ABSOLUTE CALIBRATION OF HYDROPHONES USING HETERODYNE INTERFEROMETRY AND ZERO-CROSSING SIGNAL DEMODULATION

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Abstract: The current primary method for hydrophone calibration is the three-transducer spherical-wave reciprocity at NPL, covering the frequency range between 1 kHz up to 500 kHz with expanded uncertainties as low as ± 0.5 dB. Optical methods can provide an alternative method for primary calibration as they directly measure the acoustic particle velocity at a specific point in the field. The hydrophone is then placed at the exact same point and can be calibrated directly referenced to the acoustic Pascal, with traceability to the wavelength of the light source used. This paper discusses the optical development of a heterodyne interferometer for such purpose. A transducer is placed in a water tank while an acoustically transparent pellicle is mounted at a certain distance. As sound propagates, the pellicle follows the movement of sound. A heterodyne interferometer with an 80 MHz carrier provides a reference beam while the measurement beam probes the pellicle. The reflected measurement beam is then mixed back with the reference and the output of the interferometer is a frequency modulated voltage signal with modulation depth corresponding to the amplitude of the acoustic field. This paper explains the optical arrangement required for the measurements and considers the resulting signal demodulation based on the zero-crossing point method that enables the calculation of the Doppler shift and hence the velocity due to the sound field.

Keywords: Hydrophone calibration, optical heterodyne interferometry, zero-crossing frequency demodulation
1. INTRODUCTION

Absolute measurements of sound pressure in the field of underwater acoustics are usually undertaken with hydrophones [1]. It is therefore necessary for such devices to be calibrated with a specific method traceable to specific standards [2]. Such methods are based on the principle of reciprocity [2,3] and standardised in the so-called three-transducer spherical wave reciprocity method [4].

In this last mentioned method, three hydrophones are used. One of these devices must be reciprocal; linear, passive and reversible. In this sense, the ratio of the transmitting to receiving responses needs to be equal to a constant. With regards to the measurement setup, the three hydrophones are arranged in three separate pairs and, for a given pair, one acts as the transmitter while the other acts as the receiver. In each case, the current driving the transmitting device and voltage produced by the receiving device are recorded. An additional parameter that is required is the so-called acoustic transfer impedance; this is equal to the ratio of the sound pressure at the position of the receiver to the volume velocity produced by the transmitter. In spherical wave reciprocity it depends on parameters such as the separation distance between the devices, the acoustic frequency and the density of the water. By applying the reciprocity principle in conjunction with the above measurements, the absolute sensitivity of the three hydrophones may be calculated over a standard frequency range with a typical expanded uncertainty of ±0.5 dB.

This calibration method is traceable to primary electrical standards and is derived without any knowledge of the actual pressure of the sound field generated. In addition, it relies on the acoustic field itself being spherical-wave propagated and also on the availability of a transducer being reciprocal. From a metrological perspective, an alternative method that would provide direct traceability to the acoustical Pascal, making no assumptions about the acoustic field would be more favourable as a new primary calibration standard.

Optical methods, such as interferometry, provide such a potential method [5-8]. In this case, such a system could directly measure the acoustic particle velocity in a point in water, therefore providing knowledge of the sound pressure present. The hydrophone to be calibrated would then be placed at that point in water and its sensitivity would be acquired traceable directly to the unit of pressure without the need of pairing up different hydrophones or relying on their reciprocal nature.

This paper outlines and focuses upon the details of an optical system based on heterodyne interferometry that can directly measure acoustic particle velocities in water. Special attention is also given to the demodulation method that calculates the required acoustic amplitudes. For comparison purposes, a number of measurements are illustrated against a standard hydrophone and a separate commercially available Vibrometer. Good agreement is shown between the three methods employed.

2. OPTICAL SYSTEM AND SIGNAL PROCESSING

The optical setup is essentially a Michelson interferometer in heterodyne mode. A 150 mW frequency doubled Nd:YAG source (532 nm wavelength) provides a highly collimated beam that enters a Bragg cell. The emerging zero-order serves as the measurement beam, while the resulting first order of diffraction is shifted by 80 MHz; and serves as the reference beam. The reference beam is kept within the interferometer itself,
while the measurement beam exits the system and through a suitable pinhole/beam expander probes a mounted pellicle positioned in a water tank. The pellicle itself is a 5 μm Mylar® membrane that is coated with a 25 nm thick layer of gold and is positioned normal to the laser beam so that the reflected measurement beam can re-enter the interferometer through the same beam expander/pinhole. A piston transducer placed at a distance from the pellicle provides the required acoustic excitation in the form of a repeatable tone burst.

The reflected measurement beam carries the acoustic displacement from the pellicle and is then re-combined with the reference beam in the interferometer. The combined beams produce a frequency modulated (FM) signal with the centre carrier (80 MHz) and modulation depth resulting from the acoustic displacement. The FM signal $y(t)$ is expressed as:

$$y(t) = A \sin\{2\pi f_c t + \frac{\delta}{f_m} \sin(2\pi f_m t)\}$$  \hspace{1cm} (1)$$

where $A$ is the amplitude, $f_c$ is the carrier frequency, $\delta$ is the peak deviation from the carrier and $f_m$ is the instantaneous frequency deviation due to the measurement signal. This optical FM signal is then split using a polarising prism so that the two emerging beams are brought into quadrature onto two photodiodes. Subsequent amplification produces a continuous signal with no DC offset that is captured on a high resolution oscilloscope for further processing.

From a metrological perspective, the most direct and suitable demodulation technique to extract the acoustic velocity, is the zero crossing method. Other methods such as built-in demodulation functions using the Hilbert transform in MATLAB or frequency domain matched filtering between FM signals would require software calibrations and corrections, hence increasing the overall uncertainties associated with the presented optical technique. The zero-crossing method requires, in principle, no corrections and most importantly directly measures the change in the frequency of the carrier. This method is traceable to a standard [9] that provides details on the calibration of laser vibrometers.

The captured signal from the oscilloscope consists of a number of points per cycle, however, there will be no zero-crossing point present and this needs to be identified separately. The captured sequence is analysed point by point until a unique pair of adjacent points, $x_i$ and $x_{i+1}$, are identified to meet the conditions such that $x_i$ is $<0$ and $x_{i+1}$ is $>0$. These two points can then be represented in terms of their Cartesian co-ordinates; firstly their gradient $m$ is calculated and then by analytically solving the gradient equation that relates the two Cartesian points, the equation of the line can be calculated with no knowledge of the y-axis intercept. Since the sampling of the data acquisition is known, the negative-to-positive zero-crossing point can be calculated. This operation is repeated for the entire data capture until all zero-crossing points have been calculated.

Subsequently, from the time spacing between adjacent zero-crossing points, the Doppler shift can be calculated. For each case, this frequency shift is multiplied by half the wavelength of the light source and a series of instantaneous velocity amplitudes are calculated using the following formula:

$$v_i' = \frac{\lambda}{2} \Delta f_i^*$$  \hspace{1cm} (2)$$
It is worth noting that the denominator in Eq. 2 should include the cosine of the angle between the bisector of the measurement and reference beams and the velocity vector. However, due to the experimental arrangement of the system this angle is 0°, hence its cosine is 1.

\( v_i \) is essentially the demodulated acoustic tone burst and its amplitude represents the acoustic velocity needed for the calibration. In order to accurately calculate this acoustic velocity, a simple amplitude calculation is not sufficient, mainly due to relatively low signal-to-noise ratio due to high frequency components present. This issue can be significantly reduced by calculating the discrete Fourier transform (DFT) coefficient at the applied acoustic frequency instead. In this way, only the amplitude contribution at the acoustic frequency of interest is calculated, therefore providing an accurate velocity calculation.

3. EXPERIMENTAL RESULTS

A number of experiments were carried out using the optical heterodyne interferometer discussed in the previous section. The measurements were undertaken in a small water tank with dimensions 600 mm x 300 mm x 390 mm (length x width x depth). Inside the tank, a 5 μm Mylar gold plated (25 nm layer) pellicle mounted on small ring frame was placed near the edge of the tank. On the other edge of tank (along the 600 mm dimension), a Panametrics 1 MHz 1’’ diameter immersion transducer was placed facing the pellicle was electrically driven to provide the acoustic tone burst excitation. To reduce reflections, an acoustic absorbing tile was placed behind the transducer.

The interferometer itself was placed at a distance of 1 metre away from the tank with its measurement beam probing the pellicle at 90° (from the opposite side); the exit measurement beam from the interferometer and the reflected beam from the pellicle were aligned in such a way that they coincided, therefore producing a 0° angle (the reason why the cosine factor in Eq. 2 is equal to 1). As the transducer provided the acoustic stimulus, the measurement beam probed the pellicle (following the propagated sound) and when reflected back into the interferometer was mixed with the reference beam at the 80 MHz carrier. The beam was splitted into two components that were then focused onto the two photodiodes. The electrical FM output was captured on a high resolution oscilloscope that was analysed in MATLAB using the method discussed in the previous section.

For comparison purposes, measurements were also undertaken with a commercially available laser scanning Vibrometer (Polytec PSV-400) probing the pellicle along the same axis and point on the pellicle, and a GEC 25 mm polyvinylidene difluoride (PVDF) hydrophone replacing the pellicle. Figure 1 shows the acoustic burst demodulated using the zero-crossing method from the interferometer output and the burst captured by the hydrophone when placed at the same place as the pellicle.

A number of acoustic frequencies were experimented with; in this case the results obtained at 400 kHz, 500 kHz and 600 kHz are shown. The comparison was performed between the two optical systems and the hydrophone. In all cases, the dB (rms) levels were calculated and these are shown in Table 1.

The calculated pressures from the two optical systems and the hydrophone compare well; it also seems that the difference between them is of random rather than systematic nature.
Fig. 1: The acoustic tone burst at 600 kHz demodulated using the optical interferometer (top) and captured by a calibrated hydrophone (bottom)

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Interferometer (dB rms)</th>
<th>Vibrometer (dB rms)</th>
<th>Hydrophone (dB rms)</th>
<th>Difference int.-hyd. (dB rms)</th>
<th>Difference vib.-hyd. (dB rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>144.3</td>
<td>143.8</td>
<td>143.5</td>
<td>-0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>500</td>
<td>146.0</td>
<td>146.8</td>
<td>146.3</td>
<td>-0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>600</td>
<td>149.4</td>
<td>149.5</td>
<td>149.1</td>
<td>0.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 1: Pressure comparison (dB) between the two optical methods and the hydrophone

4. DISCUSSION

There is a number of potential sources of error that need to be considered at this point. For the optical interferometer, the quality and stability of the signal depend on the power ratio between the reference and measurement beams, the speckle produced by the water in the tank, as well as the purity of the water as particles can cause sufficient scatter. Though the optical path of the measurement and reflected beams were made to coincide, a fraction of a degree deviation would cause the Doppler shift to be calculated with a degree of error. The acousto-optic effect would also need to be accounted for but in this case it would be necessary to trace the phase of the FM signal and calculate the displacements in order to correct for the effect. These issues apply for the vibrometer itself, except for the split ratio of the beams that is already fixed within the system. Though the two optical systems are effectively covering the same path length, it is necessary for both to probe the pellicle at precisely the same angle (90°), otherwise they will be measuring slightly different velocity vectors. The hydrophone itself is also extremely directional and therefore its inaccurate positioning will produce pressure discrepancies. Finally, the pellicle and hydrophone need to be placed at the same point in the sound field; a small difference in their relative position can also contribute an error. Despite all the sources of error, reasonable agreement between the three methods may be observed.

5. CONCLUSIONS

This paper presented the details of an optical interferometer and associated zero-
crossing demodulation method designed to measure particle velocities generated within underwater sound fields. A fixed high water-matched pellicle was placed inside the water tank with the transducer, with the interferometer probing the pellicle. A comparison was also performed with a commercially available vibrometer and a standard hydrophone and reasonable agreement in the derived acoustic pressure level demonstrated.

The next steps in this work include the implementation of this technique in a large tank, so that the full frequency range covered by reciprocity can be attempted. Modelling and analysis of the acousto-optic effect contribution to the FM signals will also need to be attempted, in addition to the preparation of a complete uncertainty budget to examine the limitations and suitability of the technique as a potential primary calibration standard for underwater acoustics.

6. ACKNOWLEDGEMENTS

This work was funded by the National Measurement Office of the UK Department of Business Innovation and Skills. © Crown copyright 2011. Reproduced by permission of the Controller of HMSO and Queen’s printer for Scotland.

REFERENCES