Vector Hydrophones

Technical Note

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1 Introduction

Most of us are familiar with hydrophones that measure sound pressure. At low frequencies, these hydrophones are omni directional, which is why they are often referred to as omnis. On the other hand, most of us are not familiar with vector hydrophones, i.e., hydrophones designed to respond to a pressure gradient. Vector hydrophones are also called particle velocity (PV) sensors because the force that creates particle velocity is the pressure gradient. This paper aims to fill in the gaps of understanding of vector hydrophones. How do they work? Under what circumstances should they be used? Why are they so noisy? How can the noise be minimized? How should their outputs be interpreted?

In 1985, starting with no knowledge, I began designing and testing vector hydrophones for a sonobuoy company. These were well-funded developments with access to test facilities unavailable to most people. Hundreds of hydrophones were tested for acoustic and noise performance in the lab, small bodies of water, ocean inlets, the open ocean, and a traveling-wave tube (Simms Tube), which can measure acoustic sensitivity and beam patterns at subsonic frequencies. None of the results were published because they were either proprietary or classified.

Over a period spanning six years, I designed two generations of vector hydrophone. The first was patented, US patent 4,928,263; the second built upon what I had learned during the first design cycle and contains features that minimize mechanical noise. These features are not obvious so the sonobuoy company chose not to patent or publish information about the second generation. This hydrophone, some 30+ years later, still defines the state of the art and is still in production.

GeoSpectrum's M20 series of vector hydrophones were designed using the knowledge gained decades before. A M20 won a Foreign Comparative Test (FCT) run by the USN, and, for example, is being used in the MARS observatory off Monterey California to track blue whales. GeoSpectrum's customers are using M20s in difficult operating conditions. Our conversations with these customers are developing knowledge on how to successfully use these hydrophones in currents up to 2 knots. The search for best-practice is not finished, but what is known now is in this document.

2 Functional definition of a Vector Hydrophone

A pressure hydrophone, or omni, responds to pressure regardless of the direction of arrival of the sound. At low frequencies, a pressure hydrophone is omnidirectional in all directions because it is small compared to a wavelength. In contrast, the directional channels of a vector hydrophone respond to pressure gradient, a vector, so their sensitivities vary with the cosine of the angle of arrival relative to an axis. Figure 1 shows the directivity of the three channels of a 2D vector hydrophone: X (red), Y (black), and Omni (green). The scale of the graph is in dBV. This pattern is obtained at all frequencies in good vector hydrophones. In vector hydrophones with flaws, the nulls will not be deep, the nulls will not be orthogonal and the main lobes will not be of equal amplitude.

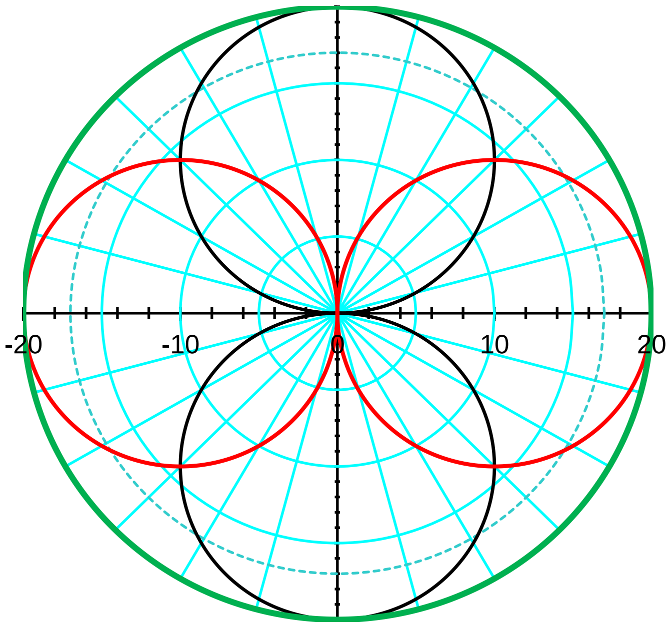

Figure 1: Directivity patterns of the X, Y, and Omni channels in a vector hydrophone

3 When you should use a Vector Hydrophone

Vector hydrophones are susceptible to mechanically-induced noise and expensive so they should only be used when necessary. They are needed when you wish to:

- Determine bearing
- Determine particle velocity
- Increase the directivity index of an array

In a plane wave, the relationship between pressure, P, and particle velocity, U, is given by

$$P = \rho c U$$

where ρ is the density and c is the speed of sound. Thus, if you measure P with an omni, you can calculate U. When you are near the source of sound or near a boundary, this relationship does not hold. When near a source, there is 1/r component to the pressure gradient that does not exist in a plane wave. When you are at the water surface, there is no pressure, but the particle velocity is high. Conversely, when you are near a solid boundary, the particle velocity is zero, but the pressure is high.

4 Types of Vector Hydrophones

Broadly speaking, there are two types of directional hydrophone:

- those that directly measure a pressure difference (subtraction of the outputs of two pressure hydrophones), and
- those that sense movement caused by a pressure difference (accelerometer based).

GeoSpectrum builds directional hydrophones of both types, but finds more applications for the accelerometer designs because they function well at subsonic frequencies and their useful frequency range is octaves greater.

4.1 Pressure difference

Figure 2 is geometric layout of a two-channel directional hydrophone that responds to pressure differences. This vector hydrophone comprises five pressure hydrophones. Each of the directional channels comprises a pair of pressure hydrophones that have been matched in sensitivity. They are wired in such a way that they have no output when they experience the same pressure. The fifth pressure hydrophone in the centre provides a phase reference to the directional channels. Phase is necessary to resolve left-right ambiguity in bearings.

Consider the X channel. The two hydrophones in the X channel are labeled +1 and -1 indicating that they have equal sensitivity but differ by 180° in the phase of their output. Because of the spatial separation of the two hydrophones, each experiences a different pressure for a sound wave traveling in the direction of the X axis. This slight difference in the output of the two X hydrophones is your desired signal. On the other hand, for acoustic waves traveling along the Y axis, each omni in the X channel experiences the same pressure at the same time and the sum of the outputs is zero. The resulting beam pattern is shown in Figure 3

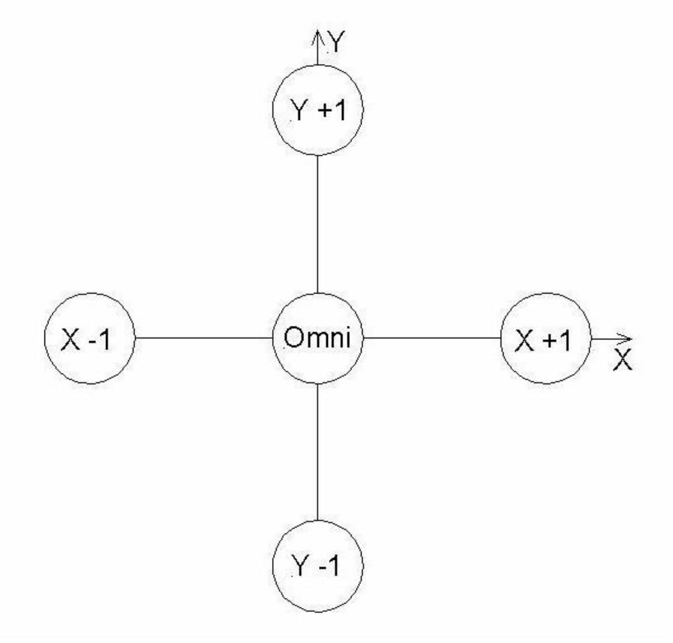

Figure 2: Geometry of a vector hydrophone made from pressure hydrophones

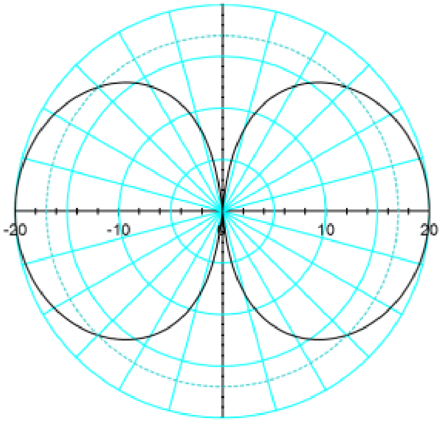

Figure 3: X-channel beam pattern

Figure 4 is a photograph of a small vector hydrophone that works well in the multi-kHz frequency range. The assembly has a plastic base designed to screw into a pressure vessel. Within the black potting are the five pressure hydrophones; the pairs that form the X and Y channels are matched closely.

Figure 4: Photograph of a vector hydrophone built from five pressure hydrophones

The big disadvantage of pressure-difference vector hydrophones is that you must have precise knowledge of the sensitivity of the hydrophones. You are subtracting two large numbers and you require the difference to be meaningful. Unequal sensitivities will degrade the null depth and limit the lowest frequency of usefulness. Nevertheless, when the separation between hydrophones is a sufficient fraction of a wavelength, these hydrophones perform well and are relatively inexpensive. Also, you can build your own if you have five pressure hydrophones that are accurately calibrated.

The root cause of the shortcoming of a pressure-differenced hydrophone is that the sensing elements are exposed to, and respond to the pressure, whereas you want them to respond only to the pressure difference. The way around this issue is to house the sensors within a pressure vessel, a topic discussed in the next section.

4.2 Accelerometer Based Vector Hydrophones

Accelerometer-based vector hydrophones contain orthogonally-arranged accelerometers and electronics within a pressure vessel as illustrated in Figure 5Figure 5. When immersed in a sound field, the pressure gradient accelerates the pressure vessel, just like it would a water molecule. The accelerometers within the pressure vessel respond to this acceleration. It is important that the pressure vessel and accelerometer mount isolate the accelerometers from the acoustic pressure.

The advantage of an accelerometer-based vector sensor is that it is directly measuring the movement created by the pressure gradient; no large signals are being subtracted. When done properly, the compact vector sensor can make meaningful measurements from about 3 Hz and up.

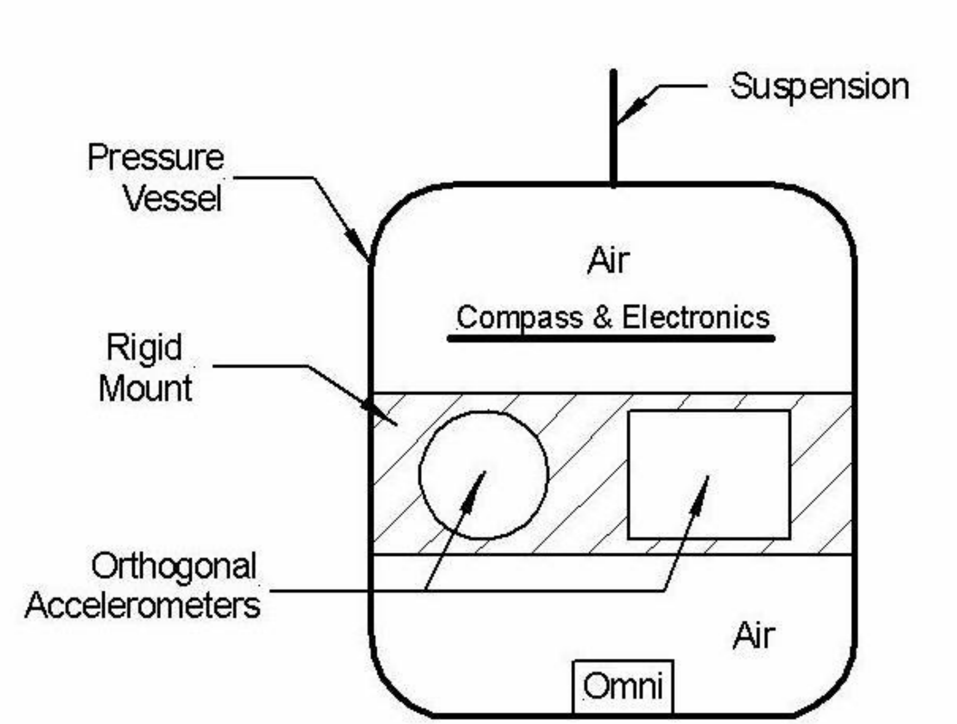

Figure 5: Schematic of Accelerometer-based directional hydrophone

Figure 6: Photo of a 2D, accelerometer-based M20

5 How to use the beams patterns and phase to determine bearings

A 2D directional hydrophone comprises X and Y directional channels arranged at right angles to each other, plus an omni (pressure) hydrophone, which provides a phase reference to the directional channels. The amplitudes and phases enable computation of bearings.

Figure 7 shows the measured beam patterns of a GeoSpectrum M20. The X and Y channels are so labeled because they have their maximum responses along the X and Y axes. Further, if sound arrives from right to left, or top to bottom, the phases of the X and Y channels lead the omni by 90°. Conversely, when the sound arrives on the negative axes, the phases of the directional channels lag the omni by 90°. The shape of a beam pattern varies as cosine of the angle measured from the relevant axis.

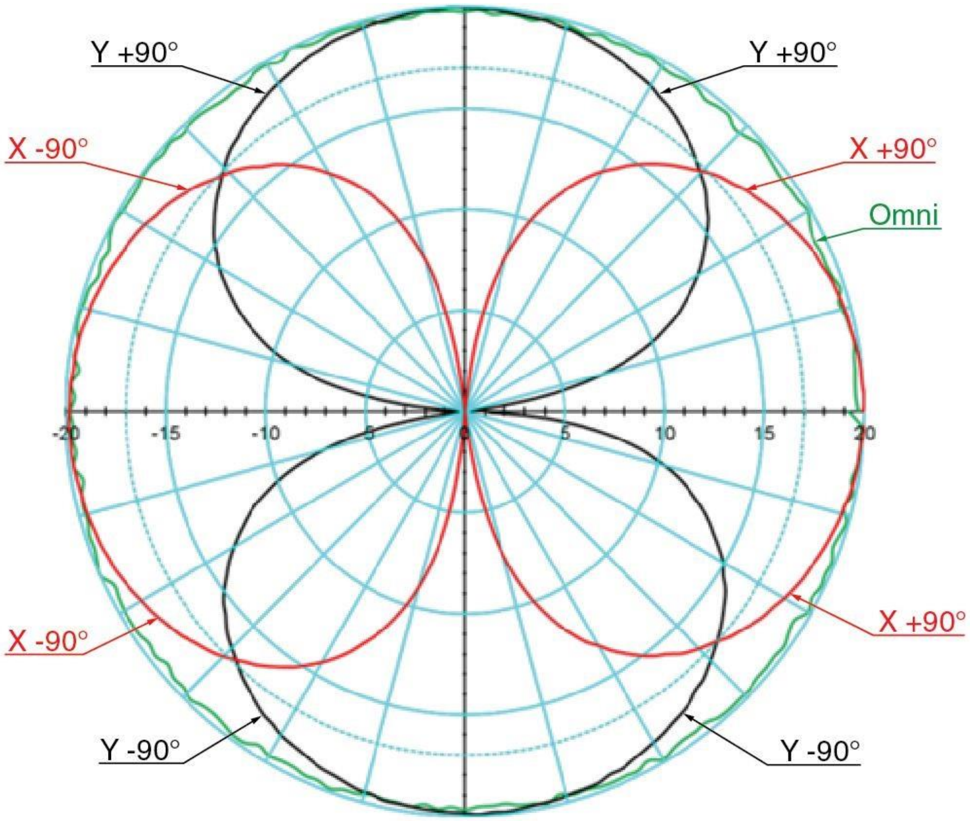

Figure 7: Measured beam patterns of a M20

The X and Y amplitudes and their phases relative to the omni are required to determine the bearing of the arriving sound. As an example, consider a situation in which the signal amplitudes of the X and Y channels are equal, the phase of the X and Y channels relative to each other is zero, and the phases of the X and Y channels relative to the omni are +90°. The X and Y channels have equal amplitude at four angles: 45°, 135°, 225°, and 315°, but the phases of the X and Y channels are only equal at two of those angles, 45° and 225°. We are left with the so-called left-right ambiguity until we compare the X and Y phases to the omni. It is only at 45° that the X and Y channel phases lead the omni by 90°.

In a lab situation, this information is enough to calculate bearing because the orientation of the hydrophone relative to magnetic north can be seen, but in some field situation, the orientation of the directional hydrophone to magnetic north is unknown so many M20s contain a compass.

The phase relationships indicated in Figure 7 are true at low frequencies, but the next sections shows that the phase relationship is more complicated.

6 Acoustic Response of an Accelerometer-Based M20

Figure 8 is a plot of the acoustic sensitivity of the X, Y and Omni channels of a 2D M20 in response to a plane wave arriving from the positive directions of the axes. Figure 9 is the corresponding phase plot of the X and Y channels relative to the omni channel. It is vitally important to understand that, even though the sensitivities are expressed relative to the plane-wave pressure, the outputs of the directional channels are the accelerometer's response to the ***acceleration*** of the pressure vessel. This acceleration is produced by the *pressure gradient* associated with that plane-wave pressure.

The sensitivity is referenced to a plane-wave pressure, so the particle velocity can be calculated from

$$P = \rho c U$$

where P is the pressure, ρ is the density of the water, c is the speed of sound in water, and U is the particle velocity. As an example, the sensitivity of the X channel is -175 dBV re 1 µPa at 100 Hz. If the signal amplitude from the X channel is at 100 Hz is -55 dBV, then the pressure is -55+175=120 dB re 1µPa = 10^6 µPa = 1 Pa. If we use typical values for ρ (1026 kg/m^3) and c (1491 m/s) in sea water, we calculate a particle velocity of 6.54 10^{-7} m/s along the X axis.

This calculation of the particle velocity is only possible because the sensitivity of the M20 is referenced to the pressure in a plane wave.

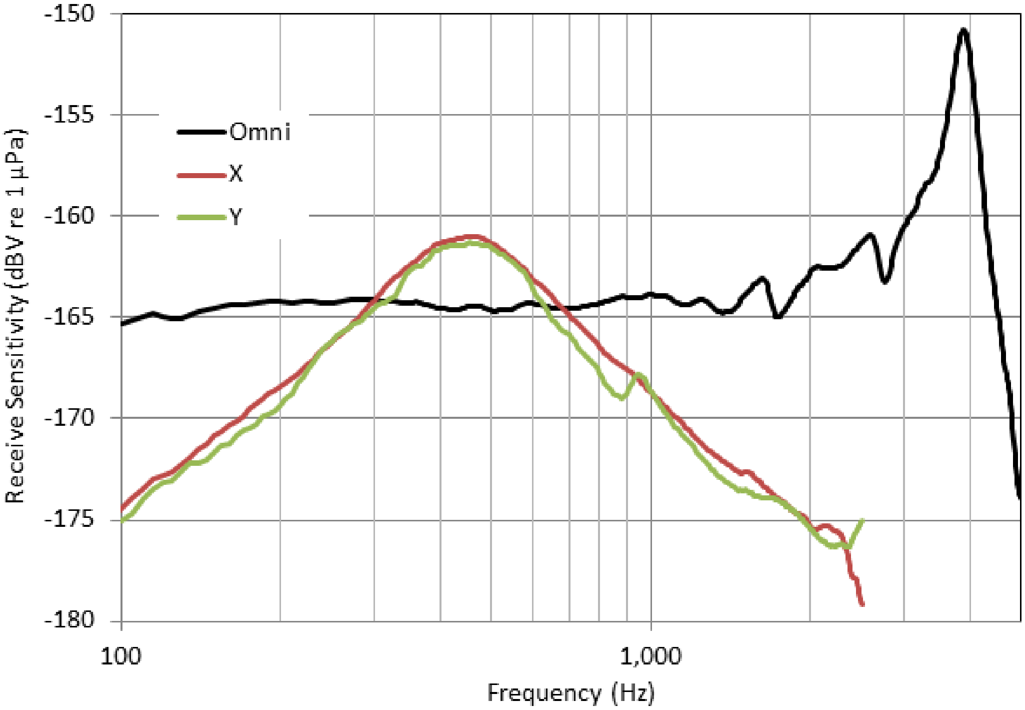

Figure 8: Acoustic Sensitivities of a M20

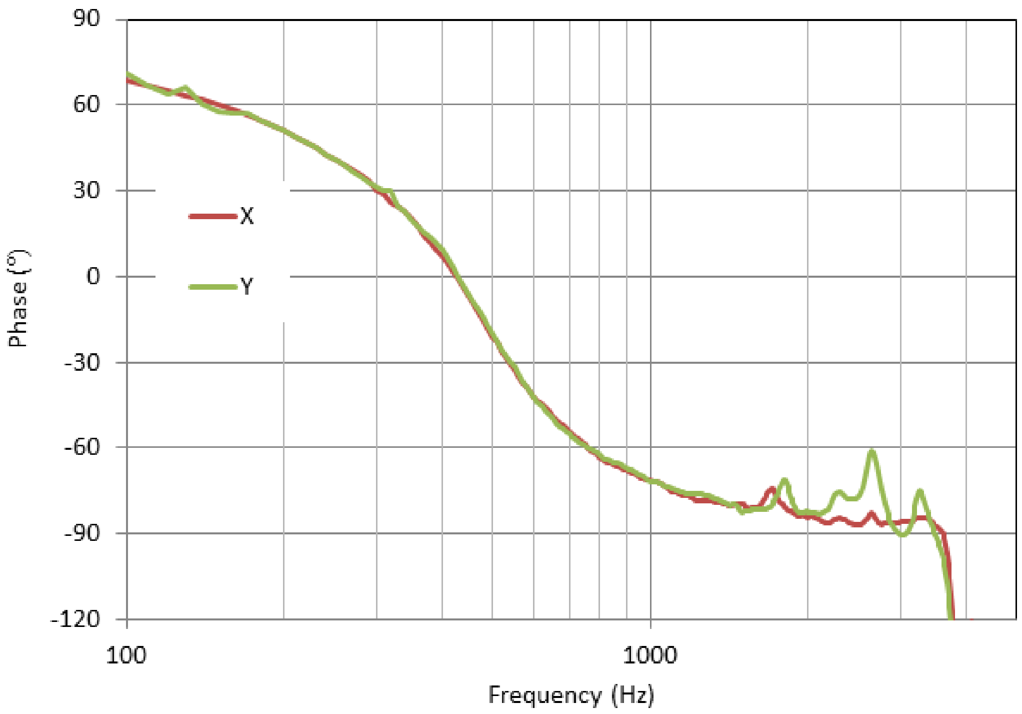

Figure 9: Phase response of the X and Y channels relative to the omni in a M20

7 What determines the shapes of the sensitivity and phase curves

The amplitude and phase plots have the shapes shown in Figure 8 and Figure 9 because the GeoSpectrum designed accelerometers within the pressure vessel have a well-damped resonance near 450 Hz, as shown in Figure 10. The accelerometer sensitivity is flat below resonance so the output of the M20 rises at 6 dB per octave because the pressure gradient, the driving force, increase at 6 dB per octave. Above resonance, the output of the accelerometer falls faster than the increase in pressure gradient, so the output of the M20 falls. The peak in the omni at 4 kHz is due to undesired resonances in the pressure vessel. At a frequency between 2.5 to 3 kHz, the amplitude tracking, phase tracking, and beam patterns begin to differ from optimal because of unwanted resonance. This is what determines the upper useful frequency limit of the M20.

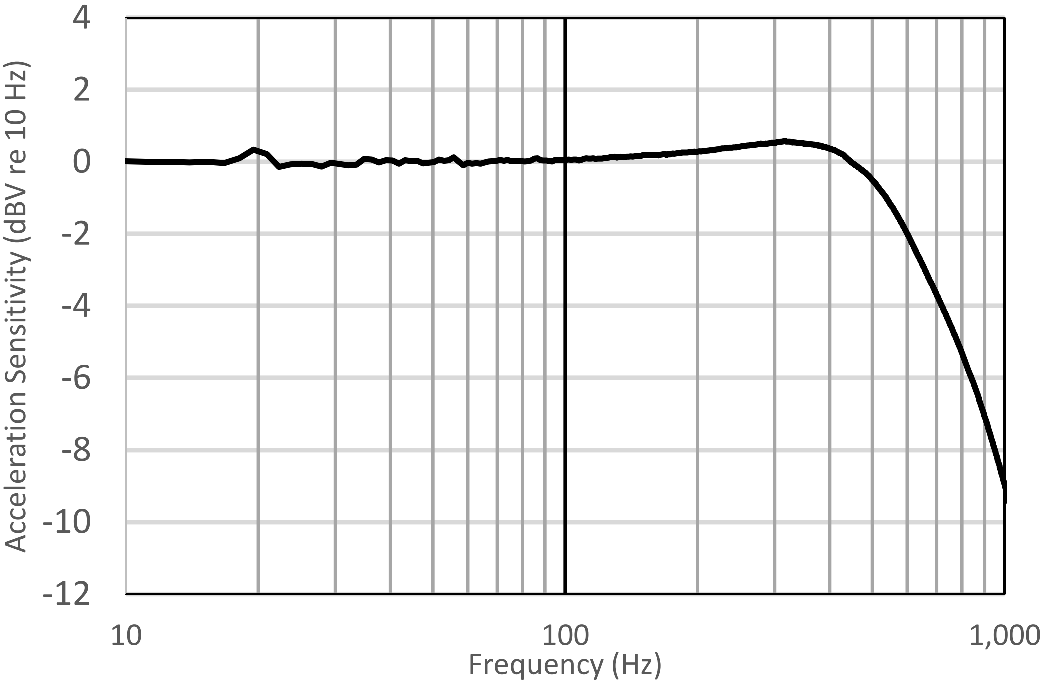

Figure 10: M20 accelerometer sensitivity

The in-band resonance of 450 Hz complicates signal processing, but is necessary to achieve sufficient acoustic sensitivity at 5 Hz to achieve the desired electrical noise floor in the preamplifiers.

8 Understanding the Phase Response of Vector Hydrophones

Figure 11 is a plot of pressure and pressure gradient in a plane wave. The horizontal axis can be thought of a snapshot in time, or the variation of pressure in space over time. Imagine that the plane wave is traveling from right to left (arriving from the +X direction). Further imagine that a M20 is at the location shown when the pressure is zero. At this time, the pressure gradient is positive and maximum. The left-hand side of the M20 experiences a greater pressure than the right-hand side so the M20 is accelerated in the positive X direction. Figure 11 illustrates that the pressure gradient leads the pressure by 90°.

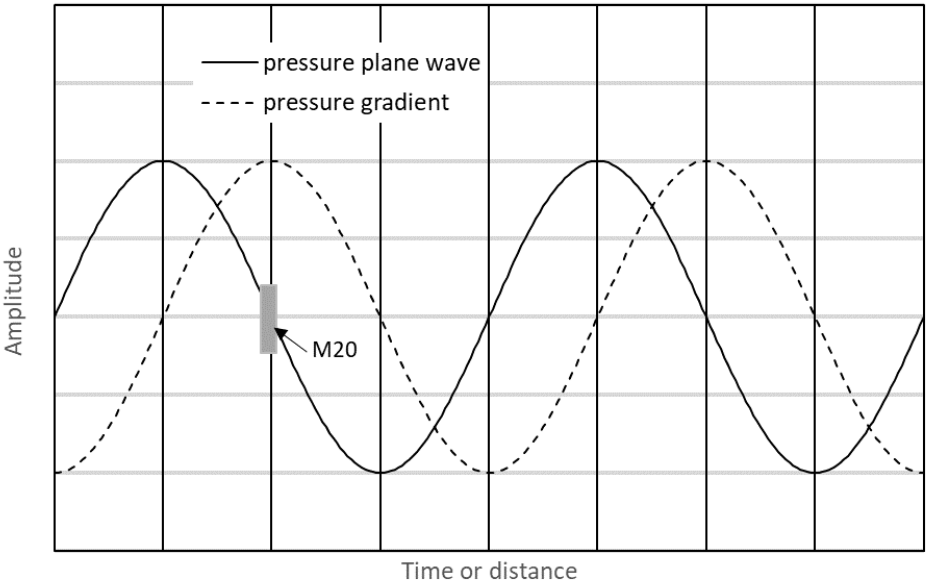

Figure 11: Relationship between plane wave pressure and pressure gradient

If the accelerometers had a resonance greater than the greatest frequency of interest, the pressure gradient would lead the pressure by 90° whenever the sound arrived along the positive X axis. In the M20, though, the resonances of the accelerometer are in-band and well damped so the 90° phase relationship is only true at the lowest frequencies. At other frequencies, you must account for the phase shift shown in Figure 9.

9 The Near Field

So far, all we have discussed is the M20's response to a plane wave, an acoustic pressure that has the same amplitude wherever the hydrophone is located. Planes wave occur when you are far from the source of sound so that the pressure amplitude has negligible 1/r dependence *compared to the pressure gradient*. You must also be far from a discontinuity of acoustic impedance, such as the water surface or a hard wall.

Figure 12Figure 12 compares the variation of pressure in space for a plane wave and one in which the sound source is nearby and on the left-hand side of the plot. In this instance, the amplitude of the pressure decreases with increasing distance from the source. In Figure 11, when a M20 was centered on a zero crossing in pressure, the pressure amplitude was equal on either side of the M20, but if there is a 1/r dependence to the pressure, the pressure difference is greater and hence the output of the M20 is greater. There is also a phase shift associated with the 1/r dependence.

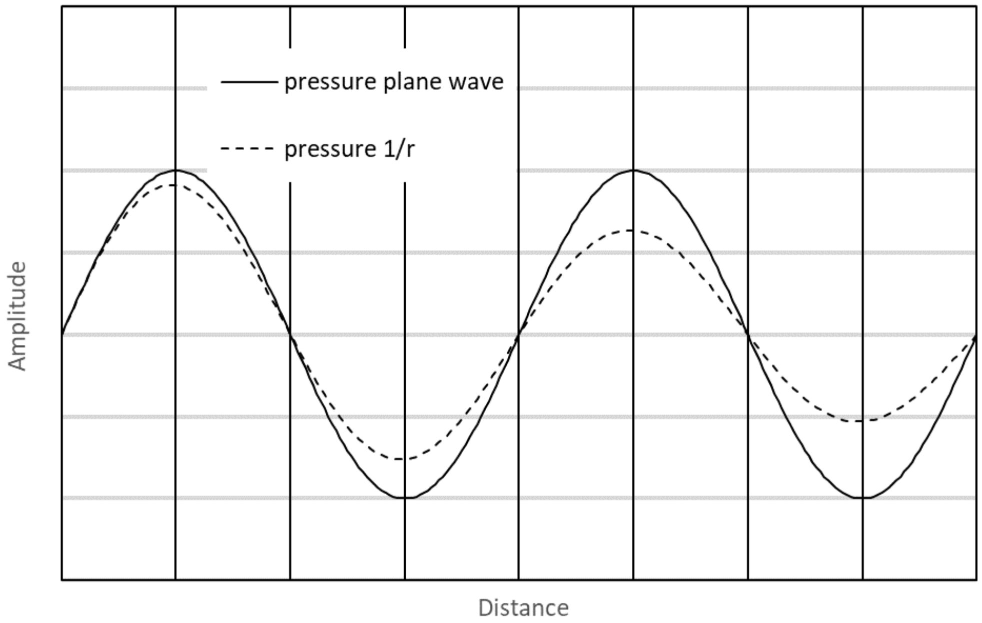

Figure 12: Relationship between pressure in a plane wave and pressure with a 1/r dependence

Near-field effects must be accounted for when calibrating a vector hydrophone.

10 Acoustic Calibration

A vector hydrophone is calibrated the same way that a pressure hydrophone is calibrated. A sound source and a reference hydrophone are placed some distance apart. The sound projector creates tones over the frequency band of interest and the output of the reference hydrophone is stored for each frequency. The reference hydrophone is then removed and the vector hydrophone is put in its place, after which the sound projector creates the same tones as the reference run. The outputs of the unknown and reference hydrophones are compared to get the sensitivity versus frequency plot. The phases of the directional channels compared to the internal omni are also recorded.

To get the greatest SNR and to provide a measurement time free of acoustic reflections from some boundary, it is desirable to minimize the distance between the sound source and hydrophone. This close proximity generates a 1/r dependence to the sound pressure. At low frequencies, where the pressure gradient is small, the 1/r dependence can be significant and must be corrected for post-calibration. Mathematically, the correction is expressed as

$$U_{Actual} = U_{PlaneWave} \ (1 ,- j/\{kr\})$$

where $k = 2\pi/\lambda$ where λ is the wavelength of sound, r is the distance from the sound source to the vector hydrophone and j indicates a complex number. At high frequencies where k is large, the correction is small, but at low frequencies, the near field pressure gradient dominates.

11 When should I use a vector hydrophone for particle velocity

If you are measuring the pressure in a plane wave and interested in particle velocity, there is no need to use a vector hydrophone; just measure the pressure and calculate the particle velocity.

If you are close to the sound source or to a boundary, then you need to use a vector hydrophone.

The lower the frequency, the more likely you need to use a vector hydrophone. The reason is that the place-wave pressure gradient is smaller at lower frequencies so any disturbances in the pressure field are more likely to be significant.

Even if you need to use a vector hydrophone, it does not mean that it is practical to do so. The next section sheds light on this.

12 Orders of Magnitude

This section calculates the magnitudes of the displacements, velocities, and accelerations that can be encountered. Assume for the moment that the specific gravity of the directional hydrophone is the same as sea water.

A well-designed directional hydrophone can measure a SPL of 80 dB re 1 µPa at 5 Hz. 80 dB is 10^{-2} Pa so

$$U = 10^{-2}/1026/1491 = 6.54 \times 10^{-9} \text{ m/s}$$

Displacement, d, = U/ω, and acceleration, a, = ωU, where ω is the angular frequency. Based on this

$$d = 6.54 \times 10^{-9}/(2\pi 5) = 2.08 \times 10^{-10} \text{ m and}$$

$$a = 6.54 \times 10^{-9} \times 2\pi 5 = 2.05\ 10^{-7} \text{ m/s}^2$$

To put this in perspective, the displacement above is 4 times the Bohr radius, the “distance” between the electron and the proton of a hydrogen atom. At higher frequencies and less SPL, the magnitudes are even smaller.

The numbers are tiny, which gives some insight into why vector hydrophones are susceptible to mechanically-induced noise.

13 Neutral Buoyancy and Hydrophone Shape

Some people believe that the vector hydrophones must be neutrally-buoyant, and that the shape of the pressure vessel must be spherical. Personally, I do not see it that way.

If the hydrophone is neutrally buoyant, its “particle” velocity equals that of the surrounding water molecules. If the specific gravity is less than water, i.e., positively buoyant, the velocity of the hydrophone will be greater than the water; if the specific gravity is greater than water, the velocity of the hydrophone will be less than water. For a spherical body, the velocity of a solid body relative to the velocity of a water molecule is

$$\mathrm{U}_{body} = \mathrm{U}_{water} \quad \frac{3\rho_{water}}{\rho_{water} + \ 2\rho_{body}}$$

Thus, if the density of the vector hydrophone is the same as water, the vector hydrophone will have the same velocity as the surrounding water. This equation is only valid for a sphere, but the concept is the same; Bodies heavier than water will move less than water; those that are lighter than water will move more.

The specific gravity of a M20 is typically 1.5 so the velocity of a M20 (if it were spherical) would be 3/4 that of the particle velocity of the water. This corresponds to a loss of sensitivity of 20 log(3/4) = 2.5 dBV. The only effect of this sensitivity loss is that the minimum detectable SPL is 2.5 dB greater if electrical noise is the limiting factor. This is not a serious penalty to pay. Even with this loss, the SPL referred electrical noise of the M20 is 70 dB at 5 Hz in a 1 Hz band.

The M20 is not spherical, but this is not important. The calibration of the M20 in water determines the relationship between pressure (pressure gradient) and particle velocity in all axes.

Prior to assembly of a M20, we measure the acceleration sensitivity of the accelerometers. Thus, after one accurate calibration, we know the mapping of acceleration sensitivity to acoustic sensitivity. We do not need to know what the attached water mass is; we measure its effect.

The real problem with neutral buoyancy, though, is mechanical noise as discussed in the next section.

14 Mechanically-Induced Noise

Accelerometer-based vector hydrophones must be able to measure picometres of displacement. It should come as no surprise, then, that the Achilles heel of vector hydrophones is they are highly sensitivity to mechanical inputs, whatever the source of the inputs. The desired input is the acceleration created by a pressure gradient; all other inputs are noise. Any mechanical inputs from the suspension can easily be greater than this and thus raise the noise floor.

GeoSpectrum's M20 is negatively buoyant and axially symmetric with one suspension point top dead center. The axis of symmetry is aligned with the Z axis. Thus, the forces from the suspension are aligned with the Z axis in a 3D M20 and this axis is the noisiest. Ideally, the suspension would introduce no force in the X and Y directions, but there is always a small component of force in a direction normal to the Z axis so the X and Y axis do pick up suspension vibrations. Nevertheless, in a M20, the X and Y channels are quieter than the Z axis.

Furthermore, the single attachment point at the top of the M20 enables GeoSpectrum to implement a noise-reducing feature in the X and Y channels of the M20. A horizontal component of force in the XY direction at the attachment point of the suspension causes the hydrophone to both rotate and translate. GeoSpectrum's M20 is designed such that the output from the rotation cancels the output from the translation. Hydrophones that employ this noise-reducing technique are 20+ dBV quieter at 5 Hz compared to hydrophones that do not employ it. This noise reduction has been confirmed in hundreds of flow tests on sonobuoys. More recently, M20s were part for a Foreign Comparative Test performed by a branch of the United States Navy. In this test, the vector hydrophones were bottom mounted on a frame with a flow shield in tidal currents of about 1 knot. The M20 was about 20 dBV quieter than the competition under these conditions.

Hydrophones that are neutrally buoyant cannot employ the noise-reducing technique. Such hydrophones must be suspended in all three directions.

15 Usage Guidelines

You must do everything you can to reduce mechanical inputs to a vector hydrophone.

If you deployed the vector hydrophone from a boat or a floating buoy, do not expect good results at very low frequencies; the mechanical inputs will mask quiet acoustic signals. In situations where there is a surface expression to the suspension, Geospectrum puts passive acoustic filters at about 30 Hz in order to avoid having the preamps saturate.

You can achieve good results from a vector hydrophone mounted in a glider so long as the glider is drifting in the current and all pumps and motors are turned off during the acoustic measurement.

The M20 can perform very well when it is bottom mounted so long as it is appropriately shielded from flow. Figure 13 shows the mount and flow shield designed and used by Keenan Ball at Woods Hole Oceanographic Institute. The M20 is suspended from the centre of the structure, which is surrounded by a fleece blanket, left hand side. The entire frame is then wrapped in a second layer of the fleece, right hand side. The metal suspension that holds the assembly introduces energy- absorbing shear into the rubber mounts. This system has been deployed but there are no measured results as of December 2022.

Figure 13: Double layer of flow shield, courtesy Keenan Ball, WHOI

GeoSpectrum also sells a triangular frame for bottom mounting with a recording system. This frame performs well so long as it is wrapped in a fleece blanket that extends to the ocean floor. This system was deployed in an area with ocean currents up to about 1 knot.

16 Summary

Vector hydrophones are far more complicated to use and their outputs are more difficult to interpret compared with an omni hydrophone. If you decide that you are going to use a vector hydrophone, expect a learning curve that will last a few months. Good luck!

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