MEASUREMENT OF UNDERWATER SOUND INTENSITY VECTOR

Daniel Hutt, Paul C. Hines and Andrew Rosenfeld
Defence Research Establishment Atlantic
P.O. Box 1012, Dartmouth, Nova Scotia, Canada, B2Y 3Z7

Localization of underwater sound sources and characterization of ambient noise fields can be achieved through measurement of the sound intensity vector. To evaluate this concept, a passive hydrophone array called SIRA (Sound Intensity Receiver Array) has been developed for measurement of underwater sound intensity in the frequency range 100 to 6000 Hz. The array is composed of three pairs of omnidirectional hydrophones with the pairs aligned along orthogonal axes. The intensity is the time average of the product of instantaneous acoustic pressure and particle velocity. The instantaneous pressure is the average of the pressures measured by a hydrophone pair and the velocity is derived from the pressure gradient. Each hydrophone pair provides one of the components of the three dimensional intensity vector.

1. Description of instrument

SIRA was developed under contract for DREA by Guigné International Ltd. (GIL), Paradise, Nfld., Canada. To achieve the full frequency range of 100 to 6000 Hz, the mounting structure can be configured for two different hydrophone spacings, 8 cm or 19 cm. The 19 cm spacing is used to make measurements at frequencies down to 100 Hz while the 8 cm spacing allows measurements to be made up to 6000 Hz. Neither spacing can provide measurements over the entire frequency range as a result of the trade-off between errors in approximating the pressure gradient at high frequencies and susceptibility to noise at low frequencies, where the gradient is small. The hydrophones used in SIRA are model 1042 transducers from International Transducer Corp., Santa Barbara, CA. They are 35 mm-diameter spheres and are omnidirectional to better than 0.5 dB below 25 kHz. The hydrophones have sensitivities of approximately -200 dB//V/µPa in the band 1 kHz to 10 kHz. A photograph of the array with hydrophone spacing of 8 cm is shown in Fig. 1.

The SIRA preamplifiers, custom-built by GIL, have built-in high- and low-pass filters with cutoff frequencies of 100 Hz and 20 kHz, respectively. The preamplifiers have a 12 dB fixed gain at the input stage with 60 dB of additional gain selectable in 12 dB increments. All preamplifiers had 60 dB gain for the measurements presented here. At 1 kHz, the pre-amplifier noise is less than -165 dB//V/Hz$^{1/2}$ at all gain settings. Phase matching between the six preamplifiers is better than ±0.3° across the frequency band. The preamplifiers were paired to minimize the phase mismatch along each SIRA axis. Phase matching between pairs is better than ±0.05° across the frequency band. The inter-channel gain matching between all preamplifiers is better than ±0.3 dB and gain matching between axial pairs is better than ±0.1 dB. Plots of the preamplifier phase and gain can be seen in Ref. 1.

The SIRA mechanical apparatus is made up of a tubular pressure vessel 20 cm in diameter by 63.5 cm long which contains the preamplifiers and other electronics. The hydrophones are supported at the end of 1-m long stainless steel tubes which are attached to the bottom of the pressure vessel.

2. Intensity signal processing

The magnitude of the intensity component in direction $\bar{x}$ is the time averaged product of the instantaneous acoustic pressure p(t) and the particle velocity component $u_x(t)$,

$$I_x = \overline{p(t) \cdot u_x(t)} \quad . \tag{1}$$

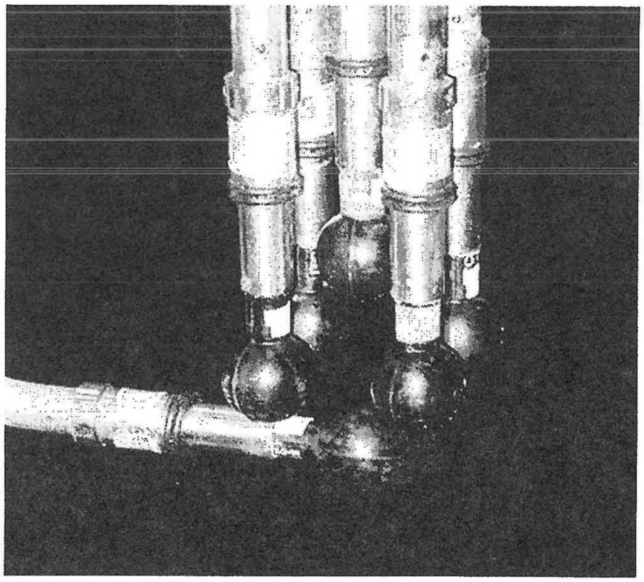

Fig. 1 Close-up of SIRA hydrophones and supporting structure. The hydrophone spacing is 8 cm.

SIRA uses pressure transducers to provide both pressure and particle velocity. This is referred to as the pressure-pressure method. The particle velocity is derived from the pressure gradient using the finite difference approximation,

$$u_x(t) = \frac{1}{\rho} \int_0^t \frac{p_{x2} - p_{x1}}{d} dt \quad , \tag{2}$$

where ρ is the water density and d is the distance between hydrophones x_1 and x_2. Equation 2 yields an exact value for the particle velocity in the limit of vanishingly small kd. In practice, kd must be large enough to give a measurable difference signal. It is easily shown that the error in $u_x(t)$ as calculated with Eq. 2 is only 5% for $kd = 1$ and 17% for $kd = 2$. For the 8 cm spacing of the SIRA hydrophones, $kd = 1$ represents a frequency of 3 kHz and $kd = 2$ represents a frequency of 6 kHz. The benefits of increased signal to noise ratio justify the measurement of intensity at these relatively high kd values.

The intensity can be calculated more efficiently by expressing Eq. 1 in terms of the Fourier transforms of $p_{x1}(t)$ and $p_{x2}(t)$. The time averaged intensity component I_x is then given by the imaginary part of the cross spectrum of the pressure signals[2],

$$I_x = \frac{\mathrm{Im}\left[S_{x1}(\omega) S^{*}_{x2}(\omega) \right]}{\rho \omega d} \quad , \tag{3}$$

where $S_{x1}(\omega)$, $S_{x2}(\omega)$ are the Fourier transforms of $p_{x1}(t)$, $p_{x2}(t)$ and ω is the angular frequency, $2\pi f$. If the measurements are made in the far field, then the three components of the intensity vector given by Eq. 3 yield the direction to the source via,

$$\theta = \tan^{-1}(I_y/I_x) \quad \text{and} \quad \phi = \cos^{-1}(I_z/I) \quad , \tag{4}$$

where $I = \sqrt{I_x^2 + I_y^2 + I_z^2}$.

3. Measurement set-up

Preliminary results presented here were obtained at the DREA acoustic calibration barge facility. The barge is 36 m long by 17 m wide and contains a rectangular well, 9 m by 18 m, which is open to the sea. The barge is located in the Bedford Basin near DREA in water of approximately 42 m depth. The array was mounted in the barge well so that its center was at a depth of 10 m. The projector was a type J11 transducer, produced by the US Naval Underwater Sound Reference Laboratory. With both the array and projector at depths of 10 m and separated by 10 m, sound pulses up to 10 ms in length could be received at the array before the arrival of the first reflection. A computer synthesized the transmitted waveforms and handled the digitization and recording of the time series data.

4. Dipole response functions

The performance of the intensity array can be evaluated by measuring the difference signal of hydrophone pairs for a narrowband acoustic wave as a function of array rotation angle. Ideally, when a pair of hydrophones is aligned with their axis perpendicular to the direction to the source, the received signals should cancel. In this orientation, any difference signal is due to imbalance in gain and phase response, scatter from the array components and the presence of system electronic noise and acoustical ambient noise. For $kd \ll 1$, and assuming a plane acoustic wave, the measured difference signals can be compared to an ideal dipole. An example is shown in Fig. 2 where measured data are displayed as dots and the curves are those of an ideal dipole given by $\cos(\theta)$ for the x axis and $\sin(\theta)$ for the y axis.

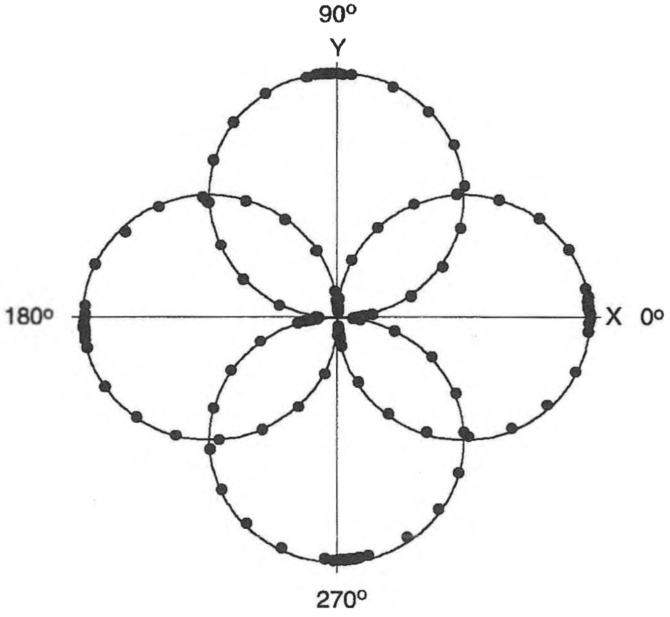

Fig. 2 Measured difference signals (points) and ideal dipole response (curves) for d = 19 cm and f = 500 Hz, plotted on a linear scale.

The measurements shown in Fig. 2 were made at a frequency of 500 Hz with a hydrophone spacing of 19 cm (kd = 0.4). The data points are based on the coherent average of 10 pulses, each of 10 ms duration. Data are normalized by the maximum value at the dipole lobes. The signal to noise ratio was approximately 35 dB during the measurements. The agreement between the measurements and ideal dipole indicates good performance for the horizontal SIRA channels. The symmetry of the dipole plots shows that the inter-channel phase matching is good. This is consistent with the fact that the best phase matching occurs at 500 Hz with an error of approximately 0.2°.

For the data shown in Fig. 2, the average value of the x and y nulls is 4.9% of the lobe maxima. If the data were expressed as intensity, the mean of the nulls would be -26 dB with respect to the lobe maxima. Measurements of the dipole pattern were obtained for frequencies from 500 Hz to 4000 Hz. The deepest set of nulls was obtained at 4000 Hz with a value of -32.5 dB. The presence of unavoidable ambient noise contributes to the residual difference signal at the nulls. Measurements made under quieter conditions and with greater angular resolution near the nulls could reveal that the SIRA nulls are deeper than presented here. Also, it is possible to correct for the measured channel phase and gain imbalances which could result in even better performance.

5. Direction to signal source

Processing the data of Fig. 2 to yield the x and y intensity vector components allows the direction to the source to be calculated via Eq. 4. A comparison of the calculated direction to the source and the measured array orientation angle is shown in Fig. 3. The standard deviation of the difference between measured and calculated angles is 1.4°. Although the width of the array is only 6% of a wavelength at 500 Hz, intensity processing allowed the direction to the source to be determined with an accuracy of 1.4°. Using conventional beamforming methods, an array would have to be several wavelengths in size to measure the direction to the source with the same accuracy.

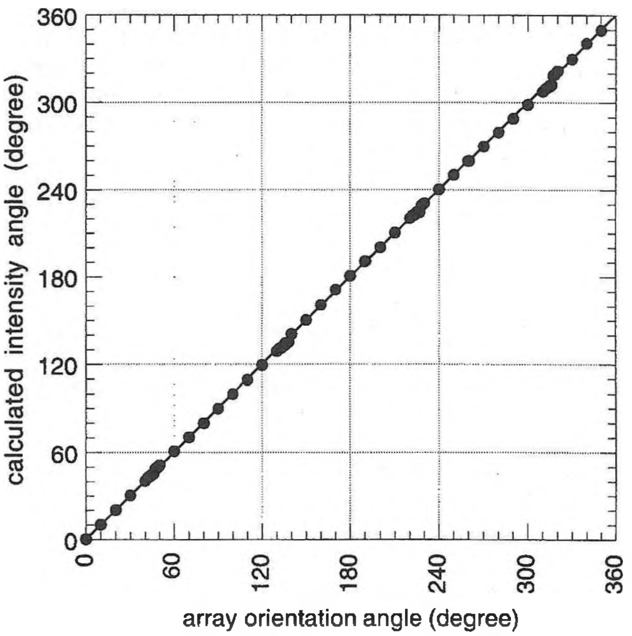

Fig. 3 Direction to acoustic source calculated from intensity vector components using Eq. 4 for f = 500 Hz and d = 19 cm.

6. References

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