A miniature vector sensor for line array applications

J. Clay Shipps, Ken Deng
Wilcoxon Research, Inc.
21 Firstfield Rd
Gaithersburg, MD, 20878, USA
Cshipps@wilcoxon.com

Until recently it was not possible to design a miniature vector sensor for line array applications which met the Navy's size and performance requirements. A vector sensor constructed using conventional PZT ceramic would result in a sensor that was too large for the existing line array space requirements and would not simultaneously achieve the bandwidth and noise requirements. The advent of PMN-PT crystals now allows a vector sensor to be constructed which meets both the Navy's size and acoustic performance requirements. A vector sensor will be discussed which utilized three PMN-PT crystal based axial accelerometers, a PZT omni-directional hydrophone, and a 4-channel amplifier. The excellent piezoelectric properties of the PMN-PT crystals allowed the vector sensor to be miniaturized and tests conducted on the vector sensor will demonstrate that the sensor met the Navy's required sensitivity, and bandwidth.

I. INTRODUCTION

Directional sensors have two appealing capabilities; the ability to selectively reject the noise emitted from discrete interfering noise sources and the ability to localize noise targets. A "vector" sensor is a directional acoustic sensors that measures both the acoustic pressure and the acoustic particle acceleration in three orthogonal axes. These four sensing elements are located in a single housing with a common acoustic phase center.

In the past, vector sensor technology for towed array applications could not meet the Navy's requirements due to limitations in the sensor's signal-to-noise ratio, its large size and associated issues with neutral buoyancy, and the robustness of the design. Recently, however, the needs of the Navy have been met through the use of a new piezoelectric material $Pb(Mb_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, also known as PMN-PT crystals, and a novel method to mechanically amplify the strain [1] induced into the crystal. Exploitation of the highly sensitive PMN-PT crystals now allow the vector sensor to be greatly reduced in size to the point where the sensor fits inside existing towed array hoses commonly used by the Navy.

II. LINE AND TOWED ARRAY SENSOR REQUIREMENTS

Historically the Navy has used Omni-directional hydrophones for most sensing applications including line and towed arrays. Therefore, array hoses have very specific inner and outer diameters to accommodate the most commonly used hydrophones for these applications. As a consequence, Naval vessels are designed to store and deploy these particular array hoses. Based on the amount of pre-existing hardware, the Navy has a strong desire to keep certain critical physical characteristics, such as sensor diameter, the same for all new sensors developed for line and towed array applications.

Although Omni-directional hydrophones have been historically "built-into" the Navy's line and towed array architecture, they are limited in their capabilities. Since they are pressure sensors, they provide only scalar information and do not provide directional, or vector, information on the target noise source which they detect. Vector sensors, on the other hand, do provide directional information because they detect both the scalar acoustic pressure as well as the acoustic particle acceleration, in all three axes, which is a vector quantity. The relationships between these four sensing elements can be use to pinpoint the location of the target noise source in three dimensional space. The four channels of the vector sensor, when combined, produce a cardiod directivity pattern which provides approximately 4.8 dB improvement [2] in the signal to noise ratio over a traditional Omni-directional sensor. The null of the cardiod can also be steered electronically to null out interfering noise sources such as the towing vessel. In addition, the vector sensor provides directional information on target noise sources.

The directional benefits of a vector sensor make it an ideal candidate for the Navy's line and towed array applications but the existing size constraints must be met, to make it a useful and cost effective alternative. First, the outer diameter of the sensor cannot exceed the inner diameter of existing line and towed array hoses for the financial reasons mentioned above. Second, the required operational bandwidth limits both the diameter and length of the sensor. The maximum dimension needs to be less than a half wavelength at the highest frequency of interest. With these goals in mind the Navy prepared a list of key design requirements for the vector sensor which are listed below:

Frequency Range	3 Hz to 7 kHz
Output Sensitivity	
Accelerometer	1.0 V/g
Hydrophone	-174 dB re 1.0 V/µPa
Environmental	
Temperature	-40 °C to 60 °C
Pressure (Operational)	0 - 1500 PSI
Pressure (Survival)	2500 PSI
Length	2.8" (71.3 mm)
Diameter	1.6" (40.7 mm)
Buoyancy	Neutral in water

III. PIEZOELECTRIC SENSING MATERIAL

Commonly used piezoelectric materials, such as PZT ceramic, do not allow the sensor designer to achieve the bandwidth, sensitivity, and size needed for towed and line array applications. To achieve the required accelerometer sensitivity using PZT, the size of the accelerometer sensing elements and the required proof masses have to increase. This increase and the need to maintain neutral buoyancy in a small package size have prohibited the use of this material for a towed vector sensor application.

The development of a small, highly sensitive, low noise accelerometer is a difficult challenge for the sensor designer but that goal is obtainable with the emergence of PMN-PT. Past research [3] into the piezoelectric properties of the crystals revealed exceptionally high values when compared to traditional PZT. Table 1 shows typical piezoelectric material properties for both PZT-4 and PMN-PT in three different sensing modes.

TABLE 1
Properties of piezoelectric materials

Parameters / Material	Symbol	PZT-4	PMN-PT
Relative Dielectric Constant	ε_{33}, ε_{31}	1350	4500
Relative Dielectric Constant	ε_{15}	1300	10000
Dielectric Loss Factor	$\tan\delta$	0.3%	0.3%
Piezoelectric Charge Coefficients (pC/N)	d_{33}	297	2000
Piezoelectric Charge Coefficients (pC/N)	d_{31}	-115	-900
Piezoelectric Charge Coefficients (pC/N)	d_{15}	580	4500
Piezoelectric Coupling Factor	k_{33}	0.58	0.91
Piezoelectric Coupling Factor	k_{31}	-0.34	-0.55
Piezoelectric Coupling Factor	k_{15}	0.71	0.95

The piezoelectric charge coefficients for PMN-PT are approximately seven times greater than those for PZT-4, and the coupling factors are approximately 1.5 times greater. These factors can be used to define a Figure of Merit for the piezoelectric material expressed as

$$(d_{ij} \cdot g_{ij} \cdot Y_{ij}) / (\tan\delta)^{1/2} \quad (1.1)$$

where g_{ij} is the piezoelectric voltage constant given by

$$g_{ij} = (d_{ij} / \varepsilon) \quad (1.2)$$

and Y_{ij} is the Young's Modulus of the material. The Figure of Merit is a unitless quantity which can be used to evaluate any piezoelectric material.

PMN-PT crystals are less stiff than PZT ceramics. This factor can make it difficult to obtain a broad bandwidth sensor. However, the Young's Modulus, or the stiffness of a piezoelectric material, varies depending on whether it is used in a short circuit or open circuit mode. The relationship between the two modes of operation is

$$Y_{ij}^{D} = Y_{ij}^{E} / (1\text{-}k_{ij}^{2}) \quad (1.3)$$

where Y_{ij}^{D} is the open circuit Young's Modulus and Y_{ij}^{E} is the short circuit Young's Modulus. This feature can be used to increase the stiffness of the material which will aid in increasing the bandwidth of the sensor. This is done by connecting the sensor to a preamplifier with a high input impedance.

IV. SENSOR DESIGN AND TEST RESULTS

The required form factor of the vector sensor was a major design consideration and drove all other features. The vector sensor is made up of one Omni-directional hydrophone, a tri-axial accelerometer, and a four channel amplifier. The hydrophone is a PZT ring which has direct contact with the outer case of the sensor. The accelerometers are mounted internally such that they detect orthogonal x, y, and z axis acceleration. Great care is given to reduce the off axis sensitivity of each accelerometer. A four channel amplifier was placed inside the vector housing to match each channels sensitivity and to provide sufficient gain. The finished sensor is shown in Fig. 1.

To determine the vector sensor's performance characteristics, the sensor was tested at a Naval Test facility. The sensor was tethered, as shown in Fig. 2., from a rotating shaft by highly compliant rubber bands both vertically and then horizontally. The sensor was suspended 25 ft. deep and was located 2 meters from the sound source. A gated pulse method was used to obtain the data.

Fig. 1. Finished vector sensor

A frequency response of the hydrophone is shown in Fig. 3. The hydrophone's response is sufficiently flat at the target sensitivity level of –174 dB re 1V/μPa over the bandwidth of interest. The resonance of the hydrophone is well above the operational bandwidth of the sensor. The frequency responses of the three accelerometers are shown in Fig. 4. The accelerometers exhibit a resonance around 13.5 kHz – 15 kHz but have a relatively uniform response to the upper operational limit of 7 kHz. As a general rule, the resonance of a sensor should be twice the highest frequency in the operational bandwidth to insure a smooth response in the frequency band of interest. In this case, the highest frequency of interest is 7 kHz.

The polar response of the hydrophone is shown in Fig. 5. As expected, the hydrophone's response is Omni-directional at this frequency. The polar responses for the x and y axis accelerometer's are shown in Fig. 6, and the z axis accelerometer polar response is shown in Fig. 7.

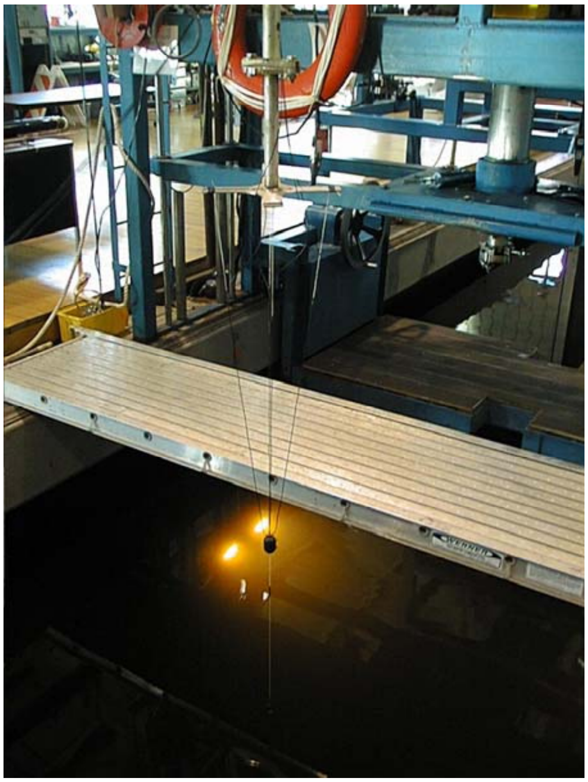

Fig. 2. Vector sensor tethered from rotation test shaft

As hoped, each accelerometer has a classical dipole pattern at 7 kHz, the upper end of the frequency band. The sensor's polar responses were also measured at 1 kHz, 3 kHz, 5 kHz, 9 kHz, 10 kHz and 13 kHz. Surprisingly the accelerometer's polar responses remained dipole in configuration up to 10 kHz. At 13 kHz the accelerometers no longer produced the classical dipole patterns due to the resonances of the system.

The off-axis nulls for each of the three accelerometers are at least 30 dB down from the on-axis response. This is an important feature that insures that a uniform cardiod response will be generated when the four sensing channels are combined mathematically.

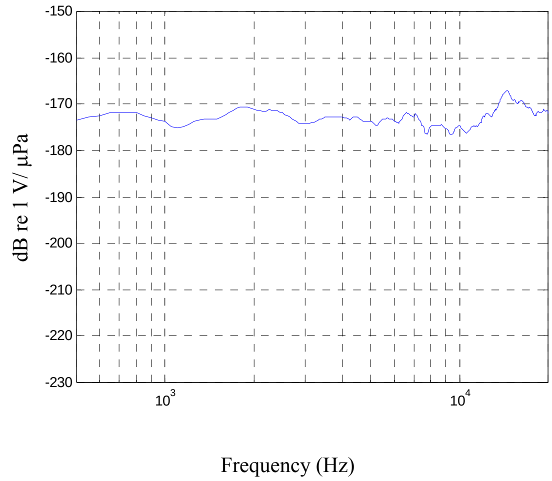

Fig. 3. Hydrophone frequency response

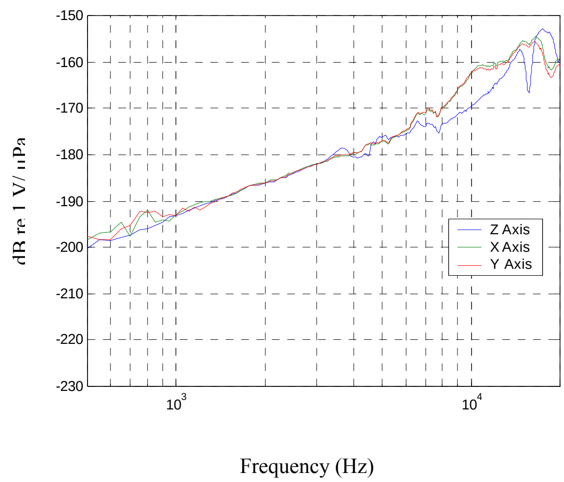

Fig. 4. Accelerometer frequency responses

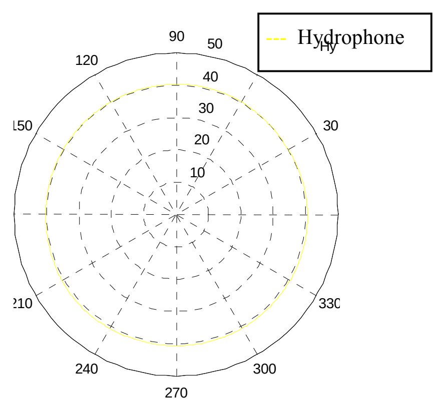

Fig. 5. Hydrophone polar response at 7 kHz.

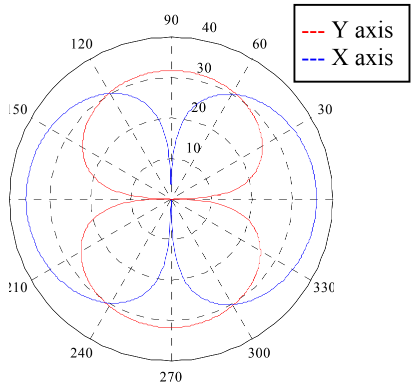

Fig. 6. X and Y axis accelerometer polar responses at 7 kHz.

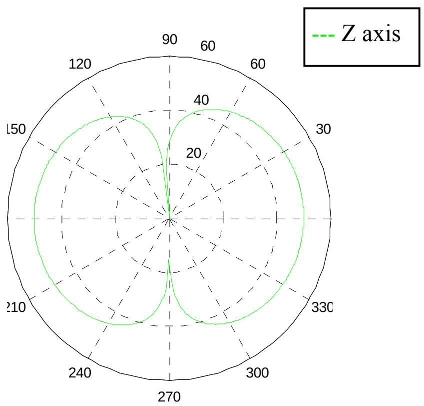

Fig. 7. Z axis accelerometer polar response at 7 kHz.

V. CONCLUSION

A miniature vector sensor was designed and constructed by Wilcoxon Research which met the Navy's requirements for towed and line arrays. The sensor's packaging was designed to be neutrally buoyant and to fit inside existing line and towed array. The vector sensor was comprised of an Omni-directional hydrophone, a tri-axial accelerometer, and an on board four channel amplifier. The sensors acoustic performance met the Navy's sensitivity and bandwidth requirements. The four channels of the vector sensor, when combined, produce a cardiod directivity pattern which provides approximately 4.8 dB improvement in the signal to noise ratio over a traditional Omni-directional sensor. The null of the cardiod can also be steered electronically to null out interfering noise sources such as the towing vessel. In addition, the vector sensor provides directional information on target noise sources.

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