Fiber optic liquid level sensors for shipboard applications

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ABSTRACT

This paper discloses a new fiber optic differential pressure sensor for liquid level measurement and control. The intended application is for U.S. Navy use in automated shipboard machinery control and monitoring and damage control systems. The sensor has been developed in response to the need for an inexpensive, yet rugged and reliable liquid level sensor, compatible with advanced automated control systems and suitable for use in hostile and difficult environments. The sensor is developed from an existing commercial design of a low-finesse, short-cavity Fabry-Perot pressure sensor. The sensor consists of a glass micro-chip etched with a shallow, optical cavity capped by a pressure sensitive silicon diaphragm. The Fabry-Perot cavity is vented to the chip base so that a differential pressure can be developed across the diaphragm. The micro-chip is fused to the optical fiber and housed in a protective capillary tube. The differential pressure developed across the diaphragm changes the depth of the Fabry-Perot cavity. This is sensed by measuring the shift in the reflected spectrum of the source LED using a dichroic ratio technique. Experimental models of the sensors have been evaluated successfully on a U. S. Navy test ship, the ex-USS SHADWELL. Since it is a true differential pressure sensor, it can be used in both pressurized and un-pressurized fluid tanks. The sensor's performance and cost attributes should make this technology suitable for many industrial process and control applications.

1. INTRODUCTION

The U.S. Navy is developing and deploying advanced shipboard automated machinery control and monitoring and damage control systems. These systems will rely heavily on the satisfactory performance of a large number of installed sensors including liquid level and flooding sensors. However, shipboard tank level gaging is still predominantly performed by magnetic float sensors with only local display readouts or manually via sounding tubes. Shipboard flooding is detected with a few deck-plate-mounted float switches or is reported as a result of visual observations by the crew. For the most part, existing shipboard fluid level gaging sensors and flooding detector switches do not provide sufficient and timely information and are frequently incompatible with the new automated control and monitoring systems. The goal of this development effort is to provide the U.S. Navy with an inexpensive, commercially available fluid level sensor which is highly reliable and rugged, compatible with a variety of fluids, is intrinsically safe and which can be multiplexed with other control and monitoring sensors. To meet these performance requirements, we have developed a unique fiber optic differential pressure sensor for liquid level measurement. The sensor uses a glass micro-chip, etched with a shallow, low finesse, Fabry-Perot cavity capped with a flexible silicon diaphragm. The sensor's rugged design, small size and low cost makes it suitable for a wide variety of shipboard and industrial liquid level measurement and control applications. It can be used to measure dirty or hostile fluids and because the sensor itself is optical, it is intrinsically safe and should be acceptable for use in combustible and flammable environments.

0-8194-1868-4/95/$6.00

2. MEASUREMENT REQUIREMENTS

The detection of liquid level for shipboard machinery control and monitoring involves many different fluids and some very challenging environments. Shipboard applications include the level measurement and control of lubricating and fuel oils, hydraulic fluids, gasoline, liquid refrigerants, seawater, potable water and waste water. Fluid interfaces include air, compressed air, gas vapor, compressed gas, steam and other fluids (e.g. seawater and fuel oil). Many of these fluids are corrosive, hostile and / or dirty and significant coatings and fouling can develop on the sensor head. Measurement spans range from a few cm to more than 10 m. Pressures can vary from 100 kPa (1 atm) to more than 30,000 kPa. The sensor must be able to withstand temperatures up to 100° C and relative humidity to 100%. The sensor may also have to withstand shock and vibration levels up to several g. Yet, the goal is to provide the U.S. Navy with inexpensive, 'install and forget' sensors. This means that the sensor should have a long life, require no preventative maintenance and require infrequent calibration. Reliability should be more than 5 years mean time between failure with a 40 year expected lifetime. Required accuracy is generally $\pm 3\%$ of actual level with $\pm 1\%$ repeatability.

Shipboard flooding sensors must meet similar requirements but they must accurately determine flooding levels to within ± 2.5 cm. As crew sizes shrink, ships will depend more on automated damage control detection and monitoring systems for survival. Accurate and timely information is required from the flooding sensors so that the damage control system can quickly and precisely determine the ship's state of seaworthiness. The flooding sensors must provide information sufficient for the damage control system to detect flooding occurrence, determine flooding location, the rate of flooding, the mean flooding level, and the amplitude and period of any free surface motion within the hull. The sensor must operate during conditions of large angles of heel and trim and it is desired that they withstand fire and smoke and, to a lesser extent, blast. The sensor must operate in crew living spaces and therefore may have to be paintable.

3. LIQUID LEVEL MEASUREMENT

There are a variety of liquid level sensing technologies that are presently used for industrial process and control that could be considered for shipboard application. Although there are at least nineteen common techniques used,[1] they generally fall into the categories of directly detecting the location of the liquid level or indirectly determining level by measuring a property of the fluid that varies with its height, e.g. its capacitance or weight.[2] If one chooses to use differential pressure sensors to measure liquid level, as we have done in this case, there are commercially available, conventional differential pressure sensors suitable for shipboard use. Unfortunately, they can be expensive and can require frequent maintenance and calibration. It is thought that the fiber optic differential pressure liquid level sensor being developed can be cost competitive with the conventional equivalents. The fiber optic sensor, however, can offer unique advantages such as greater accuracy, faster response, smaller size and weight, no electrical power required at the sensor, immunity to electromagnetic interference, no grounding or shielding, intrinsically safe operation, and ease of multiplexing for redundant / survivable sensor networking. Fiber optic sensors can also be self-calibrating, easing some of the maintenance burden on operators.

4. FIBER OPTIC LIQUID LEVEL SENSOR DESIGN

There are several liquid level sensors on the market that use the refractive index of the fluid to refract light out of a terminated or bent optical fiber or quartz rod when wetted.[3] The change in index of refraction at the fiber core-liquid boundary, or the fiber cladding-liquid boundary allows additional light to escape from the optical channel. Harmer and Scheggi give a review of these techniques.[3] These tend to be suitable only for threshold level sensing and generally require many fibers to make continuous level measurements.

A few researchers have worked out methods of using the differing index between fiber and liquids to measure liquid level continuously over a varying height. Belkerdid, Ghandeharioun and Brennan have worked out a method of using microbend loss around ever-increasing diameter circles to measure liquid height over 0 to 30 cm with a resolution of about 3 cm.[4] Danisch has developed a method of eliminating the effects of varying index of refraction of the liquid.[5] These methods suffer from one common problem: the liquid measured cannot adhere to the probes. When the liquid drops away from the probe, any liquid adhering to the probe can absorb light energy and give erroneous readings.

We considered a variety of fiber optic liquid level sensor designs, including the following:

- Index of refraction sensors to detect the presence of liquid

- Change in optical power when a notched light pipe was wetted or un-wetted
- Reflection from the back side of a flexible diaphragm to sense differential pressure
- Fabry-Perot interferometer to sense differential pressure
- Interferometer that changes resonant frequency when submerged
- Polarimetric birefringence sensors to sense differential pressure
- pH sensors
- Fluorescence sensors that detect presence of liquid

The index of refraction sensors in the format of multiplexed, multiple terminations were given serious consideration. The operating principle was extraordinarily simple. Separate fibers were mounted on a rod extending the length of the tank or compartment and terminated at separation distances of 2.5 cm to yield the required resolution. Choices of reading out the liquid level then either involved a multiplexing scheme or an array of separate optical fibers and sources. This type of system was fabricated by the authors and successfully measured liquid level over a 60 cm span. However, for large tanks, the design quickly becomes too complex and costly. For most fluids it was possible to un-wet the end of the fiber when the liquid receded below the fiber termination by pointing the fiber slightly upward. This method would still suffer from dirt contamination and would eventually stop working.

Differential pressure measurement using short-cavity Fabry-Perot interferometry was chosen as the preferred method of measuring liquid level after extensive investigation and experimentation with many of the above fiber optic sensors. The short-cavity Fabry-Perot interferometer was selected since it could reasonably meet all stated accuracy requirements and could be made tolerant of dirty fluids. A long-term performance track record cannot be established, however, until these sensors have operated onboard ships for several years.

5. DIFFERENTIAL PRESSURE SENSOR DESIGN

The design of the differential pressure sensor used for measuring liquid level is based on a Fabry-Perot interferometer known as a LED-Microshift cavity.[6,7] The sensor, manufactured by Photonetics Inc. to NSWC specifications, is the only available fiber optic differential pressure sensor known to the authors. The sensor, shown in Figure 1, is micro-machined in a monolithic glass substrate approximately 500 microns square and 300 microns deep. A shallow cavity 350 microns in diameter and approximately 1.4 to 1.7 microns deep is etched into the glass substrate. The bottom of the cavity is coated with a quarter-wave thick film of TiO_2 to form one of the reflective surfaces of the Fabry-Perot interferometer. The parallel reflective surface is formed across the top of the cavity by growing a pressure sensitive silicon diaphragm on the glass substrate. A hole, approximately 100 microns in diameter, is micro-machined into the glass substrate venting the cavity to the chip base. The completed glass chip is then aligned and fused to a dual bore capillary tube which holds the multimode optical fiber and microcapillary vent tube. The entire assembly is then fixtured into the larger mechanical structure. The larger of the expected pressures, P_1 is coupled to the front surface of the silicon diaphragm. The back of the cavity is vented, via the micro-capillary tube, to the lower expected pressure, P_2. The result is that the diaphragm responds only to the difference in pressure between P_1 and P_2 and a true differential pressure sensor is formed. For the liquid level sensor reported here, P_1 is the pressure exerted by the air (or gas) and liquid column combined and pressure P_2 is that exerted by the air (or gas) above the liquid column. The difference in pressure can then be precisely related to the height of the fluid column.

The sensor operates on the following principle. Light from a relatively broad band LED source (60 nm centered about 850 nm) is used to interrogate the micro-chip Fabry-Perot cavity. Some of the source light is reflected by the TiO_2 film at the glass-air cavity interface. The light which passes into the cavity is then reflected at the silicon diaphragm-air interface back into the optical fiber. The reflected rays from the two surfaces interfere to form the reflected light signal. The percentage of light reflected by the sensor changes with cavity depth. Plotting cavity depth versus reflected light produces a repeating waveform of multiple maxima and minima. Pressure acting on the diaphragm changes the cavity depth and thus the sensor reflectance can be correlated to pressure.

The LED-Microshift cavity sensor[7] was selected instead of large-cavity sensor designs for the following reasons. Large or deep-cavity sensors require that a measurement be made over several reflectance minima and maxima or fringes. Since fringes must be 'counted' in order to relate pressure to reflectance, if the power to the device is cycled during a measurement, the absolute reference is lost and a new reference measurement must be provided. Since the cavity depth of the LED-Microshift sensor is relatively short compared to the wavelength of the LED source, the diaphragm movement can be measured between a single reflectance minima and maxima. Although this results in a somewhat limited linear measurement range, this can be overcome by

Figure 1 - Fabry-Perot Differential Pressure Sensor

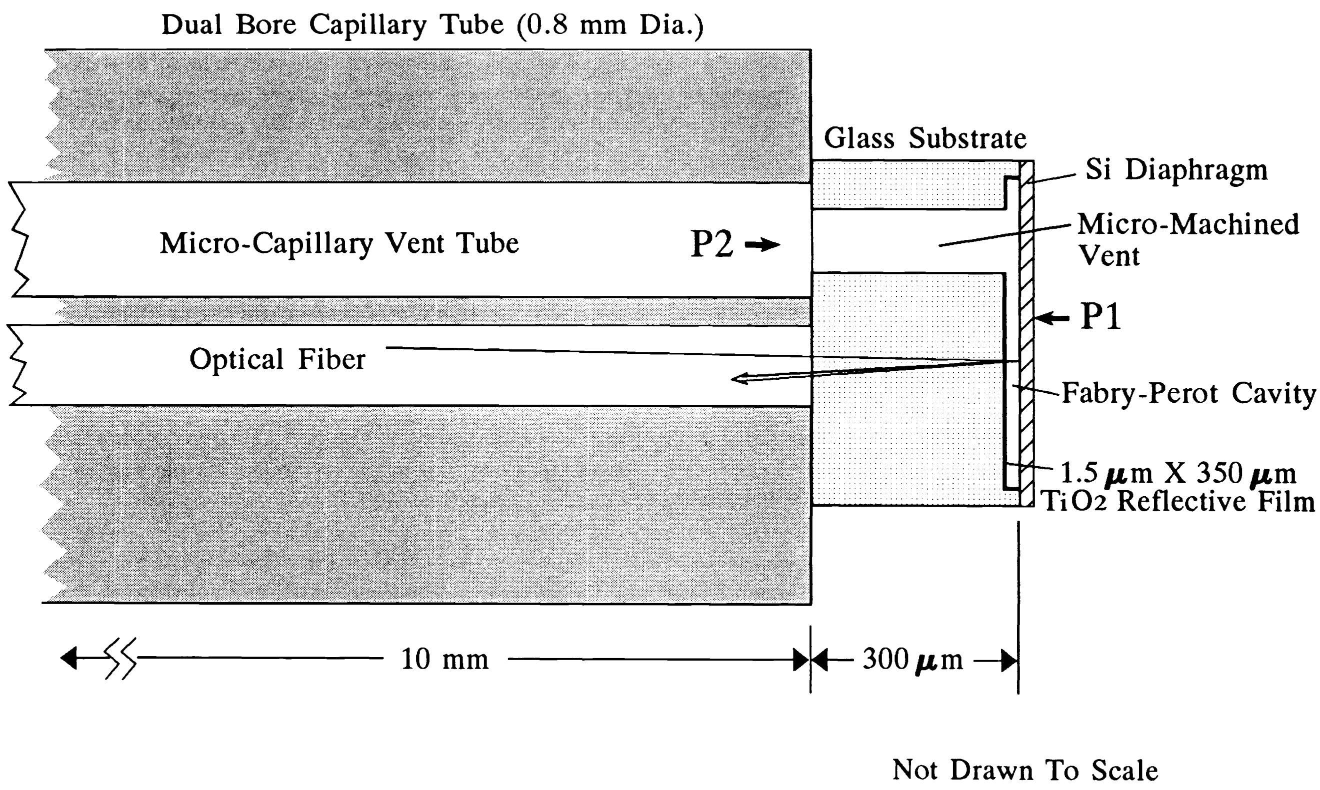
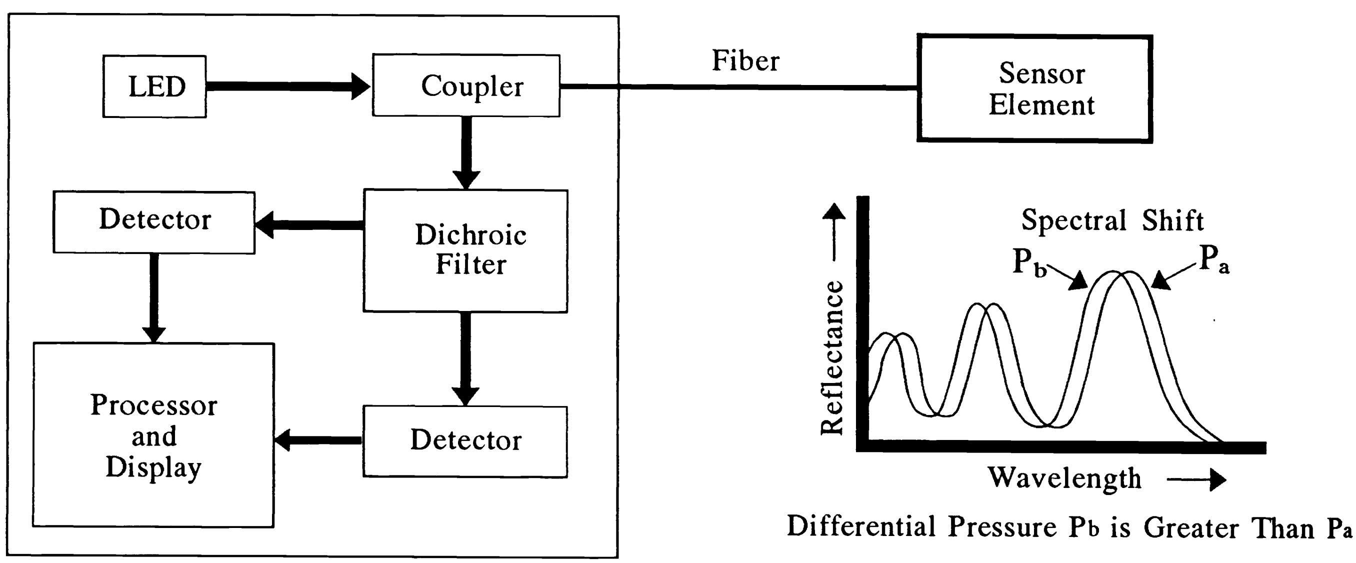


Figure 2 - Fabry-Perot Sensor Measurement Schematic



utilizing the fact that the wavelength of the reflected light also varies with cavity depth. Shown in Figure 2 is a plot of wavelength versus intensity (normalized) for two pressure measurements. This plot shows the shift in spectral content which occurs with changing cavity depth. This spectral shift can be used to extend the linear operating range of the sensor by splitting the received signal into its short and long wavelength components and performing a ratio measurement. The technique is shown in the block diagram of the Photonetics instrument in Figure 2. A dichroic mirror is used to pass only long wavelength light to one of the detectors. The total reflected light, however, is seen by the other detector. The ratio of the output of the detectors is then measured and processed. This technique eliminates most errors due to undesired deviations in the intensity of the reflected light such as fluctuations in the source intensity or micro-bending losses in the fiber, which cannot be easily distinguished from pressure changes.

The shallow Fabry-Perot cavity of 1.4 to 1.7 microns also offers other advantages. Since the depth of the cavity is much shorter than the coherence length of the LED source used to interrogate the sensor, the chip can be mounted directly to the optical fiber without using any collimating optics. This is because the spatial coherence of the reflected light is maintained by the slender cavity. The elimination of collimating optics results in a more rugged chip-fiber assembly. Furthermore, micro-machining techniques used to produce the short depth cavity are much more repeatable than techniques used to make cavities of 30 to 100 microns in depth. The result is a sensor which is rugged, small in size, and can be reliably mass produced at a lower overall cost.

Implementing this technology into a hardware package results in the sensor shown in Figure 3. The size of the sensor package is 9.5 cm by 15 cm. The two pressures are coupled through Swagelok (TM) fittings on the left side of the photograph. The fiber is connected on the right side of the sensor. A smaller package can easily be made.

Two of the major advantages of the sensor are the ease of installation and the small size compared to sensors presently in use as shown in Figure 4. The sensor on the left is a magnetic float liquid level sensor. The float, which moves up and down a rod, contains a magnet which actuates magnet reed relays in a resistive network inside the rod. The entire assembly is mounted inside the tank being monitored. If the sensor requires maintenance or repair, the interior of the tank must be accessed by ship personnel. The fiber optics sensor shown on the right is much smaller and can be mounted from outside the tank, decreasing the installation time and mean time to repair by orders of magnitude. Holes are simply bored and tapped in the tank wall to connect the pressure to the sensor input.

Figure 5 shows a calibration curve for the fiber optic liquid level sensor. The graph is linear with a worst case deviation from perfect linearity of 0.8 cm over the calibrated span of 183 cm.

6. EXPERIMENTAL EVALUATION

The fiber optic liquid level differential pressure sensor was demonstrated on the ex-USS SHADWELL during flooding research exercises in May of 1994. The ex-USS SHADWELL is the U.S. Navy's test ship for conducting shipboard damage control research and development. The ship has been modified so that controlled fire fighting exercises and flooding exercises can be run for the test and evaluation of advanced damage control concepts and equipment.

For the test, a total of 6 sensors were installed on the ship as shown in Figure 6. There were 2 of each of the following installed: the Fabry-Perot differential pressure sensors; the Fabry-Perot absolute pressure and; the acoustic ranging liquid level sensors. The operating principle of the fiber optic absolute pressure sensor is the same as that of the differential pressure sensor except that the Fabry-Perot cavity on the absolute sensor is not vented. The acoustic level sensor operates by broadcasting an ultrasonic beam down to the surface of the water. The round trip transit time of the reflected beam is measured. The acoustic level sensors were installed as a measurement reference for the differential pressure level sensors.

A Fabry-Perot absolute pressure sensor and an acoustic level sensor were each mounted in the supply tank. Only a Fabry-Perot differential pressure sensor was installed in the wet space holding tank. Three (3) sensors, one of each type tested, were installed in the wet space itself.

The flooding test sequence was conducted as follows. The supply tank and wet space holding tank, shown in Figure 6, were filled with water prior to the test start. The wet space holding tank wall has a variety of holes in it which simulate typical battle damage effects. These damage holes are temporarily plugged to allow the wet space holding tank to be filled. At the start of the test, the plugs in the wet space holding tank walls are removed. Water then flows suddenly and rapidly from the wet space holding tank into the wet space (crew area) to simulate an actual battle damage scenario. The flow of water into wet space is

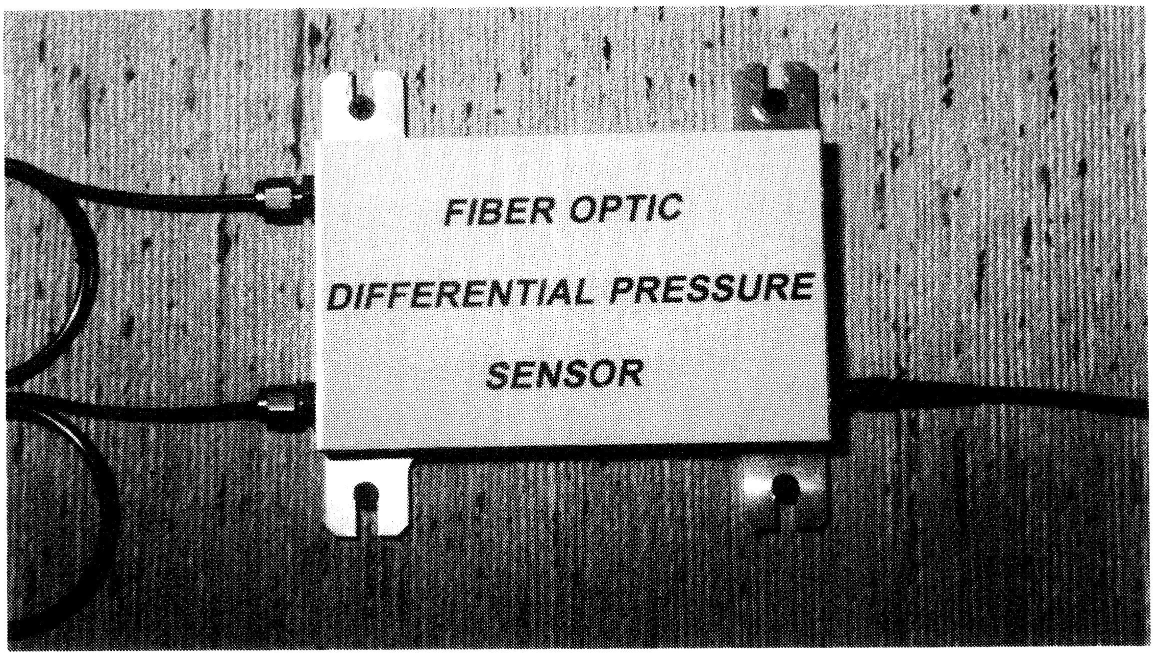


Figure 3 (Above) - Differential Pressure Sensor

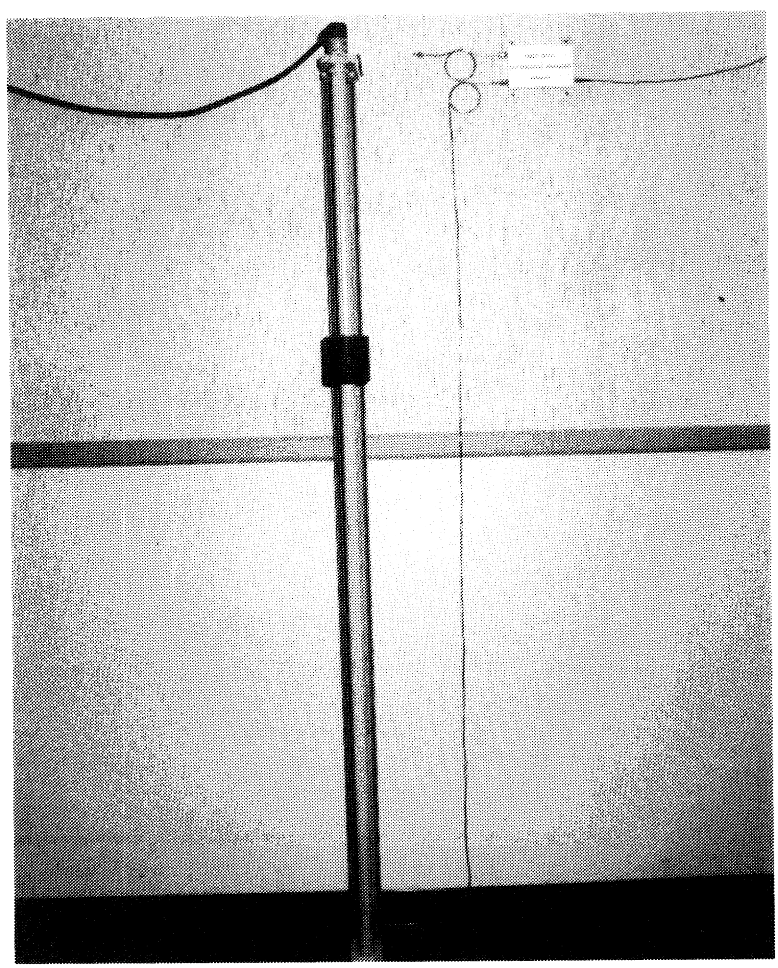


Figure 4 (Right) - Size Comparison of Fiber Optic Sensor with Magnetic Float Sensor

Figure 5 - Response of Differential Pressure Fiber Optic Liquid Level Sensor @ Atmospheric Pressure 02 Mar 94

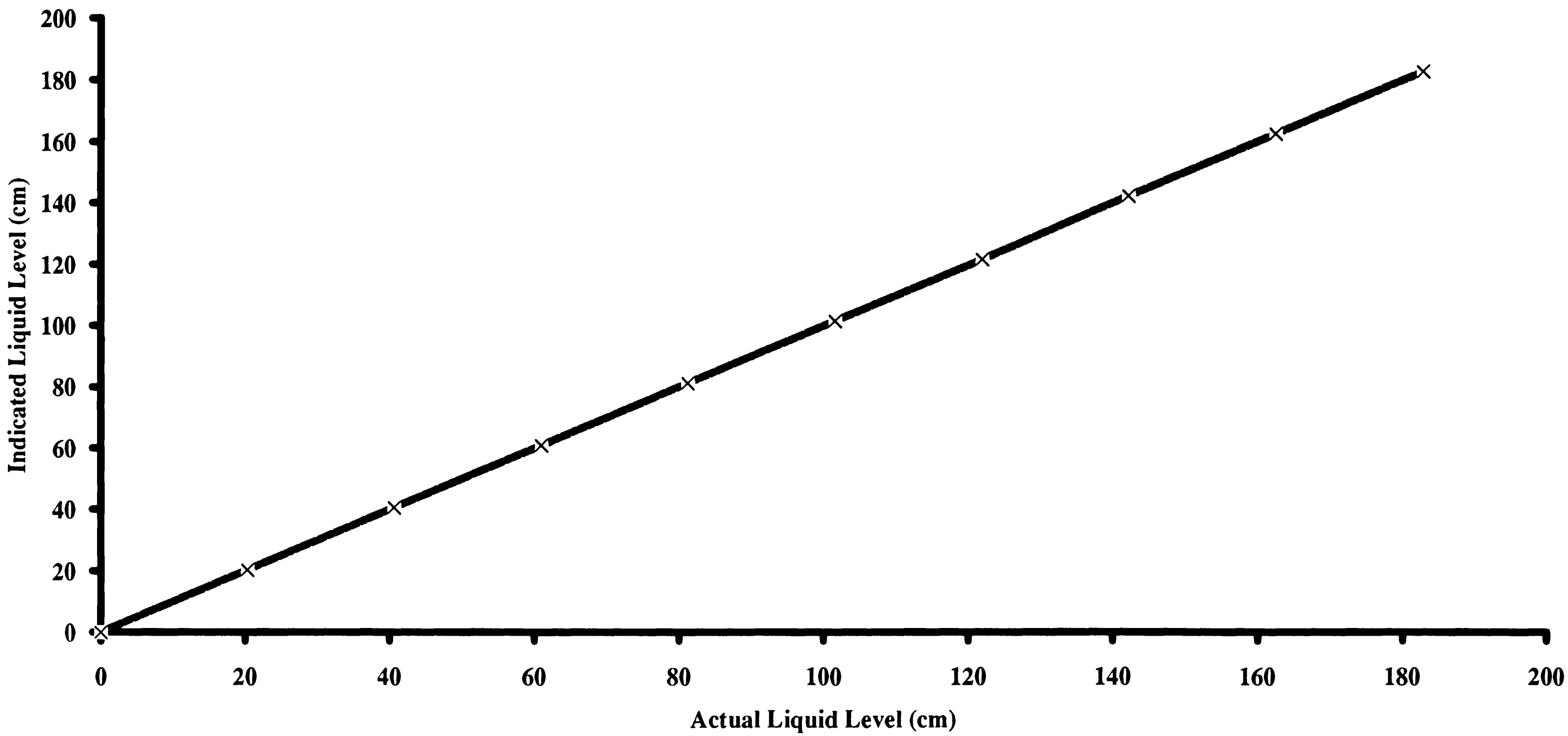


Figure 6 - Flooding Space Layout for Liquid Level Sensor Test on Ex-USS SHADWELL

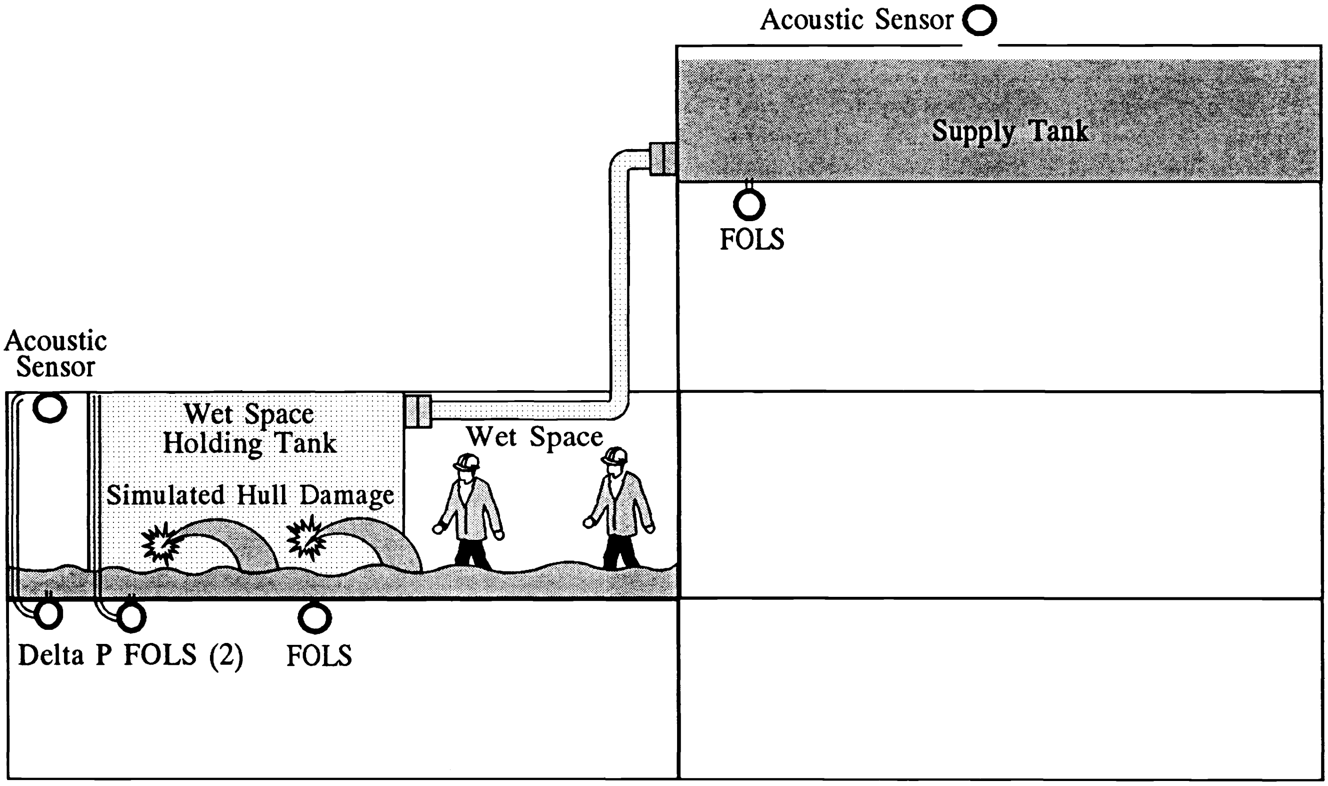
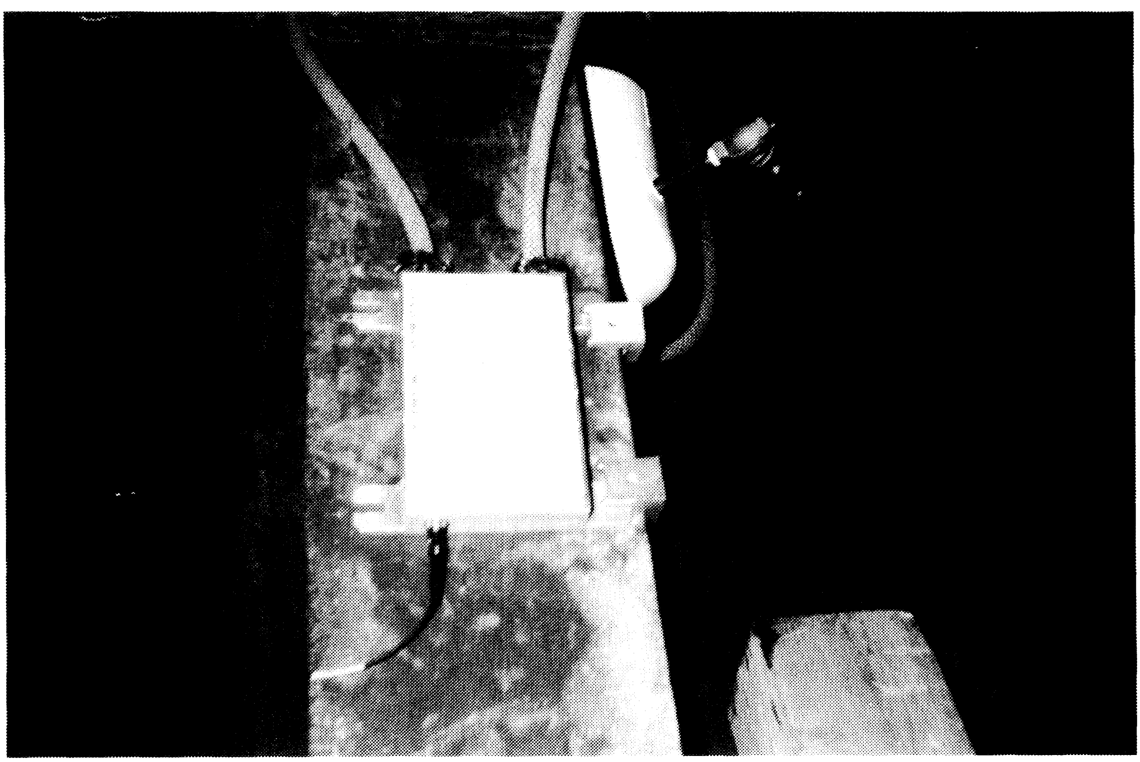


Figure 7 - Differential Pressure Sensor Installed on Ex-USS SHADWELL



maintained by the supply tank which serves as a fast supply of water for the flooding exercise. To prevent overflow, the wet space holding tank is vented to the atmosphere through a 6 m stand pipe (not shown in Figure 6).

Figure 7 shows the differential pressure sensor mounted under the deck of the wet space holding tank. Pressure from the top of the tank was coupled through a water column to the front port of the sensing diaphragm. The pressure coupling medium to the back side of the sensor diaphragm was required to be air to maintain proper calibration. Water would have changed the index of the optical path between the end of the fiber and the sensor diaphragm and affected the calibration. An accumulator was installed in the line that couples pressure from the bottom of the wet space to the low pressure port. This arrangement provided air as the pressure coupling medium into the sensor cavity and the back side of the silicon diaphragm and blocked the tank water itself from the sensor cavity. The accumulator, shown in Figure 7, is the cylinder just above and to the right of the differential pressure sensor. The differential pressure sensor used to monitor the level of water in the wet space was installed in the same way.

Some test results are shown in Figures 8 and 9. These are time histories of the amount of liquid measured in each of the two tanks and the wet space during the flooding exercises. All sensors mounted in the same volumes should have given identical measurements of the liquid level. Since there were three sensors installed in the wet space, a good comparison of the sensor measurements can be made. The fiber optic absolute pressure sensor and the acoustic sensor agree closely except for some large transients from the acoustic sensor. The fiber optic differential pressure sensor closely follows the other two sensors for level below 152 cm. Since this sensor was designed for a maximum range of 122 cm, its performance was determined to be satisfactory.

Due to the height of the supply tank, a static pressure of about 3 m was possible in the wet space tank. The differential pressure sensor mounted in the wet space holding tank demonstrated the ability to handle ambient static pressures up to 240 percent of its maximum range. The maximum height of the wet space holding tank was 254 cm and the sensor correctly measured this value even when the static water column pressure went to 610 cm during the test.

The level indications from the acoustic sensors showed some high amplitude transients in both tests, but they are especially evident in Figure 9. These transients were caused by reflections from water spray interrupting the acoustic beam and wave action on the surface of the water which scattered the beam reflection.

7. CONCLUSION

The Fabry-Perot differential pressure liquid level sensor has been demonstrated successfully for the first time in a shipboard application. Performance was completely satisfactory for this short-term application. The sensors performed well in the presence of high ambient heat and humidity and substantial vibration from nearby rotating machinery.

The sensor does require additional development before it can be reliably fielded. The vent hole in the micro-chip substrate limits the transient response of the sensor. A larger hole will improve the speed of response but will also reduce the diffusion time for water vapor to collect in the sensing cavity, potentially causing large inaccuracies. A solution may be to enlarge the hole on the back side of the sensing cavity and insert a second diaphragm to block water vapor. The selection of an appropriate material for the second diaphragm that will not cause significant pressure drop and which will resist attack from hostile fluids will be a challenging effort.

The Fabry-Perot differential pressure liquid level sensor developed in this effort should meet the project goals for a rugged, inexpensive, commercially available sensor suitable for both military and industrial use in advanced control and monitoring systems.

Figure 8 - Flooding Sensor Readings for Ex-USS SHADWELL Test MAYDC4

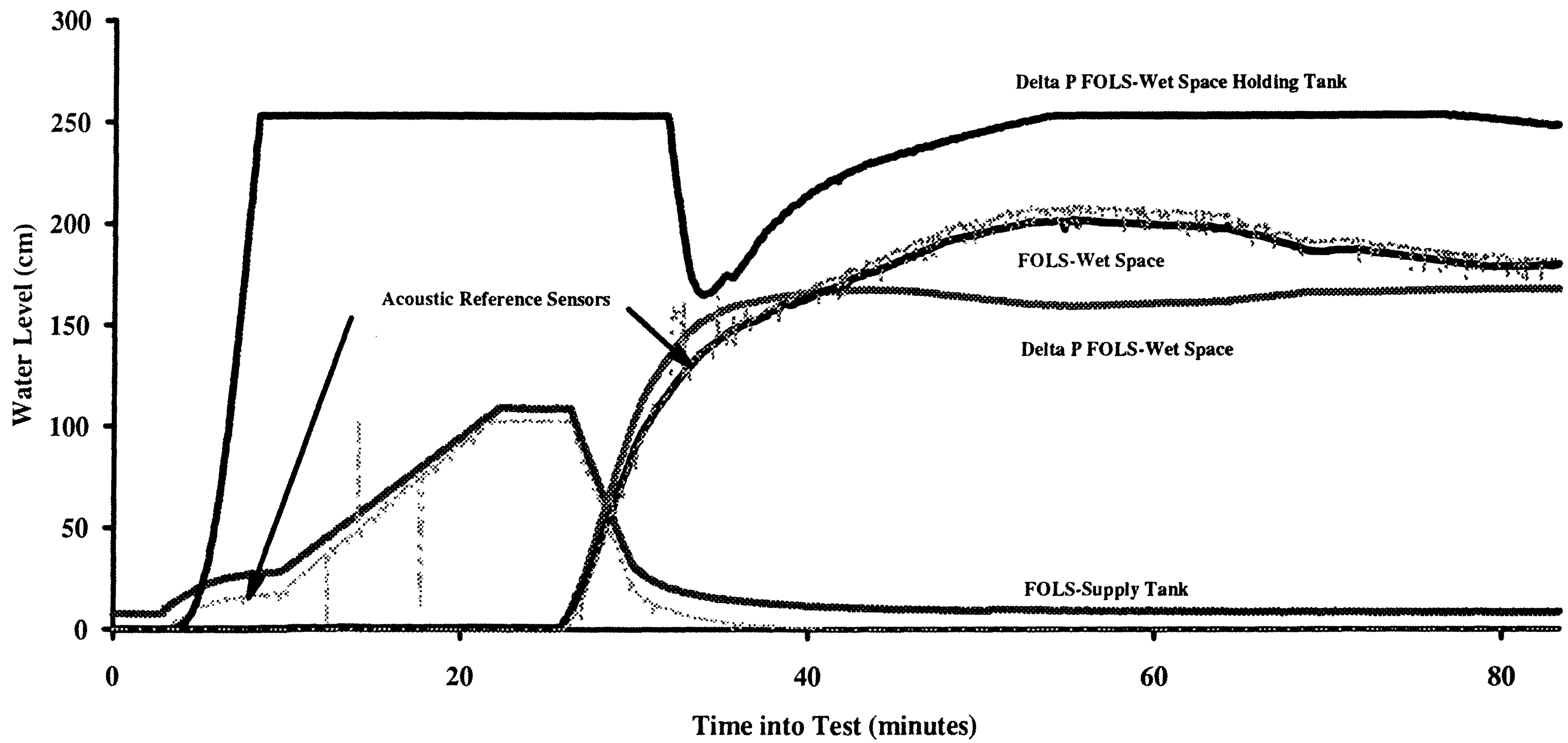
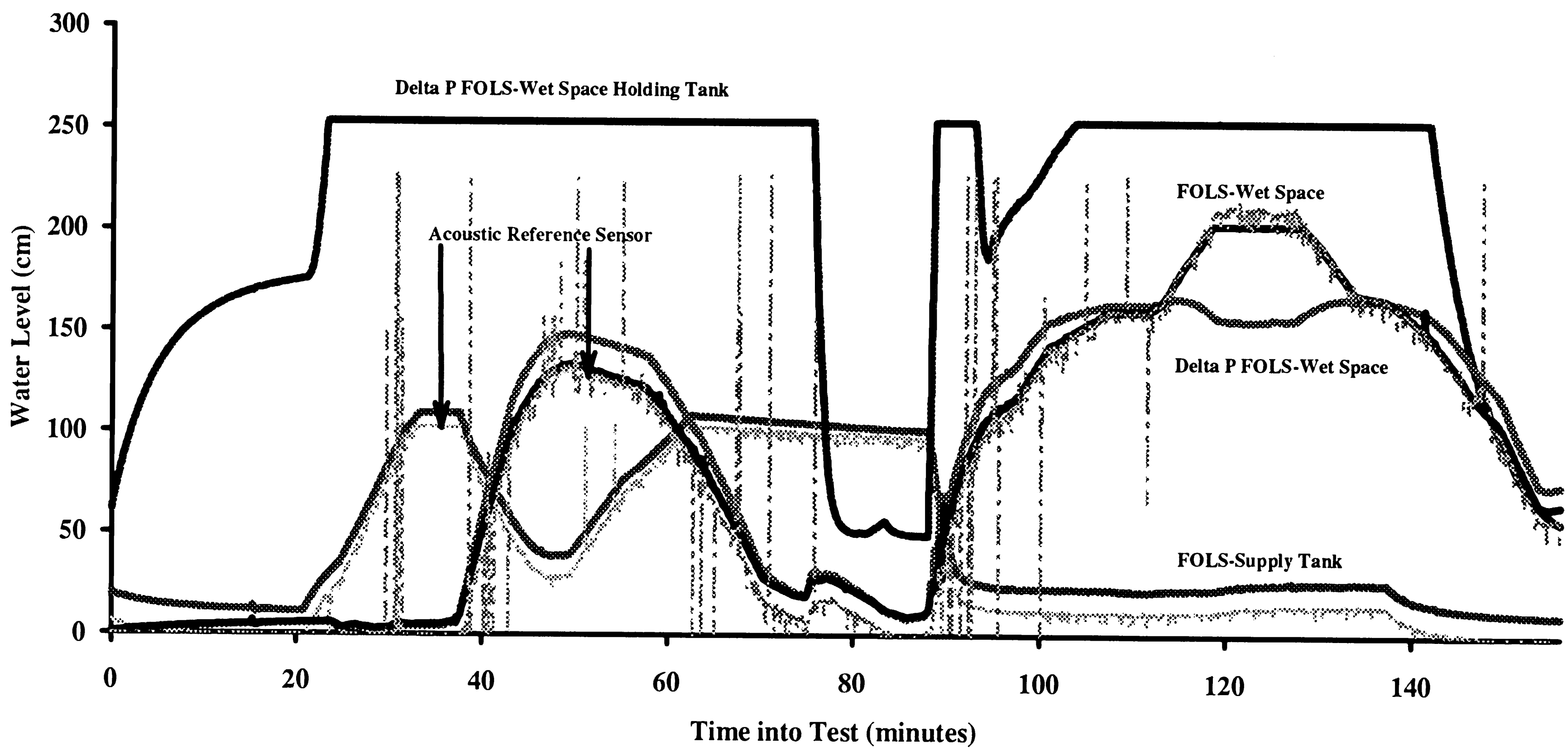


Figure 9 - Flooding Sensor Readings for Ex-USS SHADWELL Test MAYDC7



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