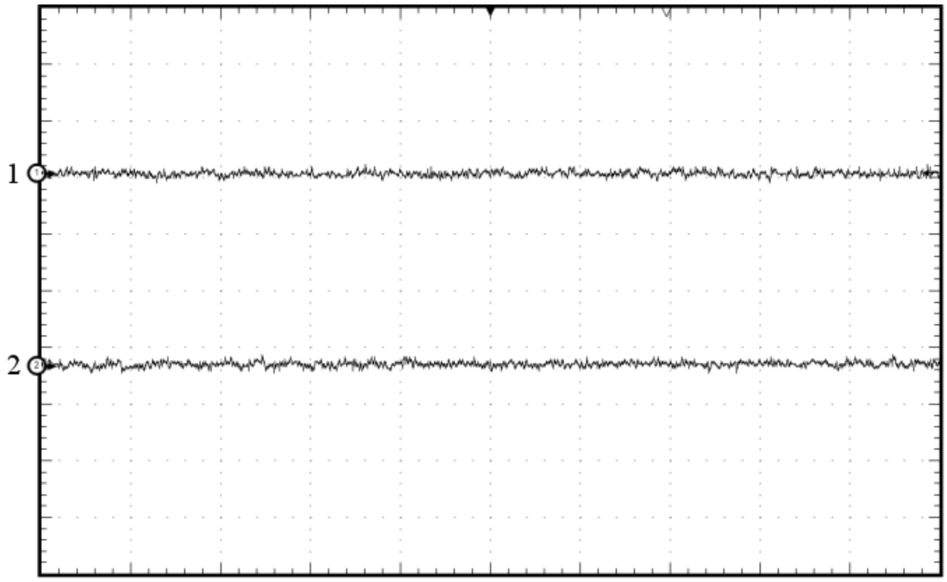

Fig. 7 Stabilized output of the homodyne interferometer at the quadrature state.

Experiments and Results. To generate ultrasonic fields with significant relatively high frequency content, a 5 MHz transducer (Panametrics type V308, 0.75 inch diameter) with a nominal focal distance of 50 mm, was used. The transducer was driven by the 33622A pulse generator (Agilent Technologies, Palo Alto, CA) gated to provide a tone-burst of twenty cycles of a 5 MHz fundamental with 200 mV amplitude, which was then connected to a R. F. power amplifier (100A250A , AR, Souderton, PA) at the full gain control. The burst period was 1 mS. Care must be taken that the signals should be recorded without interference from multiple reflections. Highly shocked waveforms in the focal region with at least 4 harmonics of the 5 MHz fundamental can be detected by the stabilized homodyne interferometer. A digital oscilloscope (DPO 7104, Tektronix) was used to digitize the output of photodiode and hydrophone respectively.

Corresponding to Fig. 8, which shows the time-domain waveform of the homodyne interferometer output when the homodyne interferometer was at the quadrature state, Fig. 9 is the time-domain waveform of the PVDF membrane hydrophone voltage output. Once the interferometer output signal and hydrophone voltage waveform were acquired, the subsequent processing was carried out using numerical computation methods. The sensitivity of the hydrophone end of cable can be derived for each harmonic component by Fourier transform of the time domain waveform.

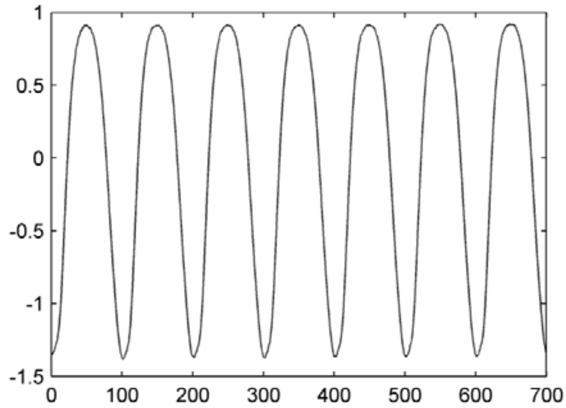

Fig. 8 Interferometer output signal representing the pellicle displacement

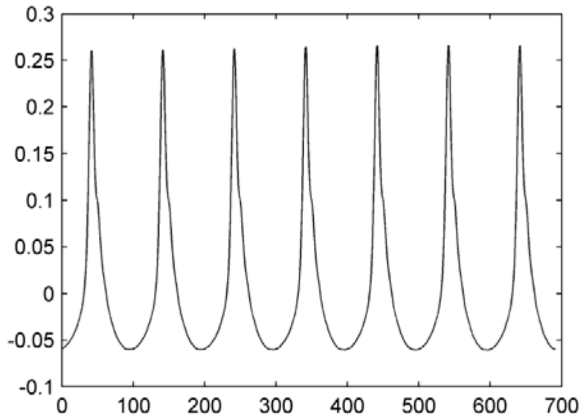

Fig. 9 The uncorrected PVDF membrane hydrophone voltage waveform

Conclusion

In this article, we described an active stabilization technique of a homodyne interferometer based on PTDC for high frequency hydrophone Calibration. Appling the PTDC technique, the feedback loop device can effectively resolve the signal fading problem, namely the random phase shifts can be tracked and compensated to maintain the phase difference between the interferometer arms at π/2. With a slight of increase of the discrepancies at higher frequencies, the uncorrected sensitivity of the hydrophone is about 43nV/Pa at 5MHz and 47nV/Pa at 15MHz respectively. To improve the feedback loop device's performance, it is essential to studied further about the linearity of the PZT and unity gain frequency of the feedback loop. Sources of uncertainties, for instance the frequency response of the photodiode, the acoustic properties of the thin pellicle, spatial averaging effects, and lack of ideal plane wave conditions and so on, need to be considered in higher frequency calibration, will be discussed in our future study.

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