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Validation of Reflectance-based Fiber-Optic Hydrophones

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ABSTRACT

Reflectance-based fiber-optic hydrophones are frequently used for high pressure ultrasound measurements. Often, damage to the fiber forces the user to re-cleave the fiber-top, necessitating a means of re-validating the calibration over a broad frequency range. A previous study proposed a validation method utilizing a stable, calibrated pulse ultrasound source operating at moderate diagnostic levels (about 6 MPa pk-pk.). This presentation will briefly review this approach, adding new results in support of the overall calibration scheme: (a) comparison of the calibration-check from the pulsed source to a conventional swept-frequency substitution method of calibration (b) recent experimental measurements of the effective aperture from 2 to 15 MHz (c) recently compiled long-term stability data for a proposed implementation of the pulsed check-source.

Keywords: optical, hydrophone, calibration

1. INTRODUCTION

Reflectance-based fiber-optic hydrophones (FOHs) are widely used for the measurement of HIFU and lithotripsy fields, primarily because they are easily repairable by a user simply re-cleaving the fiber tip whenever it is damaged. These devices work by measuring changes in the optical intensity reflection coefficient at the tip of a glass fiber immersed in water, due to the pressure dependence of water's refractive index [1].

The theory of operation of FOHs has been extensively described before [1-3]. Fig. 1 shows a sketch of an FOH. An optical fiber is cleaved and the bare tip is immersed in water. An incident acoustic pressure wave changes the index of refraction of both the water and (to a lesser extent) the glass at the tip. The change in reflected light is recorded as a change of voltage by the photoamplifier, which typically has both DC and AC output circuits (which we can denote as V_{DC} and V_{AC} (t)) and a specified relative Gain between the two.

If $\delta R(t)$ denotes the variation in the reflection coefficient of optical intensity,

$$\delta R(t)/ R_0 = [G V_{AC}(t) / (V_{DC} - V_0)] \qquad (1)$$

where V_{DC} is the voltage output of the photoamplifier under quiescent conditions (i.e., no acoustic wave is incident) and R_0 is the optical intensity's reflection coefficient under ambient temperature and pressure. The term V_0 accounts for stray light and is measured by an initial measurement with the fiber's tip immersed in a fluid which has an optical index matched to glass or, alternatively, in a series of fluids with refractive index close to glass, followed by a fitting procedure.Thus, two or more initial static measurements, one in water and at least one in an index-matched fluid, are sufficient to normalize further measurements of the voltage output to calculate the fractional change in reflection coefficient $\delta R(t)/ R_0$ in Eq. (1).

For a typical multi-mode fiber, the optical reflection coefficient may be calculated assuming an optical plane wave impinging normally on the glass-water interface, and may therefore be readily calculated from the index of optical refraction for water and of the glass of the fiber. As these material properties of glass and water are well-known functions of temperature and pressure, it is therefore possible to invert these functions to determine the pressure at the tip at a given ambient temperature, taking into account the non-linear aspects of water [3,4].

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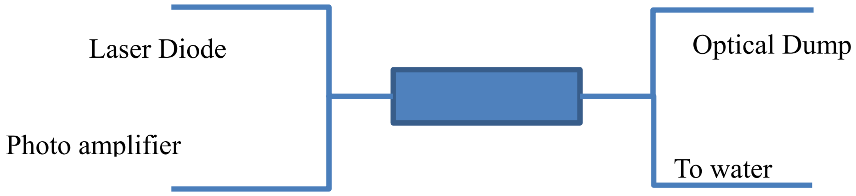

Figure 1 Schematic of a Reflectance-based Fiber-Optic Hydrophone

The pressure at the fiber tip is a superposition of the free-field pressure and the wave diffracted at the tip, and it is therefore necessary to correct for the diffracted wave in order to determine the free-field pressure of an incident wave. As this effect is frequency-dependent, a deconvolution procedure is necessary, utilizing a “deconvolution kernel” which accounts for both the magnitude and phase of the diffraction over a wide bandwidth (usually > 50 MHz) because of the high-frequency harmonics usually present in the incident pressure waveform. Because of the difficulty of direct measurement, the deconvolution kernels have often been based on a model. To first order the deconvolution kernel may be modeled by utilizing classical formulas for the average pressure from a normally incident wave scattered by a rigid cylinder [2]. A further refinement accounted for the fact that the fiber averages the pressure only over its optical core, obtaining the deconvolution kernel from a closed-form integral [5]. A more recent refinement accounted for the elasticity of the fiber by calculating the diffraction kernel from a Finite Element Analysis (FEA), obtaining good experimental agreement with results measured with a membrane hydrophone [3].

Calibration has therefore usually assumed that a previously validated calibration (whether experimentally or from a model) is still valid, even after a fiber has been re-cleaved. To address this concern, we previously proposed the use of a “Pulsed Check Source” (PCS) as a broadband check of the accuracy of an FOH, obtaining good experimental agreement between an FOH and a calibrated membrane hydrophone [3] when 8192 averages are performed to filter out noise from an Onda PCS-1000. Figure 2 shows a comparison of the deconvolved averaged FOH waveform to the membrane hydrophone. Fig. 3 shows the corresponding spectral comparison.

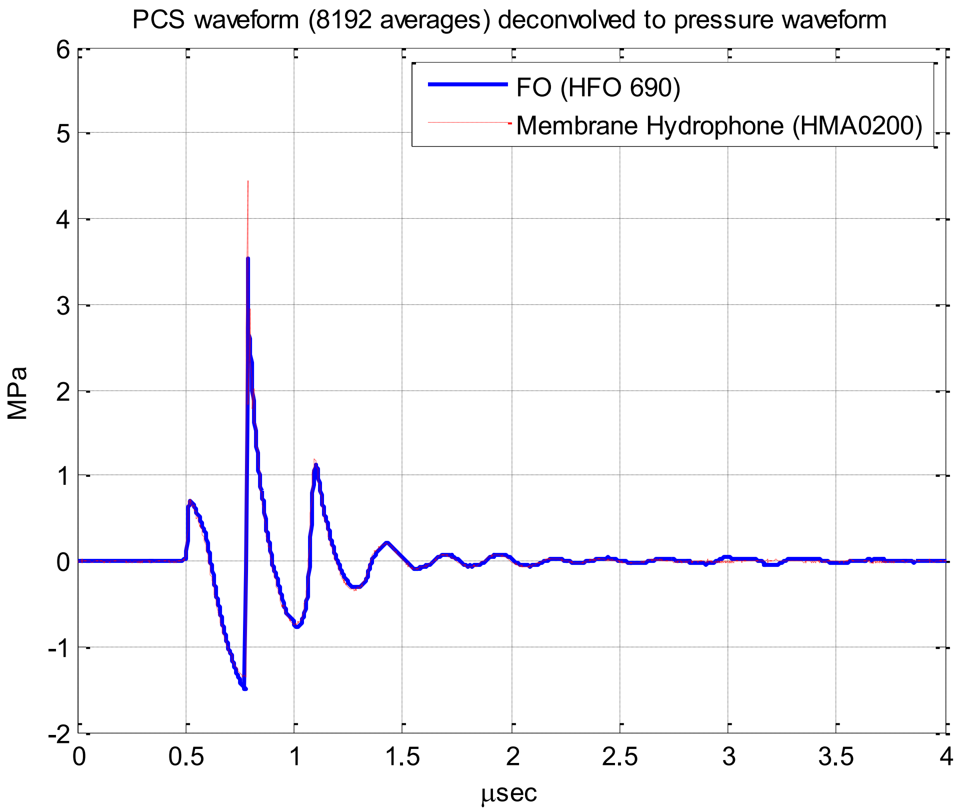

Figure 2 PCS waveform

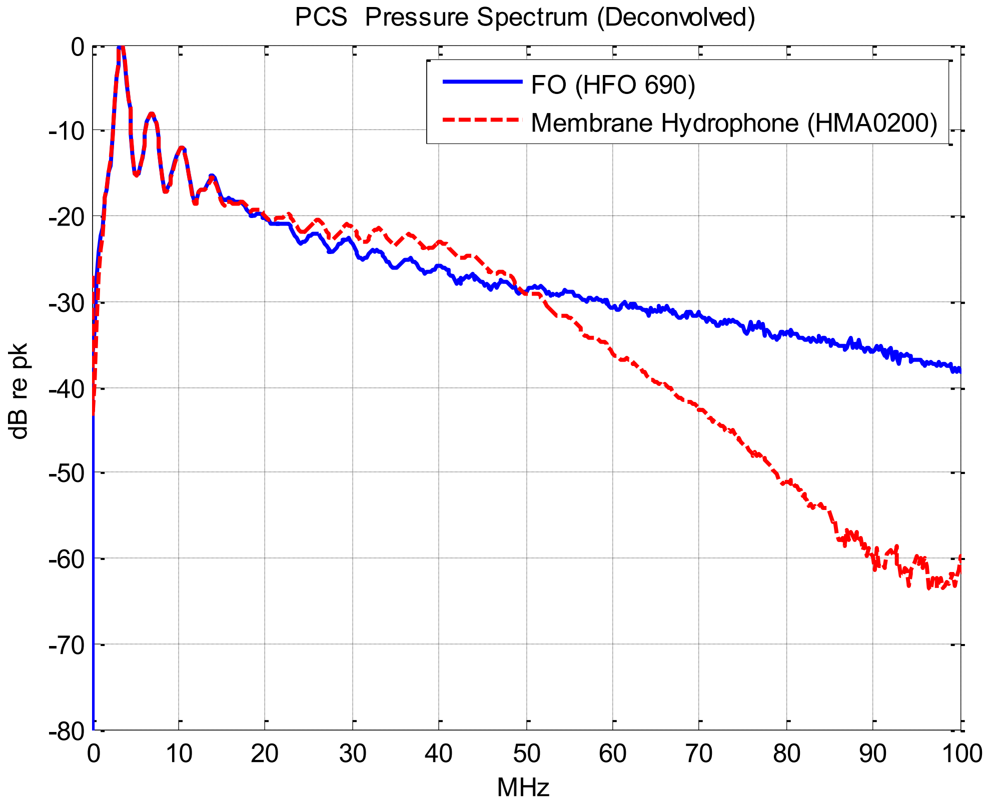

Figure 3 PCS Spectrum

The present paper validates this concept further, with the following results:

- comparison of the calibration-check from the pulsed source to a conventional swept-frequency substitution method of calibration
- recent experimental measurements of the effective aperture from 2 to 15 MHz
- recently compiled long-term stability data for a proposed implementation of the pulsed check-source

2. Comparison Between PCS Measurement and Swept-Frequency Calibration

Most conventional hydrophone calibration schemes employ pressure amplitudes that are relatively low for the typical FOH. The Onda HFO-690, for example, has sensitivity of around 7 mV/MPa and a noise equivalent pressure (NEP) of about 0.5 MPa for 100 MHz bandwidth. Calibration therefore requires extensive averaging and therefore good stability over time in a calibration setup. Recently, the sensitivity of an Onda HFO-690 was measured in Onda's standard swept-frequency calibration setup, in the range of 1-20 MHz. The setup utilizes a 2.54 cm diameter F/10 broadband PVDF transducer, as described in [6]. The transducer was driven with a 60 micro-second tone-burst while the frequency was stepped from 1 MHz to 20 MHz in increments of 50 kHz. Pressures varied from approximately 40 kPa to 110 kPa throughout the frequency range. An Onda HMA0200 piezopolymer membrane hydrophone, which was calibrated at National Physical Laboratory (UK) was placed in the tank as a reference in order to determine the frequency-dependent sensitivity of the HFO-690, following procedures described in [7]. Fig. 4 shows a comparison between the swept-frequency calibration, the theoretical FEA-based calibration of the hydrophone, and the sensitivity prediction based on the pulsed check source following the method of [3] Excellent agreement was obtained between the three methods below 20 MHz, where the HMA calibration is expected to be most accurate. The discrepancies above 20 MHz may be due to errors in the model, in the HMA calibration or in the PCS measurement (e.g., spatial averaging effects). It is planned to extend the range of conventional calibration of the HFO-690 by using the harmonic comparison method per [7] with an unfocused source; hopefully this will provide insight into this question.

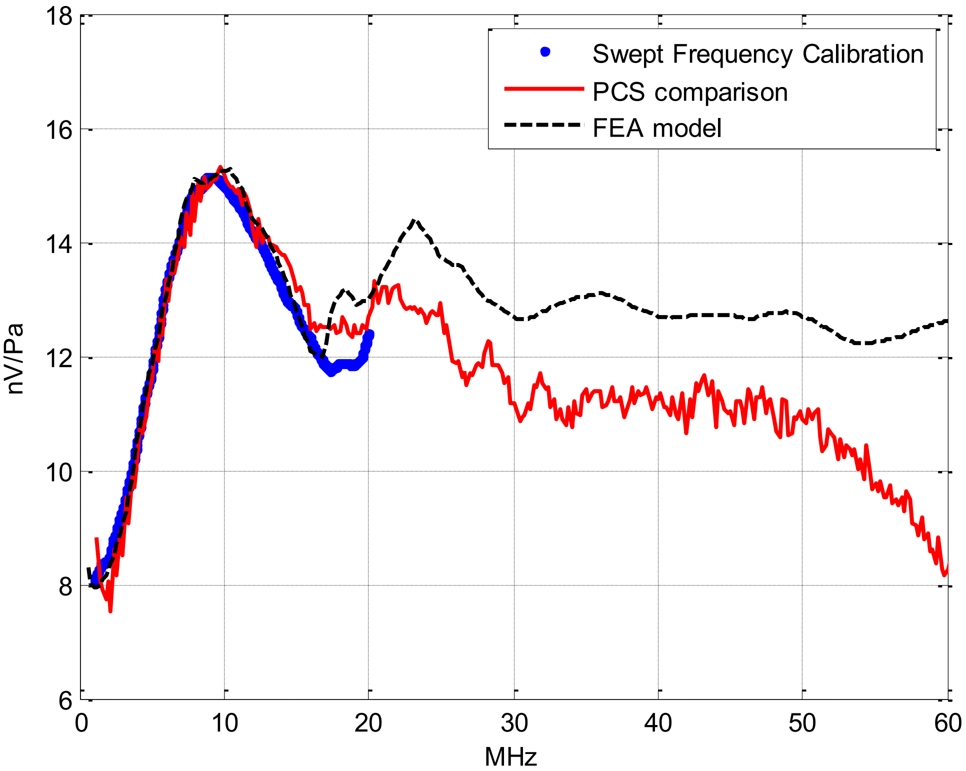

Figure 4: HFO-690 sensitivity from theoretical calibration compared to check with PCS, and to swept-frequency calibration

3. Measurements of Directivity and Effective Aperture

The setup used for swept-frequency calibration was also used to perform directivity measurements of the HFO-690. Results were previously reported in [8] and will therefore only be summarized here. Measurements were performed over +/- 90 degrees at 2.25, 3.5, 5, 7.5, 10, and 15 MHz. Several models were evaluated to find the effective radius a_{eff} which best fit the data at each frequency. The first model evaluated was the standard "Jinc" function [7]:

$$D_{RB}(k,\theta) = 2J_1(ka_{eff}\sin(\theta))/ka_{eff}\sin(\theta) \quad (2)$$

which corresponds to a rigid baffle (RB) assumption for the fiber, and where θ = angle of incidence, $k = 2\pi / \lambda$, λ = wavelength, and a_{eff} = the effective radius of the hydrophone sensitive element. The value of a_{eff} was chosen by minimizing the mean square difference between the model and the data. As frequency increased, the best-fit result for a_{eff} converged to the geometric radius of the fiber core (designated as a_g and equal to 52.5 micro-meters). However, at lower frequencies a_{eff} became much larger than a_g for the RB model of Eq. (1). Additional models were evaluated: (i) an "unbaffled model" (UB) where the standard Jinc function is multiplied by a factor of (1+cos(θ))/2 (ii) a "soft baffled" (SB) model where the Jinc function is multiplied by a factor of cos(θ) and (iii) a "rigid piston model" (RP), which is provided as an integral formula in [5] and was evaluated numerically. As shown in Fig. 5, the RP model corresponds to a consistent effective radius close to the nominal value. It is expected that this is because it provides the most physically realistic representation of the boundary conditions.

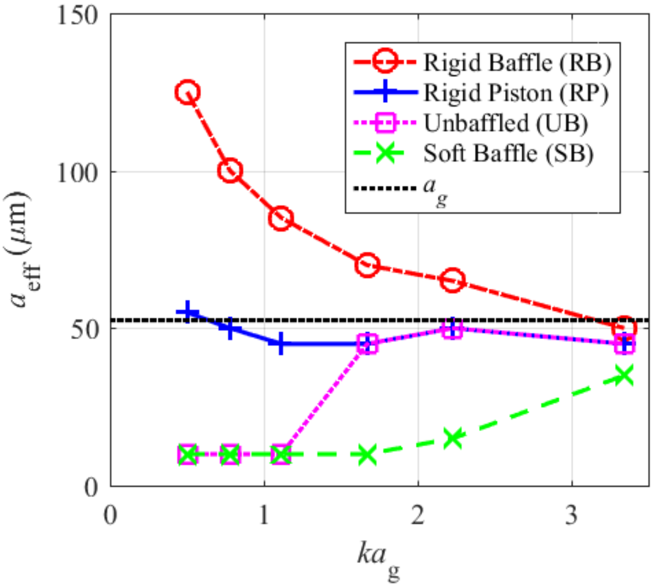

Figure 5 – Effective radius based on fit to different directivity models

4. Stability of the Pulsed Check Source

Previous work [9] has summarized the short-term repeatability and stability of the PCS-1000 pulsed check source. Temperature stability of output power is within 0.4% per deg C in the 19 deg C to 25 deg C temperature range, and variations in hydrophone measurements are primarily due to variations in alignment, which typically result in a few percent of variation.

Figure 6 shows the long-term stability of a PCS-1000, by plotting the output powers over ten years of time for a typical unit. Periodic measurements made with a radiation force balance (RFB) at Onda are shown, along with measurements at the German National Laboratory PTB. There is a long-term ageing effect on the order of one to two percent over the course of the first two to three years, which then slows down, although this trend is within measurement uncertainties.

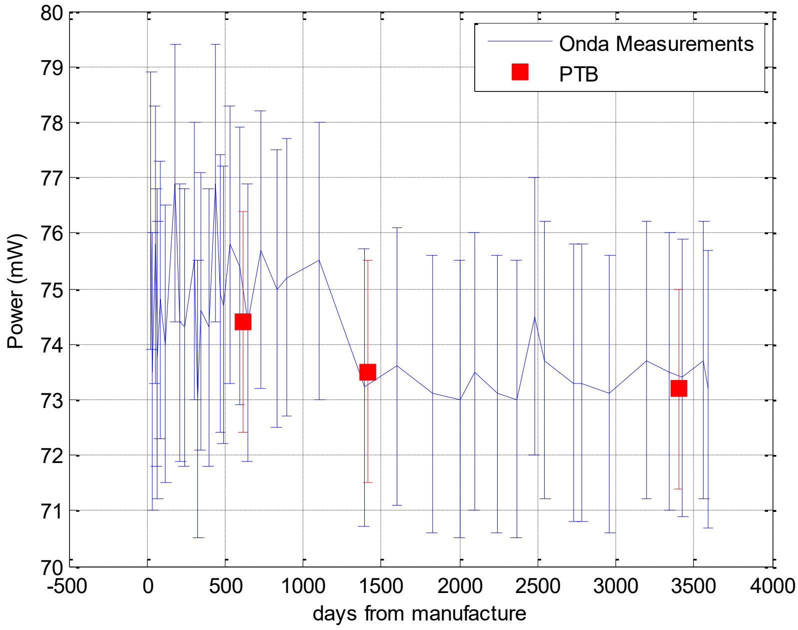

Figure 6 – Power output over time for a typical PCS-1000, with error bars

5. Conclusions

The results presented here further validate the theoretical model used to calibrate the HFO-690 fiber-optic hydrophone. In addition, the PCS-1000 pulsed check source has been shown to provide a consistent, stable check for the HFO-690.

Further work is planned to check the theoretical model by performing harmonic calibrations to higher frequencies.

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