High Accuracy Pressure Instrumentation for Underwater Applications

Mark H. Houston and Jerome M. Paros

Abstract

For many underwater observation and construction activities the accurate measurement of pressure is a key requirement The pressure measurement may be used as primary observation data such as in Tsunami detection, wave and tide gauges, and platform leveling applications, or the pressure measurements may be used as associated observation data such as in depth sensors for ROV'S, profiling instruments, and towed arrays. In all these applications pressure transducers employing quartz resonator technology have been successfully used in underwater systems that required the highest resolution, accuracy, and stability. This paper describes the construction, operation, and performance of the quartz resonator technology with specific examples of underwater applications. In addition, advances in materials and electronics promise to extend the usefulness of these devices within virtual instrumentation arrays aimed at synoptic observations.

Introduction

Resonant-quartz pressure transducers can effect a typical application accuracy of 100 ppm (0.01%FS) with a resolution of 1 x 10^{-8}. This remarkable performance can be achieved through the use of a precision oscillator whose frequency varies with pressure-induced stress on the quartz crystal resonator. Quartz crystals make excellent sensing elements because of quartz's inherent mechanical repeatability, stability, and low hysteresis. The crystal oscillations are maintained and detected with oscillator electronics similar to those used in precision clocks and counters.

A. Dual-Beam Resonator Construction

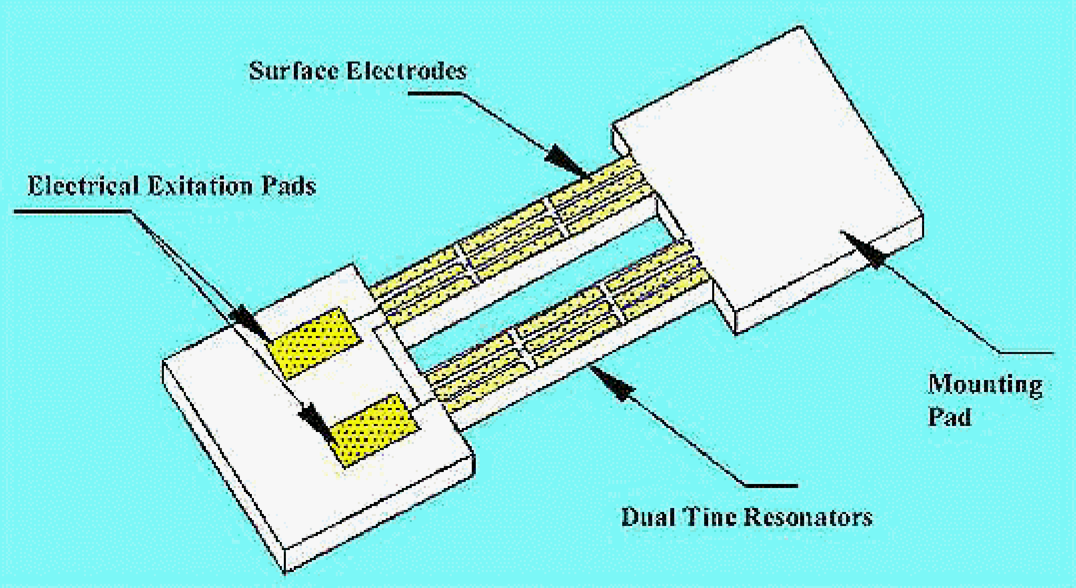


Figure 1. Dual Beam Quartz Load Resonator

Figure 1 illustrates a flexurally-vibrating, dual beam, load-sensitive resonator. This double-ended tuning fork consists of two identical quartz beams driven piezo-electrically in 180° phase opposition such that little vibration energy is transmitted to the mounting pads. The high-Q resonant frequency, like that of a violin string, is a function of the applied beam-axial load; the frequency increases with tensile and decreases with compressive force.

Although the load resonator is insensitivitive to temperature, differences in the thermal expansion coefficient between quartz and other materials produce thermal effects which are compensated for with a unique digital temperature sensor. The resonant frequency of the piezo-electrically driven, torsionally oscillating tines is a function of temperature. Combining the outputs of the two sensors into a modeling equation results in thermally-compensated, high accuracy, calculated pressure output over a wide range of temperatures.

B. Bourdon Tube Mechanism

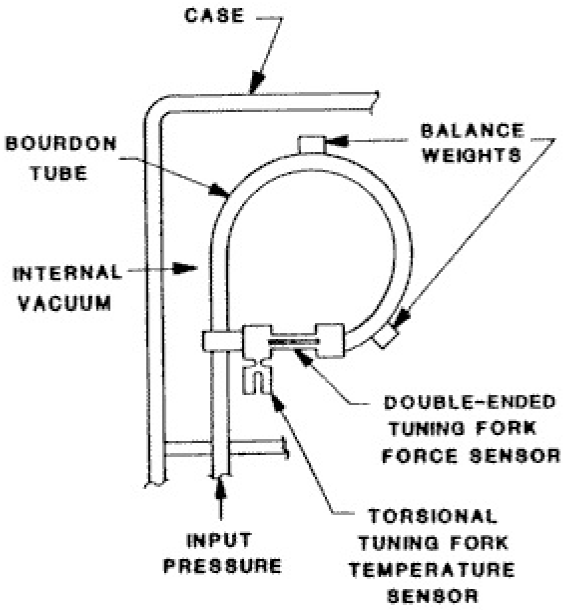


Figure 2. Bourdon Tube Mechanism.

The Bourdon Tube illustrated in Figure 2 shows one mechanical arrangement that can be used to transform pressure to force. A pressure applied to the tube interior generates a force across the quartz resonator as the tube tries to unwind with applied pressure. The change in the frequency of the quartz oscillator is a measure of the applied pressure. The tube and resonator are enclosed within anevacuated chamber to eliminate air damping, to maximize the Q of the oscillator, and to provide a reference vacuum for absolute pressure measurements. The sensitivity and pressure range of the transducer can be controlled by the physical parameters of the tube, i.e. metallurgy, wall thickness, hoop diameter, etc. Because the total mechanism movement is approximately several microns fullscale, linearity, hysteresis, and repeatability of the overall sensor are excellent.

Resonant Quartz Sensor Performance

Digiquartz transducers have demonstrated a deep-sea pressure measurement performance with a resolution of 0.15 ppm and an accuracy of 0.015% of full-scale, (0.003% corrected), for a 10,000-psi (absolute) sensor [1].

A. Resolution, Noise, & Accuracy

The ultimate resolution achievable with a transducer is limited by its measurement noise level. Noise for resonant quartz devices includes both electronic and mechanical components. For short records (less than 10^3 sec), the noise is dominated by thermal and electronic "count" errors. For stable, deep-sea environments, these errors can be limited to less than 0.2 ppm [2]. For longer records, the measurement noise includes significant contributions from oscillator noise, thermal variations, and mechanical drift. For example, yearly drift rates of 20 to 150 ppm are typical for the resonant-quartz Bourdon Tube sensors.

B. Underwater Sensor Applications Geophysical and Oceanographic Measurements

Precision pressure measurements in the deep ocean have contributed to the understanding of geophysical and oceanographic processes over a wide range of time scales.

These primary sensor measurements have included short-term events such as microseisms, surface wind-driven surface waves, and tsunamis, and long-term phenomena such as oceanic tides, planetary waves, and other atmospheric forcing events. For example, Weam and Baker [3] reported on the geostrophic transport fluctuations of the Antarctic Circumpolar Current using pressure transducers located in the Drake Passage. Bernard and Milbum [4] deployed quartz resonator sensors as part of a long-wave observational program, and Fox [5] investigated hydrothermal venting activity on the Juan de Fuca ridge.

C. Measurements for Location and Positioning

A second major underwater application domain for quartz-resonator technology is the determination of depth for use in location and positioning of instruments, sensor arrays, and underwater vehicles.

1) Profiling Instruments

The first systematic sampling of ocean properties was begun in the 1860's using hydrographic wire casts with Nansen bottles and reversing thermometers. Sample depths were calculated from measurements of the lengths of wire-out corrected for wire angle as estimated from the surface entry angle and from comparisons between protected and unprotected thermometers. Today, oceanographers use CTD instruments (conductivity, temperature, & depth) to measure "continuous" profiles of water parameters. With proper corrections for sea water compressibility, quartz-resonant depth sensors can measure oceanic depths (6000m) to an absolute accuracy of less than one meter. Moreover, these temperature-compensated, low power sensors allow construction of reliable, self-contained wireless devices with internal data recording.

2) Towed-body Depth Sensors

In many active and passive sonar systems, accurate tow depth is an important auxiliary parameter for effective data acquisition and processing. For example, the AMS deep-tow sonar side-scan system [6] uses vehicle depth to correct the geometric distortion of the side-scan multi-beam image of the bottom. Accurate depth data is also required to merge adjacent, overlapping images to form coherent sea floor topography. Towed, passive sonar systems usually employ an array of receivers. These individual receivers can be combined into synthetic aperture arrays and can be steered to maximize signal to noise, but only if the receiver geometry is well defined, through accurate depth measurements. Quartz-resonator sensors can reliably measure depths to ±10 cm to a depth of 1000 m.

3) ROV & AUV Applications

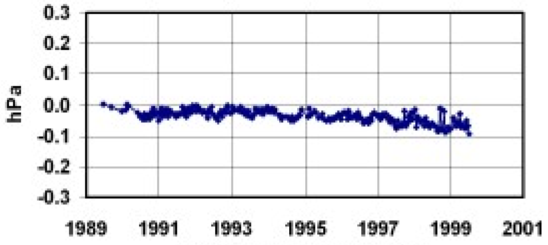
Manned underwater vehicles dominated the initial efforts to discover the ocean depths. Remote Operated Vehicles (ROV's) have garnered the major share of underwater services to support oil and gas exploration, production, and associated construction. Both the accuracy and long-term stability of the quartz-resonant depth sensors have played an important role in reducing the life-time support costs and increasing the operating usefulness of these work-horse systems. These characteristics as well as reliability and low power consumption will also play key roles in the practical use of the next generation Autonomous Underwater Vehicles (AUV's).

Performance Improvements from Technology

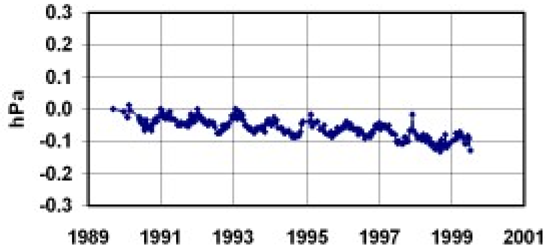
Given that the quartz-resonator technology coupled with simple mechanical structures such as the Bourdon tube currently provides outstanding performance, where and what kind of performance enhancements can we expect?

Significant improvements to the sensor's performance / price ratio can be achieved by:

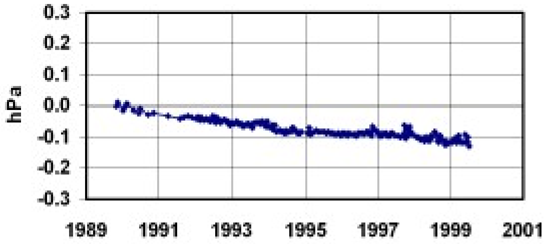
- Improving the design and manufacturability of the sensors to decrease price;
- Improving the long-term mechanical stability of the devices (reduce life-time costs);
- Improving the oscillator electronics' resolution and accuracy; and
- Improving the sensor's communications architecture to provide capabilities for synchronous sensor array sampling.



S/N 34264 Long-Term Stability



S/N 34266 Long-Term Stability



S/N 37131 Long-Term Stability

Figure 3. Barometer Drift Rate

Figure 3 plots the cumulative drift on three resonant-quartz barometers (11 - 16 psia). rates range from -3 to -11 ppm per year. The barometer design, which uses a bellows mechanism, has a much "softer" pressure-to force mechanism than the Bourdon tube design. Lower pressure mechanisms, in general, will usually exhibit a lower drift rate than higher pressure mechanisms.

A. Materials

A review of the material properties of the components of the deep-sea quartz-resonator sensors suggests that new materials for the Bourdon tube and the quartz-metal attachment interfaces may improve the long-term stability of the current sensor design.

B. Electronics

Resolution of quartz transducers is a function of resonant frequency, sampling time, and counting-clock frequency. Using high frequency, interpolating, start-stop counters, a 10-sec integration period will resolve the typical periods to a few parts per billion [7].

1) DSP Processing of Stable Sine - Wave Oscillator Signals

Useful improvements in sensor performance can be accomplished in several ways. First, resolution and accuracy of a measurement at a given sampling frequency can be increased by utilization of a low-noise, stable, sine-wave oscillator design and employment of more sophisticated processing algorithms with accurate non-integer cycle counting. Figure 4 shows the results of an experiment to show the feasibility of these ideas.

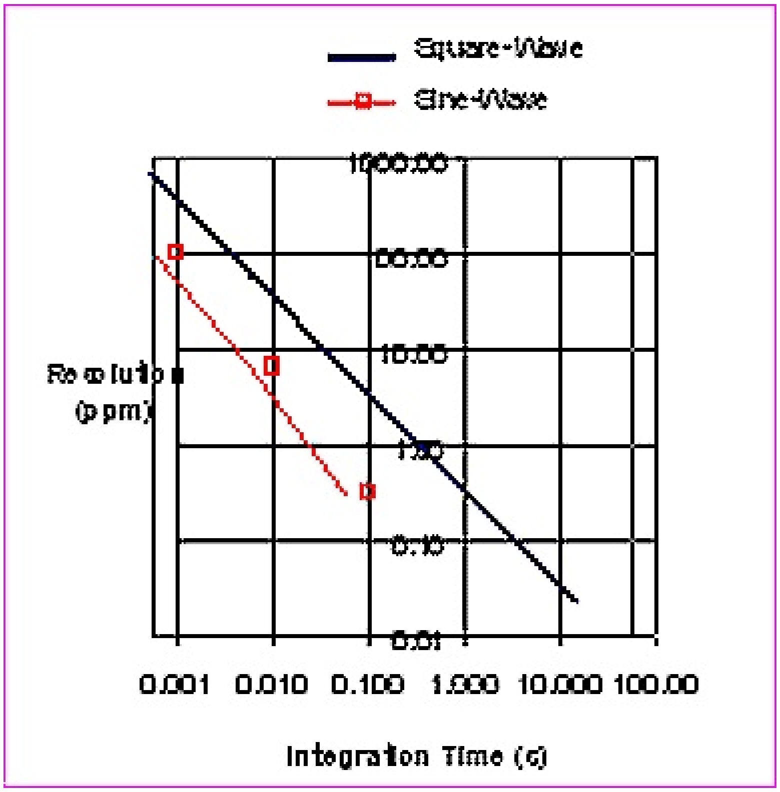


Figure 4. Resolution vs. Integration Time

The right-hand line of Figure 4 shows a plot of pressure resolution in ppm as a function of clock-count integration time for Paroscientific Intelligent Transmitters. These devices use the signal from a digital (square-wave) pressure oscillator to gate counts of an internal clock running at 15 MHz. The integration time is the span over which the reference counts are made. The resolution represents an uncertainty of ± l count over the cumulative reference-clock counts. As an example, an integration time of 0.6 sec represents a resolution of 1 ppm; an integration time of 0.01 sec gives a resolution of 60 ppm. Faster sampling yields less resolution; longer integration time produces better resolution. Of course the resolution does not increase monotonically with integration time, since thermal and oscillator noise begin to dominate the results.

The left-hand line of Figure 4 shows the results of an experimental setup with a first-cut, low noise, sine-wave oscillator. The oscillator, although of our standard design, was hand-built and thermally isolated to achieve the best noise performance with reasonable effort. The oscillator output was oversampled at 80-kHz, and then digitally processed to extract the best-fit period. The stability of the solution and therefore the resolution was determined by comparing different integration-time partitions of a continuous record span.

The results demonstrate that straightforward improvements to the sensor electronics will achieve resolution of 10 ppm for 50-Hz pressure signals without sacrificing any DC accuracy. However, to reach a level of 30 ppb for 1-sec sample rates will take additional efforts to develop a more stable oscillator.

2) Communications Architecture for Synchronous Array Sampling

The majority of pressure sensors are used as point measurement devices to sample a slowly varying pressure field. However, the ability to sample the absolute pressure-wave field with increased resolution from 0.0001-Hz to 50-Hz may suggest measurement opportunities that would benefit from sensor arrays. In order to be able to combine sensor outputs into a steerable array, hardware and software communications protocols need to be in place to ensure sampling synchronization among sensors. Some of these requirements are currently being incorporated into industry standards for "smart transmitters" (IEEE 1452.1).

Conclusions

Resonant-quartz transducers have demonstrated an excellent record of accuracy, stability and performance in underwater activities such as deep-sea research and development, oil and gas exploration and production, and undersea construction.

Advances in materials and electronics promise to extend the usefulness of these devices into virtual instrumentation arrays aimed at synoptic observations.

References

[1] Eble, M.C., and F.I. Gonzalez, 1990: *Deep-Ocean Bottom Pressure Measurements in the Northeast Pacific,* Tsunami Project, PMEL, NOAA Report 1196, 23 pp.

[2] Weam, R.B., Jr., and N.G. Larson, 1982: Measurements of the sensitivities of digiquartz pressure sensors. *Deep-Sea Res., 29,* III - 134.

[3] Weam, R.B. Jr., and D.J. Baker, Jr., 1980: Bottom pressure measurements across the Antarctic Circumpolar Current and their relation to the wind. *Deep-Sea Res.,* 27, 875-888.

[4] Bernard, E.N., and H.B. Milburn, 1985: Long-wave observations near the Galapagos Islands. *J. Geophys. Res.,* 90,3361-3366.

[5] Fox, C.G., 1990: Evidence of active ground deformation on the mid-ocean ridge: Axial

Scamount, Juan de Fuca Ridge, April-June, 1988. J *Geophys. Res.,* 9S,12813-12822.

[6] Wright, A. St. C., 1997: Deep-towed sidescan sonars. Sea Technology, 38 (6), 31-38.

[7] Weam, R.B., Jr. and J.M. Paros, 1988: Measurements of deadweight tester performance using high resolution quartz crystal pressure transducers. Presented at Instrument Society of America 34th International Instrumentation Symposium, Albuquerque, NM, May 2-5, 1986.