Calibration of a Neutrally Buoyant $p-u$ Intensity Probe

James A. McConnell" and Gerald C. Lauchle

"The Pennsylvania State University, Graduate Program in Acoustics
P.O. Box 30, State College, PA 16804

'Acoustech Corporation
P.O. Box 139, State College, PA 16804

Abstract: Theory and test methods are presented for calibrating an underwater acoustic intensity probe containing two pressure hydrophones and one moving coil velocity sensor. The intensity probe is classified as a $p-u$ probe and is neutrally buoyant in fresh water. In contrast to $p-p$ and $u-u$ probes, it determines intensity via direct measurement of the acoustic pressure and particle velocity. Specifically, intensity is computed by adjusting the time-averaged RMS cross-spectrum between the transducer output voltages by an appropriate calibration curve. Because intensity is a vector quantity, both a magnitude and a phase calibration is required. This is accomplished by a straightforward technique involving a single reference hydrophone and a priori knowledge of the acoustic field where the calibration is performed. A simple experiment was conducted using a standing-wave tube to verify the effectiveness of the calibration technique. In the experiment, the pressure and velocity sensors were calibrated, then an intensity measurement was performed. Results show that the calibration technique is highly effective. [Work supported by the Office of Naval Research and the Naval Air Warfare Center Aircraft Division via the DoD Small Business Innovation Research Program.]

SENSOR DESCRIPTION

The $p-u$ probe is a single axis intensity sensor containing two omni-directional hydrophones and one moving coil geophone embedded in a cylindrical casting of syntactic foam. The geophone (GeoSpace GS-14-L3) is located in the geometric center of the cylinder and the hydrophones (Magnavox AN/SSQ-53D) are flush mounted in the end-caps. The hydrophones are electrically connected in parallel so that they effectively measure the acoustic pressure in the middle of the probe where the geophone is located.

The dimensions of the cylinder are selected so that the weight of the transducers is offset by the buoyancy force associated with the syntactic foam, hence making the probe neutrally buoyant. Geophones which are neutrally buoyant provide a direct measurement of the acoustic particle velocity, consequently improving the accuracy of $p-u$ probes relative to $p-p$ and $u-u$ probes.

The intensity probe is suspended inside a free-flooding acoustically transparent cylindrical shell via two identical springs that operate on the mass loaded cantilever beam principle. The springs are compliant in the axial direction (i.e. the principal axis of sensitivity) and very stiff in the radial direction so that the dynamics of the mass-spring system created by the probe and the suspension do not adversely affect the performance of the geophone. The low stiffness in the axial direction facilitates a resonance frequency of about 10 Hz.

CALIBRATION PROCEDURE AND TEST RESULTS

The acoustic intensity is defined in the frequency domain as the time-averaged RMS cross-spectrum between the acoustic pressure and the particle velocity. Calibrated intensity measurements are obtained by adjusting the cross-spectrum between the transducer output voltages with an appropriate calibration curve that is indicative of a complex transfer function. This is summarized in the equation below:
\[ I = pu = G_{pu} = \frac{\hat{G}_{pu}}{H_{pu}} \]  

where \( \hat{G}_{pu} \) is the cross-spectrum between the transducer output voltages and \( H_{pu} \) is the complex transfer function associated with the transducers employed by the probe. The active and reactive intensity spectrums are found by taking the real and imaginary parts of Eq. (1). The corresponding phase between the acoustic pressure and particle velocity is found by computing the complex ratio between the reactive and active fields and taking arctangent thereof.

An experiment was performed to determine the system transfer function and subsequently use it to obtain calibrated intensity measurements inside a NRL USRD G19 Calibrator. The G19 is an open-ended column of water terminated at the bottom by an electrodynamic driver. In the experiment the intensity probe was submerged at some depth \( d \) and insonified with band-limited white noise. A Reson Systems TC-4013 hydrophone was positioned next to the probe such that its acoustic center was aligned with that of the probe. The hydrophone serves as a reference transducer whose free-field-voltage-sensitivity (FFVS) is known, but phase response is unknown.

It can be shown through the application of simple transfer function analogies in a comparison calibration format and \textit{a priori} knowledge of the standing-wave field in the G19 that the desired transfer function is:

\[ H_{pu} = -j\pi M_0^2 \tan(kd) \frac{\hat{G}_{pu}}{G_{pp}} \]  

where \( M_0 \) is the FFVS of the reference hydrophone, \( \hat{G}_{pu} \) is the cross-spectrum between the transducer output voltages, and \( G_{pp} \) is the power spectrum associated with the reference hydrophone. It is noted that any phase that is introduced by the hydrophone is identically canceled out as a result of obtaining the power spectrum.

The results of the intensity measurement are shown in Fig. 1. The data show that the reactive field is about 40 dB greater than the active field and that the corresponding phase between the acoustic pressure and particle velocity is virtually -90°. These results are consistent with the expectations of the near perfect standing-wave field produced in the G19. The small contribution of the active intensity to the total field indicates that some losses are present. The phase aberrations in the data below 30 Hz and above 2400 Hz are indicative of the limitations of the GS-14-L3 geophone.

These results clearly show that the calibration technique was successful, but more importantly, underscore the excellent performance of this sensor in acoustic fields which are predominantly reactive. The calibration technique can be applied to field measurements with only minor changes to the formulation given in Eq. (2). Developmental work continues on the \( p-u \) probe and other related sensors.

![Intensity Spectrum in G-19 Calibrator (1-Probe #3)](image1)

![Phase Between Pressure and Velocity (1-Probe #3)](image2)

FIGURE 1. Results of intensity measurements performed in a NRL USRD G19 Calibrator