Providing primary standard calibrations beyond 20MHz

C J Bickley, B Zeqiri and S P Robinson

National Physical Laboratory, Teddington, Middlesex, United Kingdom

Abstract. The number of applications of medical ultrasound utilising frequencies in excess of 20 MHz has shown a consistent increase over recent years. Coupled with the commercial availability of wide-bandwidth hydrophones whose response extends beyond 40 MHz, this has driven a growing need to develop hydrophone calibration techniques at elevated frequencies.

The current National Physical Laboratory primary standard method of calibrating hydrophones is based on an optical interferometer. This has been in operation for around 20 years and provides traceability over the frequency range of 0.3 to 20 MHz. More recently, calibrations carried out using the interferometer have been extended to 60 MHz, although the uncertainties associated with these calibrations are poor, being in excess of ±20% at high frequencies. Major contributions to the degraded calibration uncertainties arise from poor signal-to-noise at higher frequencies, the frequency response of the photodiodes used and the noise floor of the instrument.

To improve the uncertainty of hydrophone calibrations above 20 MHz, it has been necessary to build and commission a new interferometer. Important features of the new primary standard are its use of a higher power laser to improve the signal-to-noise ratio, along with photodiodes whose greater bandwidth to improve the overall frequency response.

This paper describes the design of key aspects of the new interferometer. It also presents some initial results of the performance assessment, including a detailed comparison of calibrations of NPL reference membrane hydrophones, undertaken using old and new interferometers for calibration up to 40 MHz.

1. Introduction

The current NPL laser interferometer has been the primary standard for hydrophone calibration at frequencies greater than 500 kHz since 1985 [1]. The interferometer was initially designed to calibrate hydrophones up to a frequency of 15 MHz, but in time this was extended to 20 MHz [2]. With a modification to the measurement procedure, the technique was eventually extended to 60 MHz, though with considerably degraded uncertainties [3]. With the increase in the number of applications in medical ultrasound that utilise frequencies in excess of 20 MHz over recent years, there is a need for more accurate high frequency calibrations. This has led NPL to investigate the possibility of developing an improved interferometer with a better performance, enabling significantly improved signal-to-noise ratios to be achieved at the higher frequencies.

2. Operation of the interferometer

The method used for performing primary standard calibrations has been described in detail previously [1] so only a brief outline summary will be presented here. The acoustic field produced by a transducer is detected by a thin plastic membrane (a pellicle), which is coated on one side with gold, rendering it optically reflective. The pellicle is thin enough (3.5 or 5.0 µm of Mylar coated with 25 nm of gold) to be acoustically transparent and to follow the motion of the acoustic wave. The displacement of the...
pellicle is measured using the interferometer, and the acoustic pressure calculated. The hydrophone is
then substituted for the pellicle with the acoustic centre of the hydrophone positioned at the same point
in the acoustic field that has been interrogated by the laser beam. The hydrophone then is calibrated by
measuring the output voltage corresponding to the known acoustic pressure.

For frequencies up to 20 MHz measurements are made using a single frequency technique in the far
field of a plane-piston transducer. This utilises tone-bursts, whose pressure amplitude has been limited
to ensure there is negligible nonlinear distortion of the acoustic waveform generated. These
measurements typically have expanded uncertainties around ±4% expressed for a confidence level of
95%. In order to extend the frequency range of calibrations above 20 MHz, calibrations cannot be
carried out using this linear, low-amplitude, method due to the difficulties in generating significant
pressures in the transducer far-field. Instead, calibrations are carried out using focussed transducers
which have been driven sufficiently hard to generate significant pressures at higher frequencies
through the process of nonlinear propagation. By carrying out calibrations at the focus of a 5 MHz
focussed transducer driven in bursts containing 10–15 cycles, acoustic signals are generated at
multiple harmonics of 5 MHz up to and beyond 60 MHz. Whilst the use of the focussed transducer,
nonlinearly distorted method makes it possible to calibrate hydrophones, due to the very small
displacements generated, typically less than 0.1 nm at 60 MHz, and the poor response of the
interferometer, expanded uncertainties are much larger using this technique, exceeding ±20% at
60 MHz.

3. Transition to the new interferometer

The main limitation of the existing interferometer lies in its high frequency performance which is
governed both by the frequency response of the system and its noise performance. A number of the
components of the interferometer have been identified as limiting the performance.

![Figure 1. Schematic diagram of the old interferometer](image)

The Pockels cell has 2 functions, firstly to split the light between the reference and signal beams
and also to introduce large phase shifts to the reference beam to compensate for low frequency
vibrations. This component limits the performance in a number of ways. The reference beam is power
limited to 5% of the input power leading to a signal beam with greater power rather than the desired
50-50 split. It also has a limited maximum input preventing a higher power laser being used. Whilst
the current Pockels cell has worked well these units are prone to failure and difficult to repair.

In the new interferometer, the low-frequency compensation is achieved using an
electro-mechanical shaker, which moves the reference beam mirror. A polarising beam splitter is used
to create the reference beam, which can be divided evenly to obtain better fringe visibility. The
balance between the signal and reference beams is controlled through a half-wave plate.
Without the limitations imposed by the Pockels cell it was also possible to increase the laser power used from a 5 mW HeNe laser to a 150 mW frequency doubled Nd:YAG laser. As photon noise was the limiting noise source for the old interferometer this increase in laser power will improve the noise performance.

The frequency response of the interferometer was limited by the response of the avalanche photodiodes. The response of these diodes has been shown to roll off above 15 MHz [4][3]. The new interferometer uses simple silicon photodiodes which have a much flatter frequency response to frequencies in excess of 60 MHz. Whilst these diodes are less sensitive than the avalanche diodes this is compensated for in the much higher light levels employed.

**Figure 2.** Schematic diagram of the new interferometer

### 4. Performance of the new interferometer

Measurements of the noise performance of the two interferometers under normal operating conditions were made using a spectrum analyser.

**Figure 3.** Comparison of the noise equivalent displacements of the two interferometers
Figure 3 shows the noise equivalent displacements for the two interferometers measured using a bandwidth of 150 MHz. The noise floor of the new interferometer is at least 4 times lower than the old interferometer. The decrease in the noise equivalent displacement of the old interferometer at higher frequencies is due to the lower sensitivity of the interferometer at these frequencies. The shape of the noise response gives an indication of the frequency response of the interferometer. Since the noise in the interferometer is predominantly photon noise, the response of the old interferometer falls away above about 10 MHz whereas the new interferometer appears to have a much flatter response. The response of the new interferometer will be evaluated accurately using an opto-mechanical method from 1 kHz to 100 MHz.

Using these noise measurements, it is also possible to calculate the minimum displacement the interferometer is capable of measuring. At 60 MHz for the old interferometer the minimum displacement was approximately 0.06 nm requiring a pressure of approximately 30 kPa. For the new interferometer the equivalent figures are 0.01 nm and 5 kPa.

5. Preliminary hydrophone calibrations

To evaluate check the performance of the new interferometer a comparison was made of calibrations performed on the same hydrophone using both interferometers. The hydrophones used for this process were Marconi membrane devices and had been used as reference hydrophones devices at NPL over many years.

Figure 4 shows calibration values for a 1 mm active element bilaminar hydrophone. The error bars indicate the expanded uncertainty of the old interferometer calibration \( (k=2) \). The uncertainties of calibrations derived using the new interferometer are still being assessed, so the equivalent analysis for the new interferometer is not yet available. The agreement at all frequencies is within \( \pm 3 \% \).
Figure 5 compares a calibration of a 0.5 mm active element coplanar membrane hydrophone with a preliminary calibration using the new interferometer. The uncertainty bars on the old interferometer data indicate the expanded uncertainty of the calibration. Uncertainty bars for the new interferometer are only the Type A (random) uncertainty from 4 repeat measurements, as the analysis of the Type B (systematic) uncertainties is in progress. The Type A uncertainties for the new interferometer, gradually degrade from 3% at 10 MHz to 6% at 60 MHz, which is considered to be acceptable. It was not possible to calibrate this hydrophone above 50 MHz using the old interferometer, due to the poor signal-to-noise. Between 10 and 50 MHz the average agreement between the 2 interferometers is approximately ±5%. The higher value for the calibration of the hydrophone sensitivity at 5 MHz using the new interferometer was possibly due to saturation of one of the interferometer amplifiers.

6. Conclusions
A new interferometer has been designed and built which will eventually replace the existing NPL primary standard for hydrophone calibration. Part of the rationale in developing the new interferometer lay in the need to improve the signal-to-noise performance at elevated frequencies (above 20 MHz), allowing lower uncertainty calibrations to be carried out up to 60 MHz. This improvement has been realised primarily through the use of a new, higher power laser, along with the application of greater bandwidth photodiodes which have enhanced the overall frequency response. Initial tests, undertaken as part of an extensive validation process, have shown that the noise equivalent displacement of the new interferometer is at least four times lower than that of the old interferometer and that the frequency response is flatter to frequencies in excess of 60 MHz. Preliminary calibrations of two membrane hydrophones have shown good agreement between sensitivity values obtained with the new and old interferometers. A detailed evaluation of the performance of the new primary standard continues.

References
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