Discussion of design properties and application strategies

As can be seen from Figure 1.0, the sensor response curve appears as one would expect given the design of the sensor as a tank circuit behaving as a band-stop filter. As a reminder, a sinusoidal signal of fixed amplitude is applied to the sensor as an input, and the output from the sensor is the same signal shape as the input signal, but with a change in amplitude relative to water conductivity.

To confirm that the sensor is indeed a tank circuit, the impedance of the sensor (out of water, in open air) was measured in various configurations across a range of frequencies (Figures 6.0, 6.1, 6.2, and 6.3). From this data, the intrinsic capacitance (C), inductance (L), and resistance (R) of the sensor can be calculated (Figures 7.1, 7.2, and 7.3).

In air, at an operating frequency of 1.0 MHz:

* The sensor intrinsic resistance (R3 in Figure 6.0) is 950 Ohms.
* The sensor intrinsic inductance (the two L?s added together in Figure 6.0) is 1.44E-06 Henries.
* The sensor intrinsic capacitance (C1 and C2 added together in Figure 6.0) is 1.39121E-10 Farads.

If we model the intrinsic capacitance, inductance, and resistance of the sensor as connected in series, we obtain a value of around 12 MHz as the resonant frequency of the sensor in air.

Although obvious, it is important to note that, in air, the value of capacitance contributed by water conductivity (the two C? in Figure 6.0) is assumed to be 0 Farads.

As can be seen from the Figure 7.x series of charts, the values for L, C, and R vary with frequency: while ideal inductors, capacitors, and resistors do not have frequency independent values, the sensor is a real-world example of these devices and so these constants exhibit some frequency dependence. However, this variance is fairly insignificant because the operating frequencies of the sensor are fixed so these values will be static.

To summarize, as input frequency remains constant, the total capacitance of the sensor changes relative to water conductivity and the output magnitude changes. In the development of this sensor, the output magnitude was measured by the Tsunami board.

For every operating frequency, there is one water conductivity value that corresponds to a minimum output response. From Figures 4.1, 5.1a, and 5.1b it is also easy to see that this minimum (or “trough”) is frequency dependent: The minimum appears at a lower water conductivity value as the frequency decreases. Thus, the whole response curve shifts directly dependent on frequency.

Unfortunately, the response curve of the sensor is a many-to-one function, which by definition does not have an inverse function. An inverse function, (such as one that might be useful as a calibration curve to calculate conductivity from the sensor’s output), would fail the vertical line test because a given input would have multiple outputs. Thus, for some of the possible output values from the sensor there are two corresponding possible conductivity values.

Two solutions to this problem have been considered. The first and most obvious solution is to select an operating frequency such that the trough occurs at the minimum expected water conductivity (which can be assumed is 0 µS/cm in most cases). Thus, if we ignore parts of the response curve that correlate with negative water conductivities, the response curve can be considered a one-to-one function instead of a many-to-one function. An implementation of this solution would involve greatly lowering the operating frequency of the sensor.

The problem with this approach can be deduced from Figure 4.1. As operating frequency decreases, the response of the sensor output becomes *less sensitive* (especially at higher conductivity levels); that is, the response function becomes flatter as frequency decreases. Besides decreasing dynamic range, this loss of sensitivity would also increase relative error. If the magnitude of uncertainty in the measurements remains constant , a shrinking dynamic range would increase the proportional uncertainty of the measurements. For example, let’s say that the sensor has a frequency independent uncertainty of ±3 units. At frequency A, the sensor has a dynamic range of 100 units (that is, the lowest possible measurement is 0 units, and the highest possible measurement is 100 units) and so the uncertainty in measurement is ±3%. At frequency B, if the sensor has a dynamic range of 50, the uncertainty in measurement now becomes ±6%.

This problem is further compounded by the nonlinear sensitivity of the sensor. If 60% of the dynamic range of the sensor represents only the first 25% of the expected range of measurable water conductivity values, uncertainty becomes greatly magnified as water conductivity increases.

The second solution considered avoids the previously mentioned pitfalls by maintaining the operating frequency around its most optimal value. Instead, the response curve of the sensor is split into two independent functions around the trough (example: Figure 1.1 and 1.2). Because they are one-to-one, each of these half-functions can be inverted to form two respective calibration functions. However, this does not change the fact that many (if not all) values for water conductivity will correspond with two values – one for each half-function. There must be a way to decide which half-function is to be used for a given measurement, and by logical necessity this way must involve a third variable.

This ideal third variable is phase. In an ideal band-stop filter, there is a phase inversion at the resonant frequency of the filter. For this conductivity sensor, we would expect this phase inversion to occur at the trough. In real world applied terms, this means that we would expect a negative phase shift between the sinusoidal signal input and the output from the sensor to the left of the trough, and a positive phase shift to the right of the trough. Thus, it becomes easy to decide which half-function to use is phase is also measured: if phase is negative, the half-function to the left of the trough is used. If phase is positive, the half-function to the right of the trough is used.

Sadly, due to budget and time constraints, it was not possible to implement phase measurements that effectively coordinated with the magnitude measurements made by the Tsunami board. The makers of the Tsunami board claims that it is able to measure phase, but in practice phase is only reported as an absolute magnitude without sign. This fact renders the phase-measuring capabilities of the Tsunami board useless for this application.

A less ideal third variable is frequency. Luckily, the Tsunami board is able to control and measure frequency with a useful degree of accuracy. Because the response curve of the sensor changes with input frequency, two independent responses can be obtained from the sensor by sequentially probing the sensor with two signals of different frequencies. These two measurements can each be correlated to two conductivity values (again, one for each half-function for a total of 4 values all together) using their own calibration curves, but we expect that two of these values will be identical (barring error). The identical values should be the real conductivity.

This two-frequency measurement scheme was the purpose for gathering the data shown in Figure 5.0 to 5.1b. Two frequencies were chosen such that the response curves would be sufficiently different, but that the lower frequency was not so low as to impede sensitivity of the sensor. Of course, the 2 MHz upper limit of the Tsunami board constrained the range of the higher frequency. As can be seen, the response curves for 1.52 MHz (HI) and 0.8 MHz (LO) frequencies are quite different. An attempt was made to fit calibration functions to the data corresponding to the inverse half-functions of the HI and LO responses using the free online curve fitting software MyCurveFit. An example of these fitting attempts using symmetric sigmoidal functions can be found in the Appendix. Code written for the Tsunami board that applied these calibration functions to measurements from the sensor (including an algorithm for generating and detecting the consensus values) can also be found in the Appendix.

Unfortunately, these attempts at using the two-frequency measurements were not successful for a variety of reasons. The possible reasons include:

* The Tsunami board output amplitude is unstable and is effected by output frequency, microcontroller instruction load, and power supply source.
* The two frequencies chosen have response curves that are too similar relative to error and uncertainty in the measurements
* The free curve fit “software” is insufficiently powerful to produce good calibration curves

These factors probably all contributed to failure. Instability of the Tsunami output amplitude creates error that may not be random or independent, which can compound problems from poor fit of the calibration curve.

It is likely that success may be found by trading some loss of sensitivity in the LO curve for a much bigger difference between the two response curves. In addition, the use of higher quality nonlinear regression software and better hardware than the Tsunami board would be of much help. It might also be beneficial to use quality test equipment to characterize the effect of temperature, output frequency, load, and power source on the Tsunami’s output. Unfortunately, these resources were not available during this research.