Voltage to Pressure Conversion: Are you getting “phased” by the problem?

by

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Abstract

The process of calibration provides the user with the sensitivity data necessary to convert the voltage measured at the end of the hydrophone cable to an acoustic pressure. This paper addresses the precise nature of how this data is used. Most regulatory standards simply require the user to use the sensitivity figure at the acoustic working frequency of the source in conjunction with a known (or pre-specified) “flatness” criterion for the overall frequency response. This paper questions the validity of this approach, and looks at the differences that can be obtained when the voltage to pressure conversion is accomplished by means of a deconvolution process that utilises all of the frequency response curve (as opposed a single data point). Theoretical and experimental comparisons between single frequency and full waveform deconvolution are presented.

Currently, hydrophone calibration is a magnitude only measurement, but metrological improvements offer the possibility for measurement of hydrophone phase. As a logical extension to waveform deconvolution, the influence of phase response and the impact that this has on measured data is also presented. Clearly the proposed methods require greater computation during the measurement process, but this does not necessarily require longer measurement. This paper discusses practical methods of implementing these enhanced voltage to pressure conversion techniques in a commercial environment.

Introduction

Hydrophones return a voltage that is proportional to the spatial average of acoustic pressure experienced at the active element. The constant of proportionality (hydrophone sensitivity/frequency response) is determined through a calibration process and is typically obtained over a range of frequencies. However the hydrophone sensitivity is rarely constant as a function of frequency as well as being a complex valued. Historically, hydrophone calibrations have only determined the magnitude of the frequency response. However recent developments at the PTB (Braunschweig, Germany) by Koch (2003) allow the phase response of a hydrophone to be determined, and a phase calibration service is also being developed by NPL (London, UK). Given that a thorough description of a hydrophone’s sensitivity function is now available, the question “How best should this calibration data be used?” is raised.
This paper starts by discussing the current method for converting hydrophone voltage to acoustic pressure, and identifies the limitations of this approach. An alternative method (full waveform deconvolution) is discussed and some demonstrative using both needle and membrane hydrophones are presented to show the metrological improvement that this new method provides.

The Current Procedure and its Limitations

The current method adopted in both IEC (1991) and AIUM/NEMA (1998) standards is to approximate acoustic pressure waveform $p(t)$ from the measured hydrophone voltage $V(t)$ according to the equation

$$p(t) = \frac{V(t)}{M(f_{awf})}$$

where $M(f_{awf})$ is the hydrophone sensitivity at the acoustic working frequency (AWF). This technique is only appropriate when the hydrophone sensitivity has very little variation as a function of frequency or when the source is very narrow band. Consequently both standards introduce conditions that define how much variation is allowed in the frequency response. In order to meet this “flatness criterion” it has become common practice to use membrane hydrophones in combination with matching/filter amplifiers to flatten response to within acceptable limits. It should be noted that Equation 1 does not allow the user to account for the phase data that is becoming available.

At this point it is instructive to consider the effect of using a matching amplifier. Membrane hydrophones have a characteristic shape to their frequency response curve wherein they exhibit a monotonically increasing sensitivity up to their thickness resonance frequency ($f_r$) with decreasing sensitivity beyond thereafter. Matching amplifiers typically apply a response curve that is monotonically decreasing, but with a gradient that is matched to the sub thickness resonance portion of the membrane hydrophones response. The net effect of hydrophone and amplifier is to yield a response that it reasonably flat up to $f_r$. However, beyond $f_r$ both amplifier and hydrophone have sensitivities that decrease as a function of frequency with the consequence that the combined response rapidly attenuates any harmonic components at frequencies above $f_r$. Examples of both the matched and unmatched (raw) sensitivity of two different types of membrane hydrophone can be found in Figure 1.

Figure 1 clearly shows the additional high frequency roll-off introduced by the matching amplifier. With matching amplifiers in place both hydrophones are showing a normalised amplitude of less than 0.5 at frequencies more than 25-30% beyond $f_r$. In contrast, the raw hydrophone bandwidth only returns to its low frequency value at 50% above $f_r$ for the 25 um bi-laminar hydrophone and 100% above $f_r$ for the 15 um co-planar hydrophone. Thus, if the frequency dependence of the hydrophones transfer function can be corrected for, there is the possibility of increasing the inherent usable bandwidth of a hydrophone by at least 50%.

Figure 1: Effect of matching amplifier use with two different membrane hydrophones.

Why should increasing a hydrophone's bandwidth be important? To answer this it is necessary to consider the nature of the pressure pulses typically encountered when making ultrasonic output measurements. Most diagnostic ultrasound systems have pulses with very sharp leading edges, and thus requires significant high frequency content. Consequently ultrasonic output standards require a hydrophone's bandwidth to extend to the minimum of several times the transducer's AWF, or 40 MHz. For AIUM/NEMA (1998) this multiple is five times the AWF, and for IEC(1991) the bandwidth is 8 times the...
AWF. Modern scanners often have transducers with 5 and 7 MHz centre frequencies, and the author has seen devices with an AWF in excess of 15 MHz. It is thus clear that the upper limit of 40 MHz will be routinely encountered. However, returning to Figure 1 it can be seen that neither of the sensitivity curves incorporating matching amplifiers is capable of reaching this limit. The fundamental inconsistency of the current method has thus been identified: the consequences of the hydrophone “flatness criterion” and the hydrophone bandwidth requirements of current standards are mutually incompatible for the waveforms generated by modern diagnostic ultrasound machines.

Thus far the discussion has only been restricted to magnitude of the hydrophone transfer function, but as mentioned in the Introduction, phase information is becoming available. Although changing the phase of any given component will not affect the energy contained within a signal, there will be a change of waveform shape. This means that although intensity based parameters will not be influenced by the inclusion of phase, parameters derived directly from the time waveform (such as Mechanical Index [MI]) may be affected. It is important to note that phase information is most important when there is considerable deviation from linear phase within the bandwidth of the signal being measured. A comprehensive model of a membrane hydrophone has been developed by Gelat et al (2001) and simulated results indicate that deviation from linear phase is not evident at frequencies below 70-75% of \( f_r \). However, needle (probe) hydrophones can exhibit significant phase variations at much lower frequencies due to the interaction of incident waves with those diffracted around the hydrophones tip.

**Hydrophone Deconvolution – a Better Approach?**

A process familiar to any practitioner of digital signal processing is deconvolution. For the specific case of hydrophone voltage to pressure conversion this can be expressed as

\[
p(t) = \mathcal{F}^{-1}\left\{ \frac{3V(t)}{M(f)} \right\}
\]

where \( \mathcal{F} \) and \( \mathcal{F}^{-1} \) denote the Fourier and Inverse Fourier transforms respectively, and \( M(f) \) is the (complex valued) hydrophone frequency response. The use of deconvolution is advantageous since not only does it make use of all of the available calibration data, but also it can cater for magnitude only or complex data. In fact, any other method of voltage-to-pressure conversion can only be a more crude approximation than deconvolution. This method is also under discussion for inclusion into the latest draft IEC hydrophone use standard.

It has been commented that since hydrophone calibration data are only available at discrete frequency increments, there is the possibility that the calibration increment will not match the sampling frequency with which the original hydrophone voltage waveform is acquired. In the author’s experience this is not a problem since spline interpolation (e.g. Cubic or Bezier spline) between adjacent points introduces an uncertainty in the sensitivity of the interpolated point that is well within the limits of total calibration uncertainty.

Concerns have also been raised that the additional computation required to implement Equation 2 might prove prohibitive in automated scanning systems where large numbers of measurements are made. Historically this may have been a valid concern, but this is not a problem with modern high-speed computers and communication interfaces. Specifically, automated hydrophone systems have an inherent “off-time” whilst the hydrophone is moved from one measurement location to the next. Although this period may only be a few tens of milliseconds, it is still more than long enough to transfer the data to the host computer, and conduct the necessary Fourier transform, division, and Inverse Fourier transform operations. If implemented in an effective manner the deconvolution process need incur no additional measurement time overhead, and can easily be conducted fast enough to give real-time display of deconvolved waveforms.

**Deconvolved Membrane Hydrophone Signals**

The first example that will be considered is that of a diagnostic ultrasound transducer operating at an AWF of 6 MHz. Its output was measured in water with a 15 um bi-laminar membrane hydrophone (Precision Acoustics Ltd, Dorchester, UK). The acquired voltage waveform was then converted to acoustic pressure using one of the following 3 methods
Method 1  A simple conversion according to Equation 1
Method 2  Deconvolution according to Equation 2 but using magnitude only data that had been obtained from a calibration traceable to National Standards.
Method 3  Deconvolution according to Equation 2 but using magnitude data that had been obtained from a calibration traceable to National Standards and phase data derived from the model by Gelat et al (2001) NB. At the time of preparation, phase data was not commercially available.

It is important to stress that in the following investigation the same raw hydrophone voltage waveform is the starting point for each of the three methods. The only difference is in the way that the frequency response data is used to derive the acoustic pressure waveform. In the discussion of variations that follow, method 3 will be taken as the reference.

Figure 2 contains sample pressure waveforms that have been obtained using methods 1 and 3. These cases have been selected since they show greatest differences, and the inclusion of the trace from method 2 has been omitted to improve clarity of the graph. The most significant change between the two pressure waveforms in Figure 2 is the significant overestimation of peak positive pressure resulting from the use of method 1 voltage to pressure conversion.

Figure 2: How deconvolution affects the pressure waveform derived from a membrane hydrophone measurement.

The variations in positive going cycle of this waveform can easily be understood when the inherent frequency response of a membrane hydrophone is considered. As is seen in Figure 1, the unmatched sensitivity functions of both membrane hydrophones are monotonically increasing up to \( f_r \). Given that method 1 implies uniform sensitivity as a function of frequency, this method with systematically over-estimate the higher frequency components within a broadband pulse. Fourier's theorem reveals that sharp edges require the presence of significant energy at high frequency, and it is thus obvious that overestimation of spectral content at higher frequencies will lead to exaggerated leading edges (and hence exaggerated peak positive pressures). Also of note is the slight decrease of the negative pressure, when method 3 (full waveform deconvolution) is used. A similar but converse argument to that relating to peak positive pressure is applicable. The uniformity assumption of method 1, leads to an underestimation of acoustic pressure at frequencies lower than \( f_{min} \). In the same manner that high frequency energy most affects the positive going cycle of the pulse, so the lower frequency components affect the negative going cycle.

Various acoustic output parameters were then calculated from the pressure signals obtained from each of the three conversion methods, and these values are to be found in Table 1. As is to be expected the variations in peak rarefractional pressure affect the calculated value of MI, whilst the reduction of the maximum compressional amplitude has a significant affect on PII (and hence any parameter depending upon it, such as \( I_{spta} \)). MI is also affected by the change in measured AWF which also follows from the overestimation of high frequency energy content due to method 1 (and a thus a corresponding bias of the spectrum towards higher frequency). Using method 1, peak positive pressure has been overestimated by more nearly 30%, with a corresponding overestimation of PII. It is also important to note that even a magnitude only deconvolution (Method 2) offers considerable improvement in measurement accuracy compared to the existing method (method 1). The regulatory significant parameters of MI and PII.3 derived from magnitude only (method 2) voltage to pressure conversion have less than 2% error relative to fully deconvolved waveforms. In contrast the simple method 1 approach introduces errors of about 5% for MI and 21% for PII.3
Table 1: Comparison of several standard acoustic parameters obtained from the same data trace by means of various voltage to pressure conversion methods

| Quantity | Method 3 | Method 2 | %Error Method 2 | Method 1 | % Error Method 1 |
|----------|----------|----------|-----------------|----------|------------------|
| Pp       | 4.57     | 4.55     | -0.3%           | 4.84     | -6.0%            |
| Pr.3     | 3.46     | 3.45     | -0.3%           | 3.32     | -6.0%            |
| fawf     | 5.67     | 5.67     | 0.0%            | 5.76     | -1.5%            |
| MI       | 1.45     | 1.44     | -0.5%           | 1.53     | -5.0%            |
| Pd       | 7.88     | 9.24     | 17.3%           | 10.1     | 27.8%            |
| Pd.3     | 5.96     | 6.99     | 17.3%           | 7.62     | 27.8%            |
| PII      | 2.23E-04 | 2.26E-04 | 1.3%            | 2.70E-04 | 21.0%            |
| PII.3    | 1.28E-04 | 1.29E-04 | 1.3%            | 1.54E-04 | 21.0%            |

Deconvolved Needle Hydrophone Signals

Traditionally needle hydrophones have not been recommended for the regulatory assessment of broadband acoustic signals because their non-flat frequency response has failed to meet the “flatness criteria” that have previously been imposed. However, the use of deconvolution techniques provides a good reason to re-examine this argument. A 0.5mm diameter needle hydrophone with deliberately non-flat frequency response was selected, as a worst-case scenario. This hydrophone, along with the membrane hydrophone used earlier, was used to record the pressure field produced by a highly shocked waveform. The waveform in question was produced by a 1 MHz transducer driven with 2 cycles of sinusoidal wave at 300 V pk-pk. Non-linear propagation of this high amplitude wave results in so much harmonic generation that the 100th harmonic can clearly be seen, and thus results in a very broadband source.

The voltage waveforms produced by each hydrophone (and then normalised to maximum peak negative pressure – for ease of display) can be found in Figure 3. As can be seen, the trace produced by the needle hydrophone differs from that of the membrane hydrophone in many aspects: the peak positive pressure is considerably lower, the shape of the waveform on the negative going portion of the waveform is more pronounced and the transition from peak positive to peak negative of each cycle exhibits a subtle hump (probably related to the resonance in the response of the needle hydrophone).

The voltage waveforms from both hydrophones were then processed to yield pressure waveforms. Phase information was not available for the needle hydrophone, so only Method 2 (magnitude only deconvolution) could be used. As before modelled phase information was used for the membrane hydrophone to allow full deconvolution (method 3). The results of this process can be found in Figure 4. To complete the comparison, method 1 conversion was also conducted for the needle hydrophone, but since these results have the same shape as the raw voltage trace shown in Figure 3, these results are not included in the graph.

The correlation between deconvolved data for the needle and membrane hydrophones is very good. Not only are the waveform shapes much closer, but also the variation in peak positive pressure is significantly reduced, whilst the differences in peak negative pressure are almost eliminated. It is hypothesised that the inclusion of phase data (when it becomes available) will further improve situation. As before a range of acoustic output parameters were calculated and these can be found in Table 2.

Although only method 2 voltage to pressure conversion could be used for the needle hydrophone there has clearly been a marked improvement in quality of the acoustic pressure waveform. The variation of peak positive pressure is reduced from 30% to 18% and the differences in peak negative pressure reduce to 5% from 12%. Most importantly, parameters of regulatory significance (PII.3 and MI) are now within 4% of the values obtained with a deconvolved membrane hydrophone.
Figure 3: Normalised voltage traces obtained from membrane and needle hydrophone in a broadband field

Figure 4: Deconvolved pressure traces obtained from membrane and needle hydrophones in a broadband field

| Quantity | Membrane Method 3 | Needle Method 2 | % Error Method 2 | Needle Method 1 | % Error Method 1 |
|----------|-------------------|-----------------|------------------|-----------------|------------------|
| $P_r$    | 0.258             | 0.244           | -5%              | 0.227           | -12%             |
| $P_{r.3}$| 0.073             | 0.069           | -5%              | 0.064           | -12%             |
| $f_{swf}$| 0.994             | 0.986           | -1%              | 0.988           | -1%              |
| MI       | 0.073             | 0.070           | -4%              | 0.065           | -11%             |
| $P_c$    | 0.837             | 0.690           | 18%              | 0.587           | 30%              |
| $P_{c.3}$| 0.235             | 0.194           | 18%              | 0.165           | 30%              |
| PII      | 1.31E-05          | 1.25E-05        | 4%               | 1.06E-05        | 19%              |
| PII$_{3}$| 1.04E-06          | 1.00E-06        | 4%               | 8.47E-07        | 19%              |

Table 2: Several standard acoustic parameters obtained from needle and membrane hydrophone measurements

Conclusions

Limitations with existing methods of conducting voltage to pressure conversion have been discussed and an alternative technique of hydrophone deconvolution has been examined. Full waveform deconvolution has been shown to offer significant reductions of measurement error, and even magnitude only deconvolution has been shown to provide a useful improvement when compared to a single figure conversion process. In fact, magnitude only conversion offers a way of using needle hydrophones in situations were previously only membrane hydrophones were acceptable.

References

AIUM/NEMA (1998) Acoustic Output Measurement Standard for Diagnostic Ultrasound Equipment. NEMA Standards Publication UD-2

Gélat P, Preston R and Hurrell A (2001), Development, validation and publication of a complete theoretical model for hydrophone/amplifier transfer characteristics, NPL REPORT CMAM 61, HMSO, ISSN 1369-6785

IEC (1991). Measurement and Characterisation of Ultrasonic Fields using Hydrophones in the Frequency Range 0.5 MHz to 15 MHz. International Electrotechnical Commission Publication 61102, Geneva, Switzerland

Koch C. (2003). Amplitude and Phase Calibration of Hydrophones by Heterodyne and Time-Gated Time-Delay Spectrometry. IEEE Trans. UFFC 50 (3) pp. 344-348