Ultrasonics 54 (2014) 402–407

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Calibration of high-frequency hydrophone up to 40 MHz by heterodyne interferometer

Ping Yang [a,*], Guangzhen Xing [a,b], Longbiao He [a]

[a] Division of Mechanics and Acoustics, National Institute of Metrology, Beijing 100013, China
[b] Ultra-Precision Optoelectronic Instrument Engineering Institute, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Article history:
Received 31 March 2013
Received in revised form 13 July 2013
Accepted 15 July 2013
Available online 25 July 2013

Keywords:
High-frequency hydrophone
Calibration
Heterodyne interferometer
Digital phase demodulation

ABSTRACT

A calibration technique for high-frequency hydrophone utilizing a heterodyne interferometer is presented in this article. The calibration system is mainly composed of optical and signal processing modules. In the displacement measurement, a pellicle is mounted at the surface of water to avoid acousto-optical interaction. The phase modulated carrier signal is digitized and transferred to the computer, then processed by digital phase demodulation. A phase unwrapping algorithm is employed to remove ambiguity of the arctangent function and has proven effective in large displacement measurements. Pellicle displacement and voltage output of the hydrophone in focused ultrasonic field are processed by DFT to determine the amplitudes of the fundamental and harmonic components. Experiments show that the heterodyne technique can provide hydrophone calibration up to 40 MHz, with a slightly smaller sensitivity compared with the National Physical Laboratory (NPL) calibration results for most frequency ranges. Since the heterodyne technique is independent on assumptions about the geometry of the ultrasonic field and the performance of the transducer, it can be easily extended to high frequency and high power ultrasound measurement applications.

1. Introduction

Numbers of diagnostic systems have been developed using high frequency ultrasound for imaging. For instance, in anti-cellulite therapy the device for sector imaging of subcutaneous tissue and skin utilized a probe with a frequency of 35 MHz [1]. The frequency of ultrasound imaging for assessing liver lesions was up to 40 MHz [2]. Other applications of high frequency imaging ultrasound can be found in a comprehensive review by Lockwood et al. [3]. Consequently, high-frequency hydrophones have been extensively used in medical applications. For the calibration of hydrophones, several techniques have been proposed. Those most frequently used are reciprocity [4,5], planar scanning technique [6] and optical interferometry [7–9]. Reciprocity and planar scanning technique cover the frequency range from 0.5 MHz to 15 MHz with degraded uncertainties when applied in higher frequency [10]. Both methods require corrections of diffractive effects in the ultrasonic field which is a major source of uncertainty. Optical interferometry directly determines the acoustic quantity of interest and is directly traceable to the measurement of acoustic displacement, besides it is independent on assumptions about the geometry of the ultrasonic field and the performance of the transducer.

In view of the advantages of optical interferometry over other techniques and to accomplish a primary calibration of high frequency hydrophones, a number of attempts have been undertaken up to now [7–9]. But the interferometers are a type of homodyne. However, there have been several limitations so far. It uses a piezo-driven mirror to stabilize the interferometer at quadrature working point. For processing the output signal of the interferometer, there are several approaches. For the analog displacement decoding utilizing Phase-Locked Loop (PLL) circuits, the PLL provides a noise-reduced rf-signal and the error signal of the loop can be used for an FM to AM conversion. The phase of the signal in a range of $\pm 90^\circ$ is detected and thus limited to relatively small displacements ($\pm\lambda/8$). To achieve displacement information, an analog integration of the velocity signal is needed. However, such analog integrators usually require a high pass filtering of the velocity signal to eliminate the DC bias. As a result, DC measurements are not possible in analog displacement decoding, but are limited in the dynamic range and add additional errors to the calibration chain of the system. Even for the analog velocity decoders converting the Doppler frequency into an analogue voltage proportional to the velocity of vibration that can be matched to a variety of requirements such as higher frequencies, DC response and higher velocity ranges, there are still several drawbacks that analog electronics are sensitive to drift together with aging. Also, there are several certain limits in linearity for velocity decoding.

* Corresponding author. Tel.: +86 10 64524631; fax: +86 10 64218628.
E-mail address: yangp@nim.ac.cn (P. Yang).

0041-624X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultras.2013.07.013

In this article, a heterodyne interferometer Polytec UHF-120 [11] is used to measure the pellicle displacement to calculate the ultrasonic pressure in water. In the heterodyne system, the carrier frequency is shifted using a Bragg cell. To overcome the disadvantage of analog displacement decoding of ultrasonic displacement, digital phase demodulation (DPD) is utilized to reach a much larger ultrasonic displacement and higher displacement resolution. In order to achieve the highest accuracy during the measurement, some aspects like spatial averaging and pellicle transmission coefficient have also been considered. A comparison with National Physical Laboratory (NPL, Teddington, UK) calibration results are shown in the following section.

2. Theory and method

2.1. The heterodyne interferometer

The basic idea of using optical interferometry for the calibration of high-frequency hydrophone involves the determination of the ultrasonic displacement produced by a transducer at a position in the ultrasonic field. It uses a Polyethylene Terephtalate (PET) membrane (5 μm in thickness) positioned within the field, which moves in sympathy with the ultrasonic wave. Under the condition of plane-wave propagation, the ultrasonic pressure can be derived from a simple linear relation with the displacement. Then the hydrophone being calibrated is placed at the same position to acquire the output voltage. The sensitivity of the hydrophone is achieved from the ratio of output voltage of the hydrophone to ultrasonic pressure.

To derive the pellicle displacement, a heterodyne interferometer based on the Mach–Zehnder arrangement is used as shown in Fig. 1. A compact green diode-pumped, solid-state laser (DPSS) is used as the radiation source. The laser light has a low amplitude noise with a pure Gaussian beam profile. Owing to the beam quality factor M^2-value being less than 1.1, the laser beam can be focused to a diffraction limited spot of less than 4.5 μm using a high numerical aperture microscope objective. The monochromatic light enters a Bragg cell which splits the beam into two components, an undiffracted beam and a diffracted beam. The undiffracted beam is used as the measurement beam and is turned back on its original path with the movement of the pellicle which follows the motion of the ultrasonic wave. The reference beam is frequency shifted with a Bragg cell and recombined with the measurement beam at the PIN photodiode detectors with 2 GHz bandwidth. Owing to the Bragg cells not being efficient for high frequency shift (>500 MHz) between zero and first diffraction orders, a slow-shear mode cell [12] is used. With higher diffraction orders and special Bragg-cell designs, the maximum shift of the T_eO_2-Bragg cell can reach 613 MHz [11]. The setup of a confocal laser Doppler vibrometer microscope [13] is employed to achieve the highest lateral resolution. The quarter-wave plate is used to effect necessary changes in polarization and to prevent light returning to the laser. The measurement beam is circular polarized through the quarter-wave plate which can additionally reduce the laser spot diameter [14]. The line width of the laser is 5 MHz and since the pellicle is always in the focus of the microscope objective, the interferometer can be designed as an equal path-length type. Thus output of the interferometer can be depicted as [15]

$$i_s = K[P_m + P_r + 2K\sqrt{P_m + P_r}\cos(2\pi f_B + \varphi(t))] \tag{1}$$

where i_s is the output current of the detectors, P_m is the power of the measurement beam impinging on the detector and P_r the power of the reference light. Furthermore, $K = \eta q/h\nu$ is the conversion parameter of the detector, $h = 6.6261 \times 10^{-34}$ J s is the Planck's constant, η the quantum efficiency of the photodiode and $\nu = c/\lambda$ is the laser light frequency. $\phi(t)$ is the time dependent phase modulation by the pellicle displacement $s(t)$.

$$\varphi(t) = \frac{4\pi}{\lambda}s(t) \tag{2}$$

Therefore once the phase has been demodulated, the pellicle displacement can be derived. For a plane wave approximation, the ultrasonic pressure, p, is given in the following equation:

$$p = i\rho c\varpi a \tag{3}$$

where ρ is the density of water, c is the sound velocity in water, ϖ is the acoustic angular frequency and a is the amplitude of pellicle displacement $s(t)$. Therefore, for a given acoustic pressure, the displacement amplitude a is inversely proportional to the frequency. After the characterization of the ultrasonic field, the pellicle is removed and the membrane hydrophone is inserted. After adding some water, the membrane hydrophone should be adjusted with the laser beam focused at the geometrical center. Then adjust the position of the hydrophone to make the received signal maximum. The projector should be kept untouched during the adjustment. Under equivalent conditions, the measurement is repeated, and the sensitivity of the hydrophone can be obtained.

2.2. Data acquisition and demodulation technique

According to Eq. (2), the phase modulated signal exhibits a linear relationship between $\phi(t)$ and pellicle displacement $s(t)$. The phase modulation generates a frequency modulation f_D simultaneously which is determined by the ultrasonic frequency f_{vib} and velocity amplitude of the pellicle V:

$$\Delta f_D(t) = \frac{2V}{\lambda}\cos(2\pi f_{vib}t + \phi_s) \tag{4}$$

The bandwidth of the modulated heterodyne signal is infinite theoretically [16], but practically estimated to be:

$$BW_{het} = 2(\Delta f_D + f_{vib}) \tag{5}$$

Consequently, the carrier frequency f_B has to be at least $\Delta f_{Dpeak} + f_{vib}$. As an example, with f_B chosen at 100 MHz, this condition can maintain a peak velocity of about 5 m/s and a maximum vibration frequency of 80 MHz.

Analog decoders with this high bandwidth have their own frequency responses. In addition, calibrated generators with a frequency modulation bandwidth of several 100 MHz are not yet available. To overcome the limitations of analog processing, the carrier signal from the photodiodes is demodulated digitally using modern oscilloscopes with high frequency bandwidth and

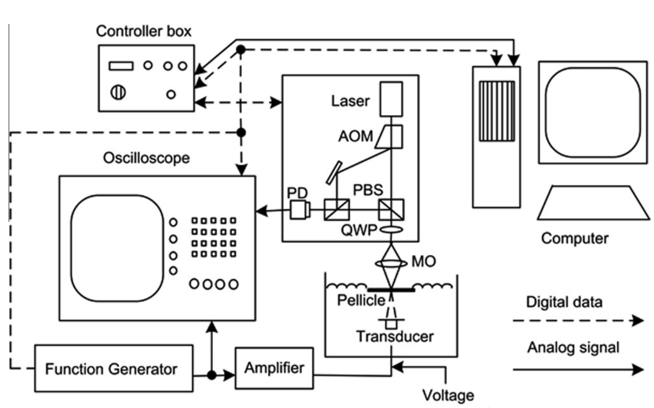

Fig. 1. Schematic diagram of the heterodyne interferometer. PBS is the polarizing beam splitter, PD is the photo detector, QWP is the quarter-wave plates, MO is the microscope objective and AOM is the acousto-optical modulator (Bragg cell).