



Sensor Design Parameters for Underwater Applications

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SENSOR DESIGN PARAMETERS FOR UNDERWATER APPLICATIONS

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ABSTRACT

Ship vibration and unsteady pressures must be measured and identified, including on-board equipment, water flow across the hull or control surface, cavitation of the screw and other sources. Sensors designed for these measurements all require some degree of protection for their intended use near or under water. This paper discusses cable attachment methods, waterproofing of cable and sensors and pressure testing of underwater cables that are used with piezoelectric accelerometers and pressure sensors to render them suitable for measurement in underwater environments.

KEY WORDS: Piezoelectric, ICP[®], underwater, hydrotest, waterblock, flow noise, wave slap, bubble energy, blast, cavitation

THE TEST ENVIRONMENT

High hydrostatic loads found in underwater applications require sensors strong enough to survive the loading conditions, yet have a functional full scale measurement range in the mili-g or mili-psi often found in noise flow measurements. Piezoelectric sensors have a wide dynamic range and are AC coupled devices, thus ignoring any ambient or static pressure. For example, this property provides these sensors with the unique ability to monitor low level dynamic pressures while being subjected to a high static background pressure level. [1] When inserted in the hull of a vessel as shown in Figure 1, the pressure sensors on the hull surface acts as water microphones.



Figure 1: Typical Open Tunnel Water Test of Ship Hull
Photo by: John F. Williams

SENSORS CONFIGURATIONS & DESIGNS

Pressure sensors and accelerometers are available in many variations. Two key features for underwater use include electrical isolation and integral over-molded cable assemblies. Electrical isolation is important when monitoring noise in the presence of electric drive vessels. The cable attachment mechanism to the sensor is vital and should be hydrotested under pressure for leaks and functionality. Some examples shown in Figure 2a & b, include pressure sensors and accelerometers with water-blocked cables.



Figure 2a - Quartz Piezoelectric Pressure Sensors for Flow Noise



Figure 2b - Ceramic Piezoelectric Accelerometers for Flow Induced Vibration

Underwater vibration and pressure environments are very harsh, so a robust sensor design is required that exceeds the test levels. With respect to accelerometers, there are a number of important sensor characteristics that benefit from a shear mode accelerometer design, which clamps the sensing crystals between a center post and seismic mass.

Figure 3 shows a compression memory ring that applies a preload force required to create a rigid linear structure. Under acceleration, the mass causes a shear stress to be applied to the sensing crystals. The advantage of this design is that by isolating the sensing crystals from the base and housing, the shear accelerometer excels in rejecting thermal transients and signal noise resulting from base bending effects. This is a very important feature when attaching them to relatively thin walled vessel hull models during wave slap applications, such as splash down testing of space capsules (Figure 4).

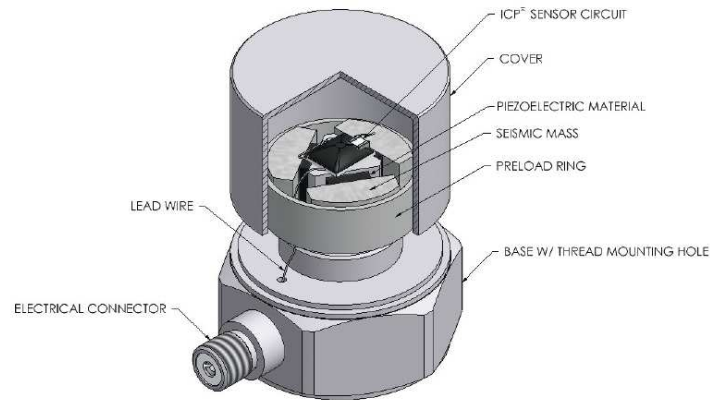


Figure 3: Shear Mode, Welded Hermetic Accelerometer



Figure 4: Orion Crew Module Drop Test

Photo by: NASA/Sean Smith

The shear geometry also lends itself to small size, which minimizes mass loading effects on the test structure. To assist in weight reduction, most low mass accelerometers are made from titanium. The accelerometer is assembled using a laser welding process to ensure good weld penetration and resulting hermetic seal.

Piezoelectric pressure sensors are suited for dynamic pressure measurements including turbulence, cavitation, or explosive blast. These measurements require a fast response or rise time, ruggedness, and high stiffness in order to obtain a high frequency response. Piezoelectric pressure sensors are available in various shapes and thread configurations to allow suitable mounting for various types of pressure measurements.

Quartz crystals are used in pressure sensors for flow noise measurement to ensure stable, repeatable operation. With an active surface diameter of 0.15 inch (3.2mm) and resonant frequency between 250k and 500 k Hz, well above those typically experience in flow or cavitation. [5] The AC coupled nature and high strength of their piezoelectric crystals allows them to measure small changes in the background of very large static loads, over 100 to 1000 times their measurement range.

Figure 5 is a general purpose pressure sensor with built-in electronics. Flush mounting of pressure sensors in a plate or wall is desirable to minimize turbulence, avoid a cavity effect, or avoid an increase in a chamber volume, especially important when measure flow noise on the external surface of an underwater vessel.

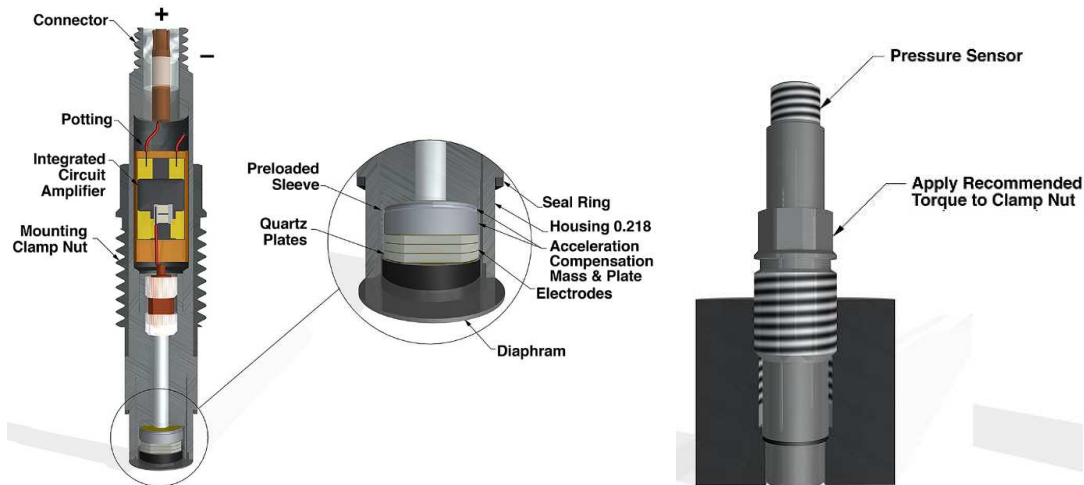


Figure 5: Typical Quartz Pressure Sensor Cross Section and a Typical Flush Mount Installation for Flow Noise Measurement

Piezoelectric pressure sensors can also measure shock waves and bubble energy associated with underwater explosion testing (Figure 6). The sensors depicted in Figure 7 are structured with a volumetrically sensitive, omnidirectional tourmaline crystal, suspended and sealed in an

insulating, oil-filled vinyl tube. They have integral ICP[®] microelectronics that provides a clean, non-resonant, high-voltage output through long cables in underwater environments. They can be supplied with a sealed cable of appropriate length up to 300 meters, ready to operate. Two physical configurations are available which allow for mounting for a free field measurement, or in a form that may be directly mounted to underwater structures.



Figure 6: Underwater Blast Test Setup

Tourmaline is a naturally occurring piezoelectric material in nature, and when used in underwater sensing, an electrical charge is generated whose magnitude depends on the hydrostatic pressure applied to it and the area over which this pressure acts. [4]

The magnitude of the piezoelectric effect is defined by the polarization vector

$$\text{Eq. 1 } P = P_{xx} + P_{yy} + P_{zz}$$

By substituting shear and normal forces acting on the crystal, for the piezoelectric coefficients for tourmaline in each axis, we obtain

$$\begin{aligned} \text{Eq. 2 } P_{xx} &= P_{yy} = 0 \\ P_{zz} &= 2d_{31}(-p) + d_{33}(-p) \end{aligned}$$

This is the key reason why tourmaline responds to hydrostatic pressure if electrodes are applied in its z-axis direction. By contrast, if the piezoelectric coefficients for quartz were substituted in Eq. 1, it would show that quartz does not possess a hydrostatic response in its x, y, or z-axes ($P_{xx} = P_{yy} = P_{zz} = 0$). [4] It is this unique property of tourmaline that makes it suitable for measuring underwater explosions.

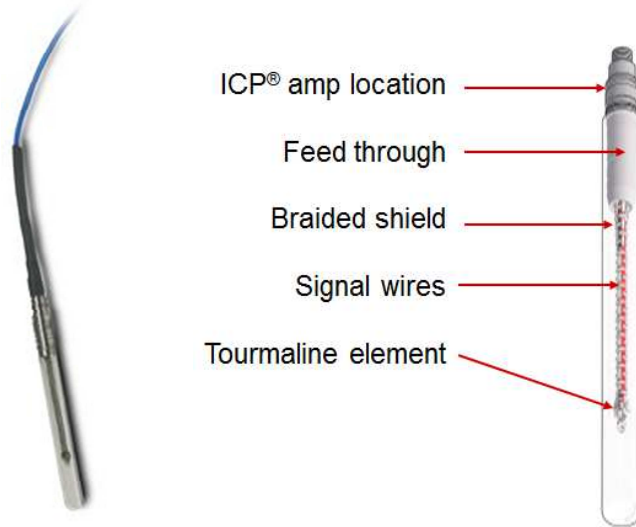


Figure 7: Tourmaline Underwater Blast pressure Sensor Configuration

LEAK TESTING

Leak testing on hermetic sensors to determine if the structure has any cracks in its welds. The two most common testing methods are a gross bubble test and a helium leak test. A bubble test is typically provided as an end of line test for all sensors to ensure their structural integrity. For fine leak test work, the helium test is performed.

The gross bubble test verifies a leak rate with less than 1×10^{-3} cc/sec flow. This relatively fast bubble test is a variation of MIL-STD-883E, Seal Test Method 1014.10, Section 3.3.1. [2][3] In this test, sensors are submerged into a tank of heated fluoro-inert liquid. The fluoro-inert is maintained at an operating temperature of approximately 100 °C (212 °F). The heated fluoro-inert causes any trapped gasses inside the sensor to expand and to bubble out of the sensor. The bubbles become visible during the test in the fluoro-inert liquid (refer to Figure 8).



Figure 8: Gross Leak Test Apparatus

For a more thorough investigation of hermeticity, accelerometers are subjected to a fine helium leak test. The fine leak test uses a mass spectrometer, where the accelerometers or their connectors are pressurized in helium. A mass spectrometer vacuum leak detector then verifies a leak flow rate of less than 2×10^{-8} cc/sec.

The sensor is pressurized to 300 psi with helium and then placed in the mass spectrometer chamber. The sensor passes this test when the leak rate is less than 2×10^{-8} cc/sec. If it does not pass, the third test is performed, which is a sniffing test to pinpoint the source of leakage. In the sniffing test, a hose is connected to the mass spectrometer test chamber. The sniff hose uses a probing needle (Figure 9) to sniff around all welds, chamber seams, the sensor connector shell, and center electrical contact to pinpoint the leak.



Figure 9: Leak Detection ‘Sniff’ Test on Weld Joint of a Hermetic Connector

GETTING THE SIGNAL OUT OF THE WATER

Piezoelectric sensors operate from power supplies with either ICP[®] constant current or constant voltage line driver. A typical sensing system including a quartz ICP[®] sensor and a simple two-wire connection and basic constant current signal conditioner is shown in Figure 10.

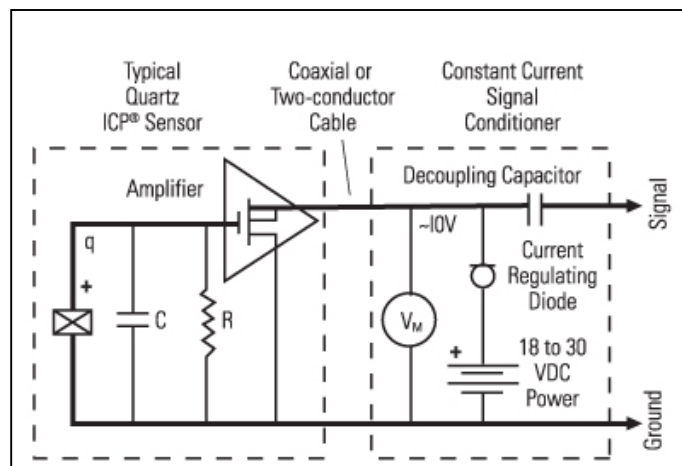


Figure 10: Typical ICP[®] Sensing System

Signal conditioning consists of a well-regulated 18 to 30 VDC source (battery or line-powered), a current-regulating diode (or equivalent constant current circuit), and a capacitor for decoupling (removing the bias voltage) the signal. The voltmeter (VM) monitors the sensor bias voltage

(normally 8 to 14 VDC) and is useful for checking sensor operation and detecting open or shorted cables and connections.

Cables used for signal transmission are the greatest source of failure in underwater sensor design. Waterblocking compound must be used in cables to impede the axial flow of water should the outer cable sheath become cut (Figure 11). There are various degrees of acceptance and tests that can be performed on a cable to determine the effectiveness of the waterblocking compound. The various test methods are typically found in MIL-DTL-915 or within the specified requirements of the procurement specifications. [6]

Another and often a more important reason to waterblock or void fill a cable cross section, is to provide the crush resistance required to operate as specified at depth.

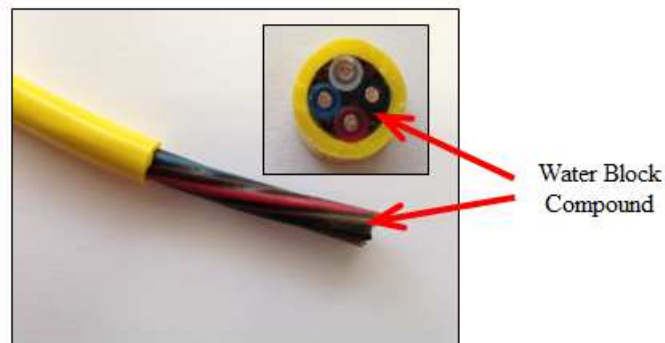
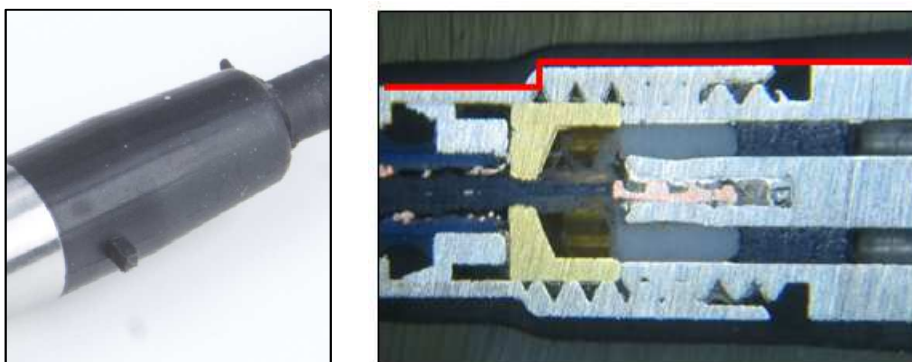


Figure 11: South Bay Waterblock Cable Cross Section View [7]

The cable material must also be compatible with thermoset materials used for attachment to the sensor housing. Thermoplastic elastomers and polyurethane materials offer good bonding characteristics and are easy to mold. An example of the over mold is shown in Figure 12. The cross section identifies the critical area of bonding required to survive hydrostatic pressures.



**Figure 12: Over-molded Cable Connector to Underwater Sensor
Cross Section Shows Bond Line Depicted by the Red Line**

SENSOR CONFIGURATIONS AND HYDROTETSING

If the bond is not well made, the first indication is typically in the form of an intermittent bias voltage measuring between $\sim 0.0\text{v DC}$ (shorted) and $\sim 30\text{v DC}$ (open circuit). When evaluating

such failures, cables are often removed and inspected piece by piece. In extreme case of leakage, cable conductors contamination is evident as shown in Figure 13.

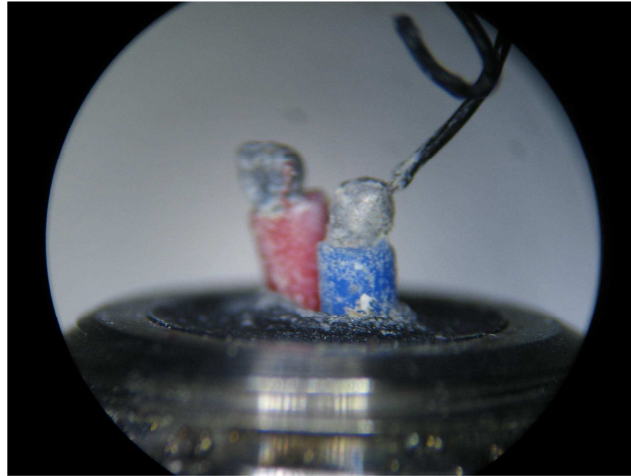


Figure 13: Salt Water Contamination of Conductors

Hydrotetsing is employed to ensure successful performance at operational depths. Testing verifies that the waterblock cable and sensor to cable over-mold assemblies resist leakage during underwater applications. The performance of the unit under test (UUT) is verified prior to being subjected to the hydro test. The UUT is mounted into a flange that will couple with a pressure vessel and the cables are inserted into feed through adapters as shown in Figure 14.

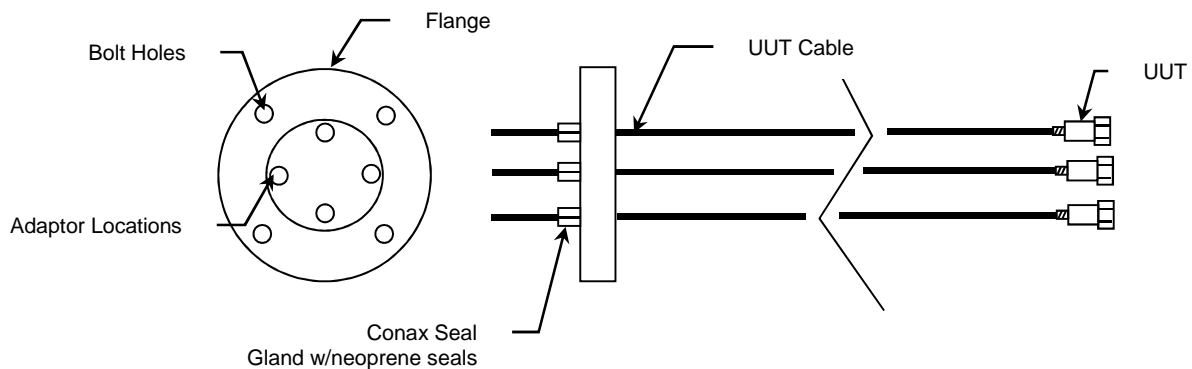


Figure 14: Sensor Arrangement Prior to Hydrotesting

The UUT assembly is placed into the pressure vessel and the water added to the desired starting level. The water is allowed to stabilize to room temperature to avoid unstable pressure levels over extended soak times. A hydraulic pump is connected to the pressure vessel and is energized until the desired test pressure is achieved and then the desired test duration begins (Figure 15). The UUT may be checked during the hydro test by monitoring characteristics such as operating bias voltage, capacitance and or continuity as appropriate for the sensor's performance characteristics.

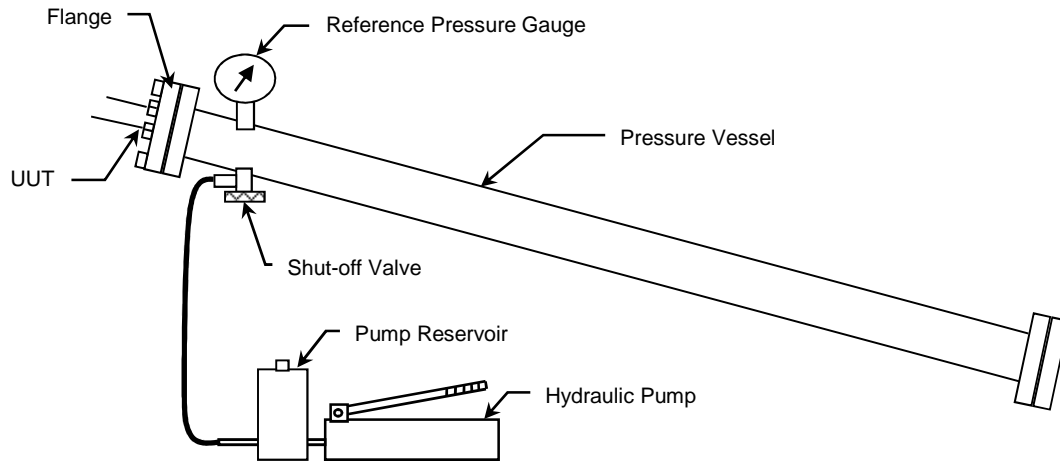


Figure 15: Hydrotesting Apparatus

SUMMARY

Piezoelectric sensors have proven to provide a high dynamic range and are well suited to measure both vibration and acoustic levels of flow noise in the presence of high hydrostatic pressures. In any application involving underwater sensing, consideration must be given to electrical isolation, sensor hermeticity and water proofing of the electrical connection to the cable.

The use of pre-amplified ICP[®] constant current sensors provides an easy to use two-wire system, with a high signal-to-noise ratio and the ability to drive high frequencies over long distance cables. The cable should also include a waterblock treatment to avoid ingress of water after an abrasion event or direct cut, and also to provide support to the internal wires from the hydrostatic forces at operational depths.

Finally, assuming a sensor will survive at depth is a high risk endeavor easily minimized through hydrotesting each sensor/cable assembly prior to use. Monitoring of bias voltage during testing can offer an understanding of performance degradation during hydrostatic loading.

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BIOGRAPHY

Bob Metz Holds a BS degree in Aeronautical and Astronautical Engineering from The Ohio State University and Master of Business Administration from State University of NY. Bob has been an instrumentation engineer for 21 years, focusing on acoustic, vibration, pressure and force measurement using piezoelectric sensors, and is currently a Director of the Aerospace & Defense Division of PCB Piezotronics, Inc. His email address is bmetz@pcb.com.



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