PARTICLE VELOCITY AND PRESSURE MEASUREMENTS OF UNDERWATER SOUND USING LASER DOPPLER ANEMOMETRY

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1 INTRODUCTION

In the area of underwater and marine acoustics, hydrophones are used to record and measure absolute pressure levels[1]. Amongst these devices, two types are widely used, namely spherical reference and plane piston, both of which rely on the piezoelectric effect, where a change in perceived pressure produces an electrical output. The former type of the previously mentioned hydrophones consists of a sphere that acts as the sensing element for underwater sound, while the latter type is similar to a piston transducer, with a round flat surface responding to the sound field.

In order to ensure measurement consistency, hydrophones need to be calibrated with traceability to specific standards[2] and, as such, the current primary calibration standard adopted is based on the three-transducer spherical wave reciprocity method[3] that depends on the reciprocity principle[2,4].

The reciprocity method is an elegant and relatively straightforward technique that yields the absolute sensitivity of the hydrophone that needs to be calibrated. In this case, three hydrophones are used and they are paired up in turn such that one acts as the transmitter and one as the receiver. For each measurement pair (part of the triad), and for each frequency step, the voltage produced by the receiving device and the current driving the transmitting device are measured; their ratio is defined as the electrical transfer impedance. In addition, the reciprocity parameter needs to be calculated and this depends on factors such as the density of the medium (water), distance between the paired up devices and acoustic frequency. This primary calibration standard is applicable for frequencies up to 500 kHz and offers an expanded uncertainty of ±0.5 dB with a 95% confidence level.

However, there are a number of drawbacks associated with the existing primary calibration reciprocity standard. One of the devices within the measurement triad needs to be reciprocal, namely linear, passive, reversible, with the ratio of the transmitting to receiving responses being equal to a well-defined constant. In practice, it is quite difficult for a device to exhibit such characteristics over the full frequency range. The method also assumes a spherical propagation of the acoustic field used as excitation and this is often quite difficult to verify in practice. Though the calibration procedure yields absolute sensitivity values, it is traceable through electrical standards and, more importantly, does not realize directly the unit of acoustic pressure.

Laser Doppler vibrometry[5] (LDV) has shown the potential of measuring in a direct and absolute way the particle velocity and hence pressure at a point in space for acoustic frequencies up to 600 kHz, with the experimental setup utilising a commercially available vibrometer by Polytec. LDV is based on heterodyne interferometry and due to its larger dynamic range compared to homodyne interferometry, is more suited for such measurements. However, a commercially available system cannot be used a primary calibration standard as it is treated as a "black box" in the sense that no direct traceability can be established.

In order to establish an optical system with complete measurement transparency in terms of providing traceability as a potential primary calibration standard, a custom made heterodyne interferometer with software Doppler demodulation was previously investigated[6]. Instead of employing a digital demodulation phase-locked control box (hence requiring further calibration depending on the signal level and possibly frequency) to reconstruct the acoustic burst and provide the particle velocity, software analysis of the output frequency modulated (FM) signal was performed based on its zero-crossing points. The system showed the potential to optically calibrate hydrophones for frequencies up to 1 MHz with good agreement with the existing primary standard.

This paper presents work towards such a potential future optical primary standard for the calibration of hydrophones in the frequency range 20 kHz - 1 MHz. Improvements on the data acquisition system that allow more accurate calculation of the required Doppler shifts and subsequent post-processing averaging of the acoustic bursts show a reduction of the discrepancies between the optical and reciprocity based calibrations and better reconstruction of the demodulated acoustic bursts. Results are presented from three different hydrophones calibrated with three separate methods.

2 REVIEW OF OPTICAL HOMODYNE AND HETERODYNE INTERFEROMETERS FOR ACOUSTIC PRESSURE ESTIMATION

In order to calculate the pressure due to propagating sound in a medium, it is first necessary to measure either the particle displacement or particle velocity using either homodyne or heterodyne interferometry respectively. One of the major differences between these two optical methods is the dynamic range they can offer.

Homodyne interferometry has been applied to the measurement of particle displacements due to propagating ultrasonic waves in water[7,8]. In this case, the optical system consists of a reference beam kept within the interferometer itself and a measurement beam that probes a suspended water-matched pellicle membrane that is placed in the path of the propagating sound. By optically mixing the two beams and through a subsequent analogue phase-locked loop control box, it is possible to measure particle displacements ranging from fractions of the wavelength of the laser source (hundreds of nanometres) down to a few tens of picometres. After applying a number of corrections relating to the transmission characteristics of the pellicle, density and temperature of water and amplitude frequency response of the photodiodes amongst others, it is possible to accurately calculate the acoustic pressure at the probing point.

In the area of underwater and marine acoustics, typical pressures may vary from tens of Pa to tens of kPa and, over the frequency range 20 kHz to 1 MHz, this relates to a very large range of particle displacements indeed; this typically translates to particle velocities ranging from tens of μms^{-1} to tens of mms^{-1}. Homodyne interferometry is therefore not suitable for such a large dynamic range and for this reason heterodyne interferometry is the most suitable approach.

A heterodyne interferometer utilises two laser beams (single wavelength, single mode, Gaussian coherent profile), one of which is frequency shifted using an optical modulator. There are two possible ways of measuring particle velocity, both of which rely on the Doppler shift of light scattered from particles that oscillate due to the propagating sound. In the first case, the two laser beams cross at an angle such that they form a three dimensional ellipsoid volume in space consisting of interference fringes; since one of the beams is frequency shifted, the fringes appear to be moving. As particles oscillate due to sound, they cross the fringes and photons are scattered. By using a suitable photodetector to capture the photons, a Fourier transformation of the signal yields the spectrum consisting of the main frequency carrier (due to the reference frequency shift) and two sidelobes whose frequency difference from the carrier is equal to the acoustic frequency of the propagated sound field. The amplitude of the sidelobes is the required particle velocity and through knowledge of characteristics such as temperature and density of water and speed of sound, one can calculate the acoustic pressure at the beams cross-over.

The main drawback of this approach is the fact that the resulting signal-to-noise ratio is relatively low due to the fact that it is only scattered optical speckle captured by the photodetector arrangement. Additionally, and given the fact that the interferometer would be placed outside a water tank and at a certain distance from the ellipsoid volume itself, a certain Keplerian or Galilean telescopic arrangement with suitable magnification would need to be installed so that it images the measurement area itself and optically delivers it to the photodetector using single mode optical coupling[9].

The most robust approach to ensure a sufficient signal-to-noise ratio of the signal to be analysed, offering a large dynamic range and being far less prone to vibrational issues, while probing a two-dimensional area rather than three-dimensional volume in space, is to combine the principle of Doppler anemometry with heterodyne interferometry, using a pellicle membrane as a reflecting target and keeping the reference beam within the optical system itself as explained for the case of homodyne interferometry but without the phase-locked loop demodulation.

More specifically, a thin strip of water-matched pellicle is suspended and placed in the path of the propagating sound field. The reference laser beam is still frequency-shifted and kept within the interferometer while the measurement beam probes a point on the pellicle that reflects it back on the interferometer. Optically mixing the reference beam and the speckle from the measurement beam, results in a frequency shifted signal that is modulated by the acoustic burst due to the Doppler effect. Subsequent analysis of the resulting frequency modulated signal based on the zero-crossing point method[10] allows for the calculation of the Doppler shifts at each crossing point and yields directly the particle velocity. Through knowledge of the water temperature and density and the speed of propagating sound, one can calculate the acoustic pressure in an absolute and direct manner without any assumptions about the propagation characteristics of the sound field or the availability of reciprocal acoustical devices.

3 OPTICAL INTERFEROMETER SYSTEM AND SIGNAL DEMODULATION ANALYSIS

The schematic arrangement of the measurement system is shown in figure 1. A water tank with dimensions 2 m by 1.5 m by 1.5 m (length by width by depth) was used, which included a fully motorized computer-controlled positioning system with two independent mounting carriages allowing movement in all three directional axes including rotation. The far carriage was used to mount the transducer providing the acoustic excitation, while the near carriage was used to mount a rectangular hollow frame onto which a 400 mm by 3 mm (length by width) strip of polyethylene terephthalate membrane, 23 μm thick and reasonably well-matched to the impedance of water, was stretched and suspended. The dimensions and material impedance of the strip ensured that it faithfully follows the oscillation of the propagating sound field but not cause any diffraction effects.

The water tank itself was designed and built in such a way that it included two transparent (glass) windows. The optical system was placed outside the tank so that it probed the pellicle through the first window on the front of the tank.

The optical system itself was a custom-made Michelson interferometer in heterodyne mode. The main source was a frequency-doubled Nd:YAG laser, 532 nm wavelength and 150 mW optical power. A Bragg cell was used on the main beam and it produced output beams at each diffraction order, each shifted in frequency increments of 80 MHz. For this system, the zero-order (non-shifted) and first order (80 MHz shifted) beams were used as measurement and reference beams respectively. The reference beam was kept within the interferometer itself, while the measurement beam probed the suspended pellicle strip through the water tank glass window. The side of the strip facing the interferometer was coated with a 40 nm layer of aluminium in order to maximise the reflected speckle from the measurement beam. The reference beam was then optically mixed with the reflected measurement speckle and the resulting optical signal was split into two beams with orthogonal polarisations with respect to each other which were directed onto two photodiodes brought in quadrature mode. The resulting electrical signal of the interferometer was effectively a frequency modulated (FM) signal due to the main reference carrier (80 MHz) modulated by the acoustic particle velocity at the probing point on the pellicle strip.

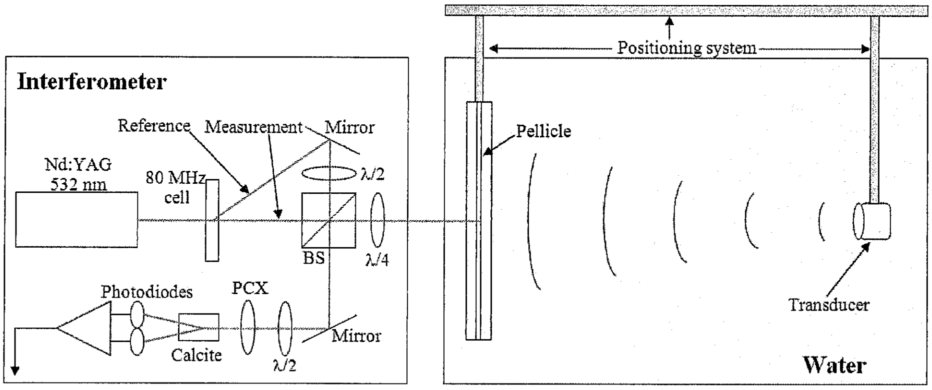

Figure 1: The schematic of the experimental arrangement for the optical calibration measurements

As mentioned earlier, it is be possible to use a custom-made frequency down-shift analogue demodulation unit to reconstruct the acoustic bursts from demodulating the main FM signal itself. In addition, it is also be possible to display the bursts on a digital oscilloscope and apply averaging to significantly increase the stability of the waveforms and hence improve the signal-to-noise ratio. However, the output waveforms are essentially voltage versus time signals and hence the control unit would need to be calibrated as a function of voltage in order to provide conversion factors between voltage and particle velocity.

To follow a primary standard approach and to ensure complete measurement and analysis traceability, such a control box was not used in the system. Instead, at each discrete frequency step, the output FM signal of the interferometer was captured directly using a Tektronix DPO7354C Digital Phosphor oscilloscope with 40 GHz sampling rate.

Each signal sequence was saved and was subsequently analysed using the zero-crossing method[10]. Each saved sequence can be represented as a time series with all its *n* zero-crossing points defined as t_i. Two time series are first calculated that define the time spacing between all zero-crossing points:

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

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

The Doppler shift at each zero-crossing point is then calculated as:

$$\Delta f_i^* = \frac{1}{\Delta t_i^*} \tag{3}$$

By combining the Doppler shifts and the wavelength of the optical source, λ, the particle velocity is given by:

$$v_i = \frac{\lambda}{2} \Delta f_i^* \tag{4}$$

It is worth mentioning that equation (4) also contains the cosine of the angle between the velocity vector and the bisector of the incident and reflected beams and the cosine of the angle between incident and reflected beams. In order to ensure that both angles were 0°, the interferometer, pellicle and transducer were carefully tilted and lined up so that their axes were aligned on a reference path defined by the measurement beam propagating in the water back and then reflecting back from a mirror mounted on the transducer post at the far end of the water tank.

The digitised captured waveform, though acquired at a very high sampling rate, did not actually capture the actual zero-crossing points. However, the high acquisition rate meant that the adjacent-to-zero points (positive and negative) were sufficiently close enough the zero points themselves such that by applying the straight line approximation, the zero points could be accurately estimated.

After going through the approach outlined through equations (1) to (4), the acoustical burst at each frequency step could be demodulated. In order to increase the signal-to-noise of the bursts, averaging would also need to be applied. However, this was not possible to perform real-time on the interferometer signal due to its FM nature. To overcome this, a set of 50 full signal acquisitions were obtained as each frequency and the resulting demodulated acoustic bursts were then averaged at the post-processing. The required single particle velocity u was then obtained by calculating the Discrete Fourier Transform (DFT) coefficient at the acoustic frequency for each averaged set of bursts (represented by the velocity series in equation 4). The free-field pressure P was then calculated by:

$$P = \rho \; c \; u \tag{5}$$

where ρ is the density of the water and c is the speed of sound in water.

4 OPTICAL CALIBRATION AND RECIPROCITY MEASUREMENT PROCEDURE

The lower frequency range limit for the experimental verification of the optical system was dictated by the size of the small tank and dimensions of the metal frame that supported the suspended pellicle strip and was 20 kHz. As for the upper frequency limit, the only limitation was the availability of calibration data of piston hydrophones at high frequencies.

Three frequency ranges were investigated and for each one, a separate transducer and hydrophone pair was used. The first pair consisted of a Reson TC1042 spherical reference sound source (75 kHz resonance) and a Reson TC4040 hydrophone for the range 20 kHz to 140 kHz; the second pair consisted of an Ultran 1.5" diameter transducer (250 kHz resonance) and a Reson TC 4034 spherical reference hydrophone for the range 200 kHz to 450 kHz; finally, the third pair consisted of a Precision Acoustics (PA) PA104 2" diameter transducer (1 MHz resonance) and a Precision Acoustics ML4X50 hydrophone covering the range 400 kHz to 1 MHz. The TC 4040 and TC 4034 hydrophones had previously been calibrated by the reciprocity method at NPL, while the PA ML4X50 was calibrated for frequencies over 500 kHz (therefore not covered by reciprocity) using the ultrasonic optical primary standard[7,8].

For each frequency range, the interferometer measurements were performed first by placing the pellicle strip at the far field of the transducer. The acoustic excitation for all transducers was provided by an Agilent 33220A function generator through a fixed 50 dB gain EIN 240L RF power amplifier. In all cases, a fixed time window of 100 µs with a 4 Hz repetition burst rate was used in order to ensure that no acoustic reflections were captured.

Having completed the interferometer measurements, the position of the pellicle where the measurements were performed was marked by a red laser diode pointing into the water tank through the second glass window by its side and by the measurement beam of the interferometer from the front glass window. The red laser was aligned so that the two beams crossed exactly at the probing point of the pellicle. The entire frame was then removed and the hydrophone under investigation was placed in the tank and positioned such that its active element centre was placed at the beams cross-over point. For the TC 4034 and TC 4040 hydrophones, since their active element centre is inside the hydrophone, their accurate placement was achieved from technical data supplied by the manufacturer and the precision of the mounting positioning system in the water tank. In the case of the ML4X50, it was positioned so that its front surface was lined up. The output of the TC 4040 and TC 4034 hydrophones was amplified by a Stanford Research Systems SR560 pre-amplifier, while the output of the ML4X50 was amplified using a Reson VP1000 amplifier.

Two corrections needed to be applied for the hydrophone measurements. The first related to the gain of the amplifiers; even though their gains were adjusted and fixed for each transducer/hydrophone pair, in practice the gain depends upon the amplitude and frequency of the input signal. For the measurements of all hydrophones, the amplitudes of the waveforms were recorded. After all measurements were completed, the Agilent function generator was used to provide sinusoidal signals of similar amplitudes at each frequency on the amplifiers in order to calculate the exact amplification ratio. The second correction was only applied for the ML4X50 piston hydrophone and it related to spatial averaging corrections due to the disk element and was dependent on the acoustic frequency and dimensions of the source and hydrophone and their distance[11].

Figure 2 shows a typical example between acoustic bursts at 250 kHz produced by the TC 4034 hydrophone (left) and the software Doppler shift demodulated waveform from the interferometer output captured by the digital oscilloscope following the method described above. The agreement seems very good and, in addition, the waveform produced by the optical method yields the particle velocity (by calculating the DFT coefficient at the acoustic frequency) in a direct and absolute manner.

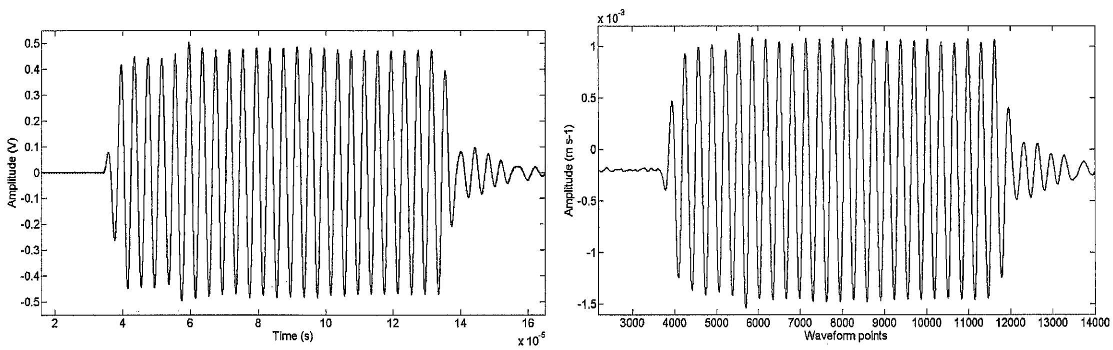

Figure 2: Acoustic burst 250 kHz resulting from the TC 4034 hydrophone (left) and demodulated from the interferometer output signal (right)

5 DISCUSSION ON EXPERIMENTAL RESULTS

In order to compare in more accurate manner the optical method and reciprocity, a calibration approached was followed. Reciprocity yields the sensitivity of a hydrophone that needs to be calibrated as a function of frequency with units in dB re: 1V/µPa. To perform an optical calibration of a hydrophone, it is necessary first to measure the particle velocity (using the pellicle strip approach) and then calculate the acoustic pressure in Pa. The hydrophone then replaces the pellicle, is placed at the same point of measurement and its voltage measured and corrected for the amplifier amplitude response. As mentioned earlier, for each frequency range the interferometer measurements take place first measuring the pressure for each frequency; the pellicle is replaced with the hydrophone and the voltage at each frequency step is measured. The sensitivity of the hydrophone is then calculated using the following formula:

$$Mi = 20\log_{10}\left(\frac{V_i}{P_i \times 10^6}\right) \tag{6}$$

where M_i is the calculated sensitivity, V_i is the hydrophone voltage, P_i is the pressure measured by the hydrophone and i represents the index for each frequency step. This last equation has been formulated in such a way to provide the same units as those given by reciprocity.

Following the optical calibrations, the three frequency ranges resulting from the three transducer/hydrophone pairs were combined and the difference in sensitivity compared to reciprocity was calculated. Figure 3 shows the discrepancy between the two methods; the disagreement seems random rather than systematic and in most cases it is better than 0.6 dB.

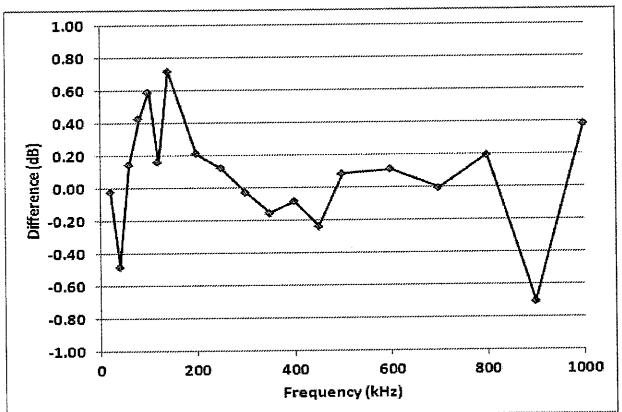

Figure 3: difference in dB between optical calibration and reciprocity in the combined range 20 kHz to 1 MHz for the three hydrophones investigated

Though the agreement is very reasonable, there are a number of potential factors contributing to the observed discrepancies. The dominant factor is the accurate estimation of the zero-crossing points. Even though the sampling rate was set to 40 GHz resulting into adjacent points very close indeed to the each zero-crossing point, the straight line is likely to introduce the largest uncertainty contribution. Other factors that need to be investigated into more detail and been taken into account as further correction factors include the presence of the acousto-optic effect and the transmission loss of the pellicle membrane. Finally, the frequency stability of the laser source itself and the Bragg cell may also be contributing to the deviation between the two presented methods.

6 CONCLUSIONS

This paper has presented an optical method that can be used as a potential primary standard for the calibration of hydrophones in the range 20 kHz to 1 MHz. The method combines the principle of laser Doppler anemometry and optical heterodyne interferometry to accurately measure particle velocities due to propagating underwater sound. To achieve this, a thin strip of pellicle strip with water-matched impedance is placed in the far-field of acoustical transducers, with the interferometer probing a fixed point on the pellicle. By capturing the interferometer signal at high sampling rate, software analysis of the Doppler shifts allows the demodulation of the resulting acoustic bursts. The optical procedure is followed for discrete frequency steps. The hydrophone to be calibrated subsequently replaces the pellicle and it is exposed at the same acoustical excitation conditions at the same frequency steps. By measuring the hydrophone voltage and through knowledge of the pressures measured by the interferometer, an optical calibration of the hydrophone can take place, in a direct and absolute manner, most importantly through the realization of the unit of acoustic pressure.

Results have been presented for the optical calibration of three hydrophones (two spherical reference and one piston), with very good agreement to calibration data obtained by the reciprocity method and an additional primary homodyne interferometer method. The optical method offers a high dynamic range; based on the experimental results presented, particle velocities ranged from 33 μms^{-1} to 11 mms^{-1}, equivalent to 50 Pa and 17 kPa respectively.

The next steps of this work will include fine frequency calibrations over the entire frequency range offered by the technique. A number of repeats will be attempted that should also reduce the disagreement with reciprocity even further. Finally, a full uncertainty budget to investigate and minimize any further sources of systematic and random errors will also be prepared.

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