Technique for the calibration of hydrophones in the frequency range 10 to 600 kHz using a heterodyne interferometer and an acoustically compliant membrane

Pete D. Theobald, Stephen P. Robinson, Alex D. Thompson, and Roy C. Preston
National Physical Laboratory, Teddington, Middlesex TW11 0LW, United Kingdom

Paul A. Lepper
Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom

Wang Yuebing
Hangzhou Applied Acoustics Research Institute, 80 Guihuaxi Road, Hangzhou, Zhejiang, 311400, China

(Received 31 January 2005; revised 15 August 2005; accepted 19 August 2005)

A technique for the calibration of hydrophones using an optical method is presented. In the method, a measurement is made of the acoustic particle velocity in the field of a transducer by use of a thin plastic pellicle that is used to reflect the optical beam of a laser vibrometer, the pellicle being acoustically transparent at the frequency of interest. The hydrophone under test is then substituted for the pellicle, and the hydrophone response to the known acoustic field is measured. A commercially available laser vibrometer is used to undertake the calibrations, and results are presented over a frequency range from 10 to 600 kHz. A comparison is made with the method of three-transducer spherical-wave reciprocity, with agreement of better than 0.5 dB over the majority of the frequency range. The pellicle used is in the form of a narrow strip of thin Mylar©, and a discussion is given of the effect of the properties of the pellicle on the measurement results. The initial results presented here show that the method has the potential to form the basis of a primary standard method, with the calibration traceable to standards of length measurement through the wavelength of the laser light. [DOI: 10.1121/1.2063068]

PACS number(s): 43.58.Vb [AJZ] Pages: 3110–3116

I. INTRODUCTION

In underwater acoustics, hydrophones are typically used to make absolute measurements of acoustic fields.[1] For example, they may be required to measure the level of ambient noise in the ocean, or the level of unwanted sound produced in the ocean by manmade sources. Alternatively, hydrophones may be used to characterize the output of transducers used in active sonar systems, where the source level and transmit sensitivity are vital in determining the system range or detection limits. If absolute measurements are to be meaningful, the hydrophone used must be calibrated using an appropriate method and the calibration must be traceable to agreed standards.[2]

The free-field receive sensitivity of a hydrophone is the quotient of the open-circuit voltage developed by the hydrophone in response to the acoustic pressure from a plane wave. In the definition, the pressure used is that which exists at the position of the acoustic center of the hydrophone, but in the absence of the hydrophone from the field. The established methods for the calibration of hydrophones are the classic methods based on the principle of reciprocity,[2,3] and there is an international standard specifying the free-field calibration of a hydrophone by the method of three-transducer spherical-wave reciprocity.[4] In this method, three hydrophones are required, at least one of which must be a reciprocal device. For a device to be reciprocal, it must be linear, passive, and reversible, with the ratio of the transmitting and receiving response of the device equal to a constant. The hydrophones are paired off in three measurement arrangements, for each of which one device is used as a transmitter and one as a receiver. At each stage, measurements are made of the current used to drive the transmitting device, and the voltage developed by the receiver. Knowledge is also required of the acoustic transfer impedance, which is equal to the quotient of the sound pressure at the position of the receiver to the volume velocity produced by the transmitter.[5] For a spherical-wave field, this depends upon the acoustic frequency, the density of the medium, and the separation distance. This is common to each of the measurement arrangements and is often given in terms of a constant factor, termed the reciprocity factor.[6] From these purely electrical measurements, and knowledge of the reciprocity factor, the absolute sensitivity of any of the three transducers may be determined, with the calibration traceable to electrical primary standards.

The strength of the reciprocity method is that it does not require any absolute measurement of an acoustic field parameter, and this is one of the main reasons why it displaced other calibration methods as the preferred choice for a primary acoustical calibration method. However, it does have weaknesses in that it depends on the nature of the acoustic field (for example, on the existence of a spherical-wave field), and on the availability of a transducer that is reciprocal (not an easy property to validate).[3] From a metrological perspective, it may also be considered less satisfactory, in that it does not provide a direct realization of the acoustic pascal.

Optical methods have long been used as a nonperturbing way of detecting acoustic fields, usually by measuring the acoustic particle velocity or displacement using an interferometer-based technique or a technique based on measuring the Doppler shift of scattered light. Optical methods have the advantage that they do not depend on a transducer being reciprocal, or whether the acoustic field has a particular geometry, and may facilitate a more direct realization of an acoustic quantity. They also provide the potential for accurate measurement, with traceability to primary standards of length via the wavelength of the laser light.

An example of such a technique is that of laser Doppler anemometry, which has been used to measure the acoustic particle velocity in air.[7] This method involves intersecting two laser beams and detecting the Doppler shift of the light scattered from the particles crossing the small intersecting volume. This method has been configured to provide free-field calibrations of microphones.[8,9] The same method has also been reported for use in water.[10] However, this method has been shown to have limitations when measurements are required at a point in a water-borne field. This is because the optical beam responds not only to the movement of the particles, but also to refractive index changes along the paths of the beam caused by the compressional and rarefractional pressure variations in the medium during the passage of the acoustic wave. Although not significant for measurements made in air, when measuring in water this acousto-optic interaction can lead to difficulty in interpreting the measurements.[11]

This acousto-optic effect has been exploited to provide a technique for measuring acoustic fields in water, where the optical beam is configured to be orthogonal to the direction of the acoustic beam (parallel to the acoustic wave fronts) in order to maximize the interaction.[12] When combined with tomographic techniques, this provides a potentially powerful and rapid technique for mapping acoustic fields.[13,14] However, for the calibration of hydrophones, a measurement is required of a field parameter at a point in the field. Since methods utilizing the acousto-optic interaction almost invariably rely on an integrated effect along the length of the optical beam, this limits the usefulness of the methods for hydrophone calibration.

For ultrasonic frequencies in the range from 500 kHz to 20 MHz, optical methods are now well established.[15] At the National Physical Laboratory, UK, such a method is used for the primary calibration of miniature ultrasonic hydrophones.[16,17] The methods use optical interferometry to measure the displacement of a thin plastic membrane (termed a pellicle) placed in the farfield of an ultrasonic transducer. The membrane is used to reflect the optical signal beam of a Michelson interferometer, the pellicle being thin enough to be acoustically transparent at the frequency of interest. The interferometer is sensitive to the optical phase changes induced by movement of the pellicle and provides a measurement of acoustic particle displacement, the acoustic pressure then being derived from the measured displacement. In the method, the optical beam is arranged to be parallel to the direction of the acoustic beam (orthogonal to the wave fronts). In such a configuration, the effect of the acousto-optic interaction is minimized and is amenable to the simplified theoretical treatment of Bacon.[18] Modified versions of such methods have recently been extended to frequencies as high as 60 MHz at NPL,[19] and to 70 MHz at PTB in Germany using a similar method, where the acousto-optic effect is eliminated by placing the membrane on the water surface so that the entire optical path is through air.[20]

Recently, initial attempts to extend pellicle-based calibration methods down to the lower kilohertz range have been reported using a commercial laser vibrometer to measure the acoustic particle velocity.[21,22] A report has already been given of a comparison of this method with the NPL primary standard interferometer at frequencies of 500 kHz to 1 MHz,[23] and of initial attempts to use the technique at NPL at lower frequencies.[24]

Presented in this paper are the results of a feasibility study of applying the same technique to the calibration of underwater acoustic hydrophones.[25,26] Initial results are presented for the calibration of a hydrophone in the frequency range of 10 to 600 kHz using a commercial vibrometer to undertake the optical measurement, and a comparison is made with results obtained by the method of three-transducer spherical-wave reciprocity. In the paper we further consider the response of the pellicle and its effect on the results, with a theoretical and practical study of the membrane behavior in the presence of an acoustic field.

II. OPTICAL MEASUREMENT OF ACOUSTIC PARTICLE VELOCITY

In order to perform a free-field calibration of a hydrophone, it must be exposed to a known acoustic pressure, p, in a plane-wave field. The acoustic pressure used in the calculation of the free-field sensitivity is that which exists in the field at that position when the hydrophone is absent from the field. Although optical interferometry does not provide a direct measure of acoustic pressure, it offers a method to measure the acoustic particle velocity, u, from which the acoustic pressure can be derived using the following:

$$p = \rho\, c\, u, \tag{1}$$

where ρ is the density and c is the speed of sound in the medium. The direct measurement of acoustic particle velocity can be achieved by employing a laser Doppler interferometric technique, where the interferometer is designed to be sensitive to a frequency shift between the reference arm and the measurement arm. The Doppler frequency shift, $\delta\nu$, can be related to the laser wavelength, λ, and the particle velocity vector, u, by the following equation:[15]

$$\delta\nu = \frac{2u}{\lambda} \cos\beta \cos\left(\frac{1}{2}\phi\right), \tag{2}$$

where β is the angle the velocity vector u makes with the bisector of the incident and reflected beams. In practice, the incident and reflected beams are aligned so that they traverse similar paths such that $\phi \to 0$, where ϕ is the angle between the incident and reflected beams. The Doppler shift can therefore be written as

$$\delta\nu = \frac{2u}{\lambda}\cos\beta. \tag{3}$$

With knowledge of the laser wavelength, this Doppler beat frequency obtained from the detector allows a determination of the absolute particle velocity and thus the acoustic pressure.

The use of a Doppler heterodyne interferometer is favored over a conventional homodyne phase-locked interferometer for this application due to the potentially large dynamic range required of up to 5 mm/s and the requirement for a relatively low-frequency measurement capability down to 1 kHz. Phase-locked homodyne interferometers do have the advantage that they do not require Doppler decoding electronics but they are limited in dynamic range to the linear section of the fringe pattern and the phase-locking prohibits low-frequency measurements because of the necessary vibration compensation.[15]

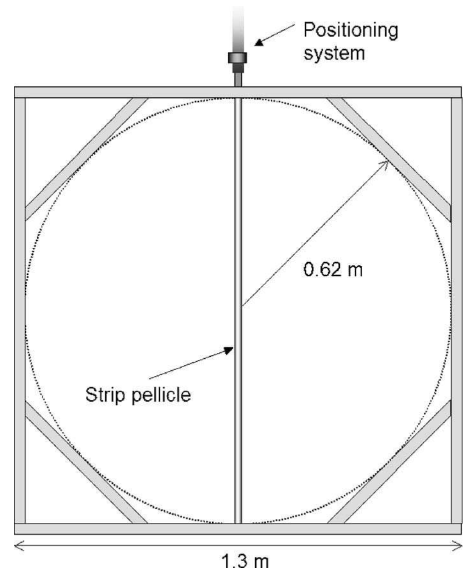

FIG. 1. Mounting frame and strip pellicle.

III. EXPERIMENTAL METHODOLOGY

Measurements of the acoustic particle velocity at a point in the field of an acoustic transducer were performed using a commercial laser Doppler vibrometer. The measurement was conducted by reflecting the laser light from a thin plastic pellicle suspended in the field. The principle behind the use of a pellicle is to enable the measurement to be made at a specific point in the field, with pellicle thickness being small compared to the acoustic wavelength and the acoustic impedance being similar to that of water so that the motion of the pellicle follows the motion of the water particles. The vibrometer provides an output that is proportional to velocity, and the time-resolved signal may be displayed on a digitizing oscilloscope in the same manner as a hydrophone signal. From the measured velocity, the acoustic pressure was calculated using the expression given in Eq. (1). The hydrophone under test was then substituted for the pellicle and the hydrophone voltage measured, with the hydrophone sensitivity calculated from the quotient of the hydrophone voltage and the acoustic pressure.

The vibrometer used was a Polytec PSV-3000 scanning vibrometer, which provided a maximum measurement bandwidth of 1.5 MHz.

The test tank used for the measurements has dimensions of 2 m long by 1.5 m wide by 1.5 m deep and incorporates a two-carriage precision positioning system for positioning and orienting devices. A glass window is set into one end of the tank to allow optical interrogation of the acoustic field.

The pellicle used was in the form of a narrow plastic strip, which was made from a 23 μm thick Mylar© membrane coated on one side with 40 nm of aluminium so as to render it a specular reflector of the optical beam. A number of different widths of pellicle were tried during the measurements, from strips as narrow as 2 mm to strips as broad as 12.6 mm. The pellicle was tensioned over a frame measuring 1.3 m square and constructed from 30 mm extruded aluminium, as shown in Fig. 1. The mounting frame provided a reflection-free time window of around 0.65 ms for a transmitter–receiver separation of 0.5 m. The frame was mounted on one of the carriages of the positioning system adjacent to the optical window, with the acoustic projector mounted on the other carriage, as shown in Fig. 2. The vibrometer beam was then aligned through the optical window of the tank on the acoustic center of the projector. For the flat face piston projectors used, the limited optical reflection from the surface of the transducer was used to align the optical beam of the vibrometer with the acoustic axis of the transducer. The membrane was then positioned to intercept the laser beam and reflect the light back through the glass window and into the optical collection head of the vibrometer. It was possible to align the optical beam very precisely with the pellicle because of its specular reflecting properties. The above procedure ensured that the acoustic beam was colinear with both the incident and return paths of the optical beam. A transmitter–receiver separation of 0.5 m was used, which was sufficient to ensure a measurement in the acoustic farfield. To undertake measurements with the hydrophone, it was substituted for the pellicle mount and aligned using the positioning system so the laser beam was incident on the acoustic center of the hydrophone. The device under test was a Reson TC4034 reference hydrophone, which has a 6 mm diameter spherical element and a resonance frequency of ap-

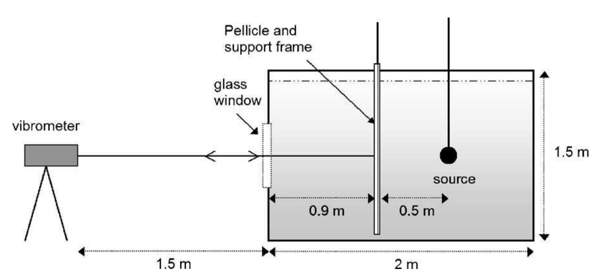

FIG. 2. Measurement arrangement used to measure acoustic velocity using an optical vibrometer.

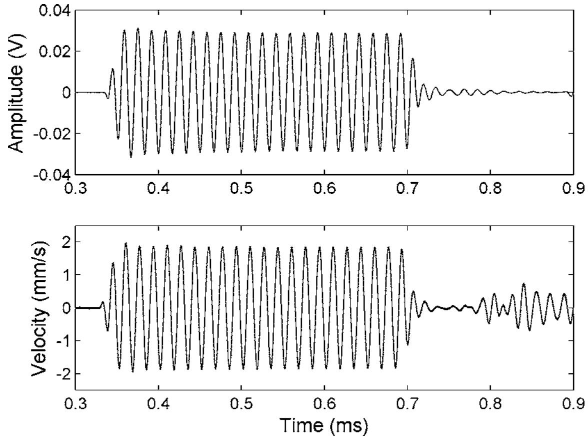

FIG. 3. A comparison of waveforms recorded by the reference hydrophone (upper plot) and the vibrometer (lower plot) for an acoustic signal of 60 kHz.

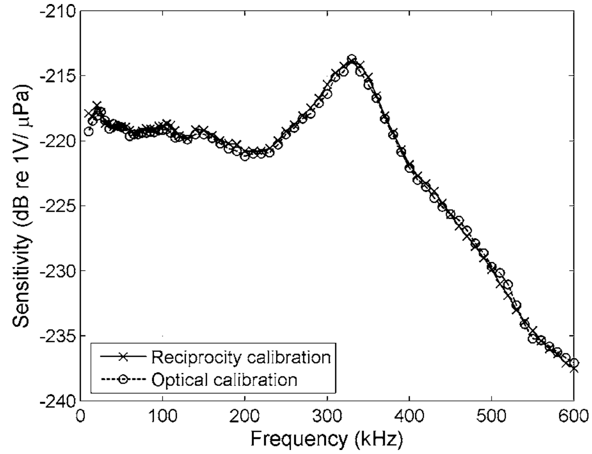

FIG. 4. A comparison of sensitivities for a TC4034 hydrophone obtained by the free-field reciprocity method and the optical method using a 2 mm wide pellicle.

proximately 350 kHz. The hydrophone had previously been calibrated using the method of three-transducer spherical-wave reciprocity.

Three transducers were used as acoustic projectors to cover a frequency range from 10 to 600 kHz: an ITC1042, 25 mm diameter spherical transducer with a resonance frequency of 75 kHz was used for the range 10 to 120 kHz; a 1.5 inc. diameter piston transducer manufactured by Ultran with a resonance frequency of 250 kHz was used for the range 100 to 400 kHz; a 1 inc. diameter piston transducer with a resonance frequency of 500 kHz manufactured by Panametrics was used for the range 300 to 600 kHz. The acoustic projectors were driven with discrete frequency tone-burst signals, with time-gating techniques used to isolate reflections from the tank boundaries. The tone bursts were produced by a HP33120A arbitrary waveform generator and an electronic gating unit, a B&K2713 power amplifier being used with the ITC1042 projector, and a Krohn-Hite 7500 power amplifier being used with the piston transducers. Both amplifiers were set to a 40 dB gain, the maximum peak voltages driving the projectors being 60 V for the ITC1042, 40 V for the 250 kHz piston and 15 V for the 500 kHz piston.

The output voltages for both the vibrometer and the reference hydrophone were captured using a HP89410A vector signal analyzer, after amplification using a Reson VP1000 preamplifier and electronic filtering by a Krohn-Hite 3944 filter. The voltage measurements were performed by measuring the steady-state portion of the tone-burst signals. When using the optical vibrometer, the velocities were calculated using the manufacturer's stated calibration factor of $25\ (\mathrm{mm/s})/\mathrm{V}$.

IV. RESULTS

Figure 3 shows a comparison of waveforms recorded with the optical method and with the hydrophone for an acoustic frequency of 60 kHz. The waveform obtained from the vibrometer has been scaled by the sensitivity setting of the vibrometer to provide a reading of velocity in millimeters per second, whereas the hydrophone waveform is in Volts. The two waveforms compare very well with the arrival of the direct path signal occurring at approximately 0.33 ms and a similar shape to the tone-burst envelope apparent in both signals. For the vibrometer waveform, the reflected signal from the pellicle frame is observed arriving at approximately 0.77 ms (this is absent from the hydrophone waveform since the frame is not in place during the hydrophone measurement).

Figure 4 shows the calibration results obtained using the optical method in the frequency range from 10 to 600 kHz for the TC4034 reference hydrophone. The measurements of acoustic particle velocity were obtained using a 2 mm wide pellicle. Also shown on the plot are data from the calibration of the hydrophone by the three-transducer spherical-wave reciprocity method. Good agreement can be seen between the two methods, and this is highlighted by Fig. 5, where the difference between the results is plotted (the optical results have been subtracted from the reciprocity results to give a positive difference when the reciprocity results are of a higher value). Agreement between the results is better than 0.5 dB over the majority of the frequency range. The overall uncertainty for the free-field reciprocity calibration varies with frequency but is typically of the order of 0.5 dB when

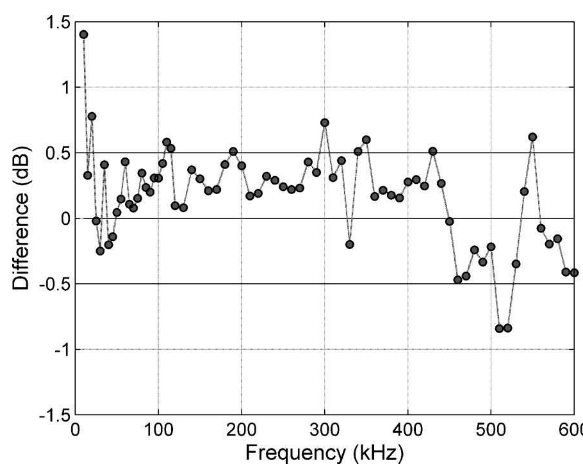

FIG. 5. The difference between hydrophone sensitivity determined using the free-field reciprocity method and the optical method using a 2 mm wide pellicle.

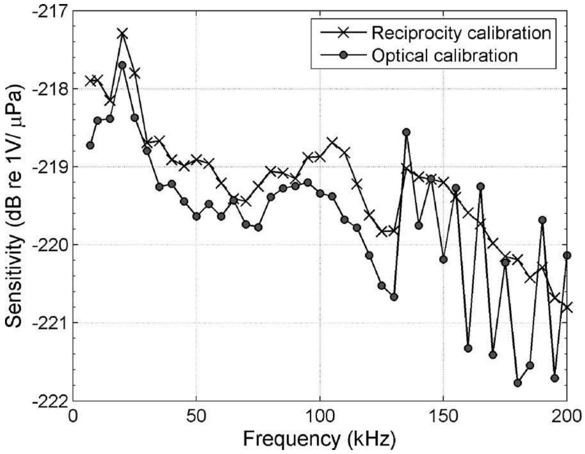

FIG. 6. A comparison of sensitivities for a TC4034 hydrophone obtained by the free-field reciprocity method and the optical method using a 12.6 mm wide pellicle.

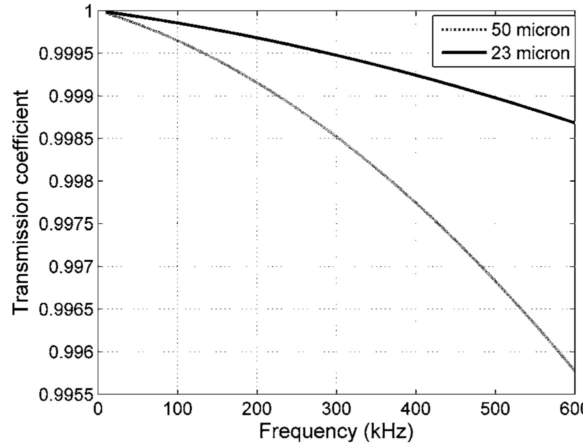

FIG. 7. The results of modeling the pellicle acoustic transmission coefficient for infinite planar membranes of thickness of 23 and 50 μm.

expressed as an expanded uncertainty for a coverage factor of $k=2$. A definitive uncertainty analysis has not yet been completed for the optical method.

Measurements were also performed using a wider pellicle made from a 12.6 mm strip of Mylar© film. Figure 6 shows a comparison of the hydrophone sensitivities for the TC4034 hydrophone obtained using the ITC1042 projector and the 12.6 mm pellicle in the frequency range from 7 to 200 kHz. The low-frequency agreement is again of the order of 0.5 dB or better, but at frequencies greater than about 120 kHz the results from the two methods depart from each other with the results for the optical method showing rapid fluctuations with frequency.

An examination of the results clearly showed that the fluctuations are present in the velocity data measured by the vibrometer (they were not observed in the hydrophone voltage).

The method depends on the pellicle following the motion of the water particles, and if this assumption is violated, inaccuracies will be introduced to the measurements made using the optical method. The material properties and the geometry of the pellicle used may affect the accuracy of the measurements, preventing the pellicle from moving in sympathy with the water particles. An investigation was undertaken into the effect of the pellicle properties on the measurements, and this is described in the next section.

V. DISCUSSION

When using interferometry for the measurement of the movement of a thin membrane in an acoustic field, there are several factors that could contribute to the overall uncertainty of the measurement.

A. Pellicle transmission loss

The measurement of velocity at the pellicle surface is made on the "back surface," i.e., after the acoustic wave has passed through the pellicle. Therefore, any reflection or absorption in the pellicle membrane will influence the measured velocity. The effect of pellicle transmission was investigated by Bacon,[16] and later by Esward and Robinson[19] using an insertion method to experimentally determine the extent of transmission loss at higher frequencies. The transmission losses at frequencies of 10 MHz and more were small but measurable, and allowed a correction to be made when calibrating miniature ultrasonic hydrophones at megahertz frequencies.[17] At the lower frequencies of interest in the work reported here (below 500 kHz), the transmission loss is expected to be negligible. To predict the transmission losses at lower frequencies, a simple layered model was used to represent an infinite water layer, a Mylar© layer, an aluminium layer, and a second infinite water layer.[27] The results of the model agree well with the experimental data from megahertz frequencies where the measurable proportion of the incident sound field is reflected from the membrane.[19] The model prediction for frequencies below 600 kHz are shown in Fig. 7 and are based on a 23 and a 50 μm thick infinite membrane of Mylar© coated with a 40 nm aluminium film and surrounded by water.

The model predictions show that the transmission loss is essentially negligible for a 23 μm membrane at frequencies below 500 kHz. Increasing the thickness of the membrane causes the expected increase in the transmission loss, although this is still very small for a 50 μm membrane at 500 kHz. Note that over this frequency range, such thin pellicles show a monotonic variation in transmission loss with no fluctuations apparent with frequency.

However, this very simple model assumes that the membrane is of an infinite extent and the incident wave is a plane wave. For the NPL primary standard interferometer at megahertz frequencies, this assumption is reasonable. The pellicle used is in the form of a sheet of Mylar© supported by a 100 mm diameter annular ring, and the collimated acoustic fields produced by the piston projectors used pass through the support ring without a significant sound being scattered from the support itself. This type of pellicle was not considered practical for work at the frequencies used here since the support ring would have to be of the order of 1 m or more in diameter to avoid reflected sound from the support ring impinging on the pellicle before acoustic steady-state conditions are achieved. For the work reported here, the pellicle chosen has a finite width, and this can influence the motion of the pellicle in response to the acoustic wave.

B. Pellicle modes

The displacement or velocity of a pellicle or membrane in response to an acoustic field may not always be fully representative of particle movement in the surrounding medium. There is a possibility that pellicle movement is governed by modes excited by the acoustic field. In the case of the pellicle membrane stretched across an annular ring, as used with the NPL primary standard interferometer for megahertz frequencies, the radial modes (the "drum-skin modes") occur at very low frequencies and are in any case heavily damped by the surrounding water. However, Bacon has shown that for certain angles of incidence, the acoustic field may excite Lamb waves in the pellicle membrane.[16]

The pellicle used in this work is in the form of a strip and does not approximate to an infinite plane. The modes of vibration of such a structure will depend on the boundary conditions imposed. The mounting method for the pellicle (see Fig. 2) dictates that the ends are clamped, while the edges of the pellicle can move freely within the medium. To investigate the vibration modes of the pellicle in this configuration, the vibration of the pellicle strip was determined experimentally by scanning the vibrometer beam across the pellicle strip in the water tank shown Fig. 2.

Scans of the vibration profile of the pellicle were performed using the Polytec PSV-3000 scanning vibrometer, consisting of an OFV 056 scanning head and a PSV-Z-040-F control unit. The vibrometer scans the beam across the width of the pellicle by changing the angle at which the laser beam exits the optical aperture of the vibrometer, thus changing the angle of the optical beam subtended to the pellicle surface. This deviation of the laser beam from the central axis of the pellicle could potentially lead to an error since the vibrometer measures the component of velocity along the axis of the optical beam. A correction is therefore applied for the cosine of the angle at which the laser beam is incident on the pellicle surface. The incident angle of the optical beam with the pellicle was minimized by maximizing the standoff distance of the vibrometer from the pellicle, thus reducing this effect. This also minimizes any acousto-optic influences due to the incident and reflected optical beams traversing slightly different paths. A number of different pellicle widths were investigated using the same experimental arrangement as that used for the hydrophone calibration measurements. Figure 8 shows the velocity magnitude obtained for a one-dimensional line scan across the width of a 5 mm pellicle. The spatial scan resolution of the vibrometer limited the number of scan points that could be obtained across the 5 mm width of the pellicle.

The line profiles shown in Fig. 8 clearly show the presence of modes across the width of the pellicle at certain frequencies. Due to the limited spatial resolution of the scans, it is not possible to be certain about the wavelength of a given mode at, say, 250 kHz, where it appears that approximately one wavelength occurs across the 5 mm width of the

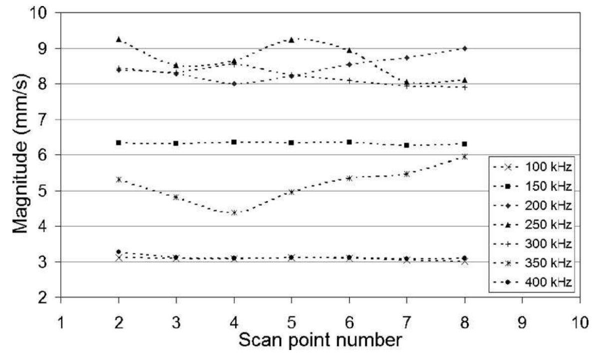

FIG. 8. Velocity magnitude obtained for a one-dimensional line scan across the width of a 5 mm pellicle at selected frequencies in the range 100 to 400 kHz.

pellicle since it is impossible to exclude the possibility of aliasing. The results do, however, show that modes do exist and that they are a function of frequency. There appears to be very limited variation across the 5 mm wide pellicle at 100, 150, and 400 kHz, but significant velocity variation across the pellicle between 250 and 350 kHz. The presence of these modes could lead to uncertainties in the hydrophone calibration using the optical method and are believed to be the reason for the fluctuations above 120 kHz observed in the optical calibration data shown in Fig. 6.

C. Other sources of error

Other sources of error in the method include the presence of signals due to the acousto-optic interaction in addition to the signals due to the pellicle movement. The rate of change of the refractive index along the optical pathlength can give rise to signals that are effectively interpreted as velocities by the vibrometer. This effect is exploited in configurations where the optical beam and acoustic beam are arranged to be orthogonal, as in the work of Harland.[14] The configuration for the work reported here is designed to measure only the pellicle movement, but if the laser beam subtends an angle to the direction of acoustic propagation, there may be some component of the signal due to the refractive index variation along the optical beam, leading to an error in the measurement of pellicle velocity.

Due to the specular reflecting properties of the pellicle, the optical beam can be aligned very precisely with the pellicle. However, alignment of the optical beam or the pellicle with the acoustic beam is more difficult. For spherical projectors, this problem is solved by first aligning the optical beam on the acoustic center of the projector and then inserting the pellicle into the path of the optical beam, ensuring that the acoustic beam and the pellicle are both aligned with the optical beam. For flat-faced piston-type projectors where the acoustic beam is produced at a normal incidence to the face of the projector, the small component of the optical beam reflected from the surface of the projector can be used to aid in alignment. However, the optical scattering produced at the surface of the transducer may give rise to a small angular error. The work of Bacon has shown the error in a hydrophone calibration to be insignificant for a small angular error of around 0.5°.[28]

One difficulty when using a commercial vibrometer is that of reliance on the calibration of the instrument, for example, reliance on the 25 (mm/s)/V setting on the Polytec system used for much of the work described here. For use in metrology, the instrument calibration must be traceable. As described in Sec. II, the velocity is dependent on the Doppler shift of the optical frequency, which in turn is traceable to standards of length via the laser wavelength. However, a vibrometer requires the Doppler shift to be converted to a voltage proportional to the velocity if a time-resolved signal is to be derived, and this typically requires the use of frequency mixing, filtering, and phase-lock loop circuitry.[25] The errors introduced by this signal processing are crucial in governing the absolute accuracy of the vibrometer, and for the most accurate work, the signal processing circuitry should be carefully characterized. Since this is not easy to do for a "black-box" commercial unit, it is necessary to design a custom-made vibrometer where each stage of the system can be characterized independently.[26]

VI. CONCLUSIONS

A novel technique for the absolute calibration of hydrophones in water using an optical method based on laser vibrometry has been presented. The method relies on the use of a thin plastic pellicle that is used to reflect the signal beam of a commercial laser vibrometer, the pellicle being thin enough to be acoustically transparent at the frequency of interest. The pellicle motion is taken to represent the acoustic particle velocity in the medium. The hydrophone response to a known acoustic field is measured and the hydrophone sensitivity derived. Results have been presented of the calibration of a reference measuring hydrophone over the frequency range 10 to 600 kHz. Excellent agreement has been achieved with the classic method of three-transducer spherical-wave reciprocity, with agreement to better than 0.5 dB over the majority of the frequency range.

An initial discussion of some of the sources of uncertainty has been presented. In particular, the influence of the properties of the pellicle has been the subject of preliminary study, both experimentally and theoretically. This has shown that the modes of vibration of the pellicle strip used can significantly degrade the accuracy of the results. However, if the pellicle is made sufficiently narrow the resonant modes are forced above the measurement frequency of interest, allowing accurate measurements to be performed. The method has been shown to offer the potential for a new primary standard method, with the calibration traceable to standards of length measurement through the wavelength of the laser light. More extensive studies are required to assess the sources of uncertainty before definitive conclusions can be drawn as to the accuracy.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support of the UK Department of Trade & Industry (National Measurement System Directorate).

[1] R. J. Urick. *Principles of Underwater Sound*, 3rd ed. (McGraw-Hill, New York, 1983).
[2] R. J. Bobber, *Underwater Electroacoustic Measurements*, 2nd ed. (Peninsula Press, Los Altos, 1988).
[3] W. R. Maclean, "Absolute measurement of sound without a primary standard," J. Acoust. Soc. Am., **12**, 140–146 (1940).
[4] IEC 565, The Calibration of Hydrophones, International Electrotechnical Commission, Geneva, Switzerland, 1977.
[5] L. E. Kinsler and A. R. Frey, *Fundamentals of Acoustics* (Wiley, New York, 1982).
[6] R. J. Bobber, "General reciprocity parameter," J. Acoust. Soc. Am. **39**, 680–687 (1966).
[7] K. J. Taylor, "Absolute measurement of acoustic particle velocity," J. Acoust. Soc. Am., **59**, 691–694 (1976).
[8] K. J. Taylor, "Absolute calibration of microphones by a laser Doppler technique," J. Acoust. Soc. Am. **70**, 939–945 (1981).
[9] T. MacGillivray, D. Campbell, C. Greated, and R. Barham, "The development of a microphone calibration technique using laser Doppler anemometry," Acta. Acust. Acust. **88**, 135–141 (2002).
[10] P. S. Dubbleday and H. C Shau, "Laser Doppler anemometry detection of hydroacoustic particle velocity," J. Acoust. Soc. Am. **86**, 891–894 (1989).
[11] R. I. Crickmore, S. H. Jack, D. B. Hann, and C. A. Greated, "Laser Doppler anemometry and the acousto-optic effect," Opt. Laser Technol. **31**, 85–94 (1999).
[12] A. R. Harland, J. N. Petzing, and J. R. Tyrer, "Non-invasive measurements of underwater pressure fields using laser Doppler velocimetry," J. Sound Vib. **252**, 169–177 (2002).
[13] T. A. Pitts and J. F. Greenleaf, "Three-dimensional optical measurement of instantaneous pressure," J. Acoust. Soc. Am. **108**, 2873–2883 (2000).
[14] A. R. Harland, J. N. Petzing, and J. R. Tyrer, "Nonperturbing measurements of spatially distributed underwater acoustic fields using a scanning laser Doppler vibrometer," J. Acoust. Soc. Am. **115**, 187–195 (2004).
[15] C. B. Scruby and L. E. Drain, *Laser Ultrasonics* (Adam Hilger, Bristol, 1990).
[16] D. R. Bacon, "Primary calibration of ultrasonic hydrophones using optical interferometry," IEEE Trans. Ultrason. Ferroelectr. Freq. Control **35**, 152–161 (1988).
[17] R. C. Preston, S. P. Robinson, B. Zeqiri, T. J. Esward, P. N. Gelat, and N. D. Lee, "Primary calibration of membrane hydrophones in the frequency range 0.5 MHz to 60 MHz," Metrologia **36**, 331–343 (1999).
[18] D. R. Bacon, R. C. Chivers, and J. N. Som, "The acousto-optic interaction in the interferometric measurement of ultrasonic transducer surface motion," Ultrasonics **31**, 321–325 (1993).
[19] T. J. Esward and S. P. Robinson, "Extending the frequency range of the National Physical Laboratory primary standard laser interferometer for hydrophone calibrations to 60 MHz," IEEE Trans. Ultrason. Ferroelectr. Freq. Control **46**, 737–744 (1999).
[20] C. Koch and W. Molkenstruck, "Primary calibration of hydrophones with extended frequency range 1 to 70 MHz using optical interferometry," IEEE Trans. Ultrason. Ferroelectr. Freq. Control **46**, 1303–1314 (1999).
[21] W. Yuebing and H. Yongjun, "Calibration of hydrophones using an optical technique," Acta Acust. (Beijing) **26**, 29–33 (2001).
[22] W. Yuebing, "The application of optical interferometry in the measurement of hydrophones," *Proceedings of the Institute of Acoustics*, 2003, Vol. **25**.
[23] A. R. Harland, J. N. Petzing, C. Bickley, S. P. Robinson, J. R. Tyrer, and R. C. Preston, "Application and assessment of laser Doppler velocimetry for underwater acoustic measurements," J. Sound Vib. **265**, 627–645 (2003).
[24] P. D. Theobald, C. J. Bickley, and S. P. Robinson, "Recent progress at NPL in the use of optical techniques for hydrophone calibration," *Proceedings of the Institute of Acoustics*, 2003, Vol. **25**.
[25] P. D. Theobald, S. P. Robinson, A. D. Thompson, R. C. Preston, P. Lepper, W. Yuebing, C. Swift, and J. Tyrer, "Fundamental standards for acoustics based on optical methods—Phase two report for sound in water," NPL Report CAIR 3, 2002.
[26] P. D. Theobald, A. D. Thompson, S. P. Robinson, R. C. Preston, P. Lepper, W. Yuebing, C. Swift, and J. Tyrer, "Fundamental standards for acoustics based on optical methods—Phase three report for sound in water," NPL Report CAIR 9, 2004.
[27] L. M. Brekhovskikh, *Waves in Layered Media*, 2nd ed. (Academic, New York, 1980).
[28] D. R. Bacon, "The improvement and evaluation of a laser interferometer for the absolute measurement of ultrasonic displacements in the frequency range up to 15 MHz," NPL Report Ac 109, 1986.