Signal Processing Algorithm Implementation for In Vessel Level Measurement

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ABSTRACT

The basis for ultrasonic waveguide based level measurement is that the velocity of propagation of torsional stress waves along the waveguide varies with the density of the surrounding liquid. Thus by launching a torsional wave into the waveguide near its proximal end and measuring the reflected wave's return time from the distal end of the waveguide the liquid level can be determined. In the present implementation a time enveloped sinusoidal (Blackman window) torsional stress wave is launched down the waveguide as the excitation pulse. The sinusoid frequency is experimentally tuned to the mechanical resonances of the waveguide. The reflected signal is measured and processed to detect the return time of the reflected wave. A sequence of filtering steps is employed to determine the reflected signal return time. First a bandpass filter is employed around the drive signal frequency to remove amplifier electronics induced signals. Next correlation filtering is employed to focus the measurement sensitivity on signals matching the drive signal shape. Finally, square-law detection and low-pass filtering are employed to locate the peaks of the measured signals.

1 INTRODUCTION

The principles underlying stress acoustic wave generation and propagation are well known and will only be adumbrated here. The central concept underlying the measurement is that the inertia of the surrounding medium will influence the propagation velocity of a torsional wave in a non-circular waveguide immersed in a fluid. Initial modeling of the phenomenon and its application to fluid-density profile measurement was performed in 1977.[1] Mathematically, the speed of any torsional elastic wave propagating down a waveguide is proportional to the square root of the stiffness of the rod divided by the sum of the waveguide and the surrounding fluid inertias. A larger fluid inertia, therefore, results in a lower torsional wave propagation velocity. The fluid's apparent inertia is a combination of its density and viscosity. In the case of a water-like fluid, for realistic probe dimensions and ultrasonic wave frequencies, Kim and Bau have shown that the fluid viscosity can be neglected[2] resulting in a wave propagation delay inversely proportional to the fluid density.

The waveguide stiffness and inertia also alter the torsional wave propagation velocity. Waveguide inertia is fixed and determined by its cross section. The waveguide stiffness varies with temperature. The waveguide temperature, however, also changes the length of the waveguide. This property is employed in ultrasonic waveguide based thermometry systems. Extensional waves are only minimally impacted by the waveguide surrounding fluid. Thus launching an extensional wave down the waveguide and measuring the return time enables measurement of the average waveguide temperature. A distributed temperature profile along the waveguide can be obtained by incorporating a series of fiducial notches along the waveguide. This enables direct compensation for temperature effects on the fluid density measurement. While this is not required under normal operating conditions when the coolant is in saturation and thus at constant temperature, temperature compensation would become important if the coolant becomes superheated during accident conditions. Fortunately, ultrasonic probe extensional wave thermometry has been repeatedly demonstrated for measurements in-core[3] as a departure from nucleate boiling diagnostic and indeed in molten corium temperature measurements.

2 SIGNAL GENERATION

Explanation of the electrical and mechanical system for signal generation and processing is the subject of this project's next letter report. Hence this report is limited to the sketching the system concepts and explaining the techniques. The functioning of the electrical signal to stress wave transducer is based on magnetostriction. Essentially, magnetostriction is the alignment of the magnetic domains of a ferromagnetic material when subjected to an external magnetic field. The domain alignment alters the mechanical dimensions of the magnetostrictive material—the piece becomes longer in the direction along the applied magnetic field. This project employs magnetostriction to generate a propagating torsional stress wave following the technique developed by Kim et al.[4] Figure 1 illustrates the principal components of the magnetostrictive drive system. When power is applied to the solenoid coil the resultant magnetic flux causes the magnetostrictive stripe, attached to the blade surface at a 45° angle relative the pipe axis, to lengthen slightly. As explained in this project's letter report issued in July of 2006, the magnetic field lines produced by the solenoid winding are strongly oriented by the magnetostrictive stripes along their long axis. This results in both a twisting (torsional) and a lengthening (extensional) motion within the blade.

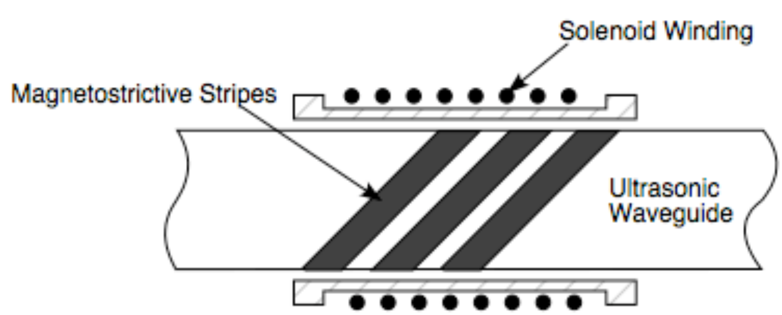


Figure 1—Oriented Magnetostriction Torsional Wave Generation Concept

An ultrasonic fluid-level measurement transducer is a complex component involving multiple materials with non-uniform cross sections. Previous work by Kim and Bau [5] has shown that an ultrasonic blade diamond profile with a particular aspect ratio has outperforms other blade cross sections in terms of torsional wave propagation velocity variance with surrounding fluid density. Kim and Bau further showed that level measurement sensitivity is maximized by maximizing the ratio the torsional inertia of the fluid surrounding the waveguide as compared to the torsional inertia of the waveguide itself. A cusped diamond profile with an aspect ratio of 2.7 was selected based upon these criteria for the 3D modeling of the blade. Figure 2 shows the ORNL implementation of the magnetostrictive transducer fitted onto the cusped diamond blade. Propagation of torsional waves in noncircular cross-section waveguides tends to be dispersive unless the wavelength is large compared to the waveguide's largest cross-sectional dimension.[6] This is not anticipated to be a system limitation as the blade dimensions and drive frequencies employed in this project are within the typical range employed in previous work.

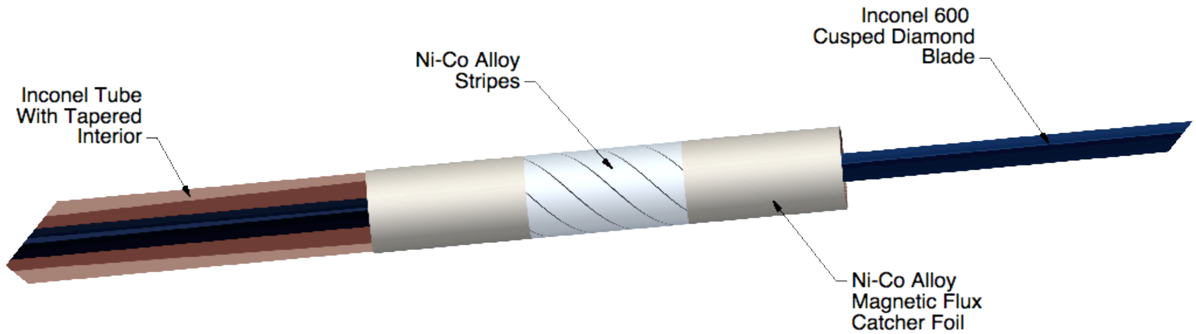


Figure 2—ORNL Implementation of Magnetostrictive Transducer Without External Coils

The present ORNL magnetostrictive transducer drive employs a "windowed" sine wave excitation. Windowing is a technique to restrict the time space of a function by multiplying an input function by another that is zero valued except for within a particular interval (window). The width of the window and the shape of its rising and trailing edges define the characteristics of the window. The current ORNL ultrasonic drive system employs a Blackman window that passes a few periods of the primary sine wave. Figure 3 shows a typical input drive pulse consisting of a "windowed" sine wave with a center frequency of 80 kHz.

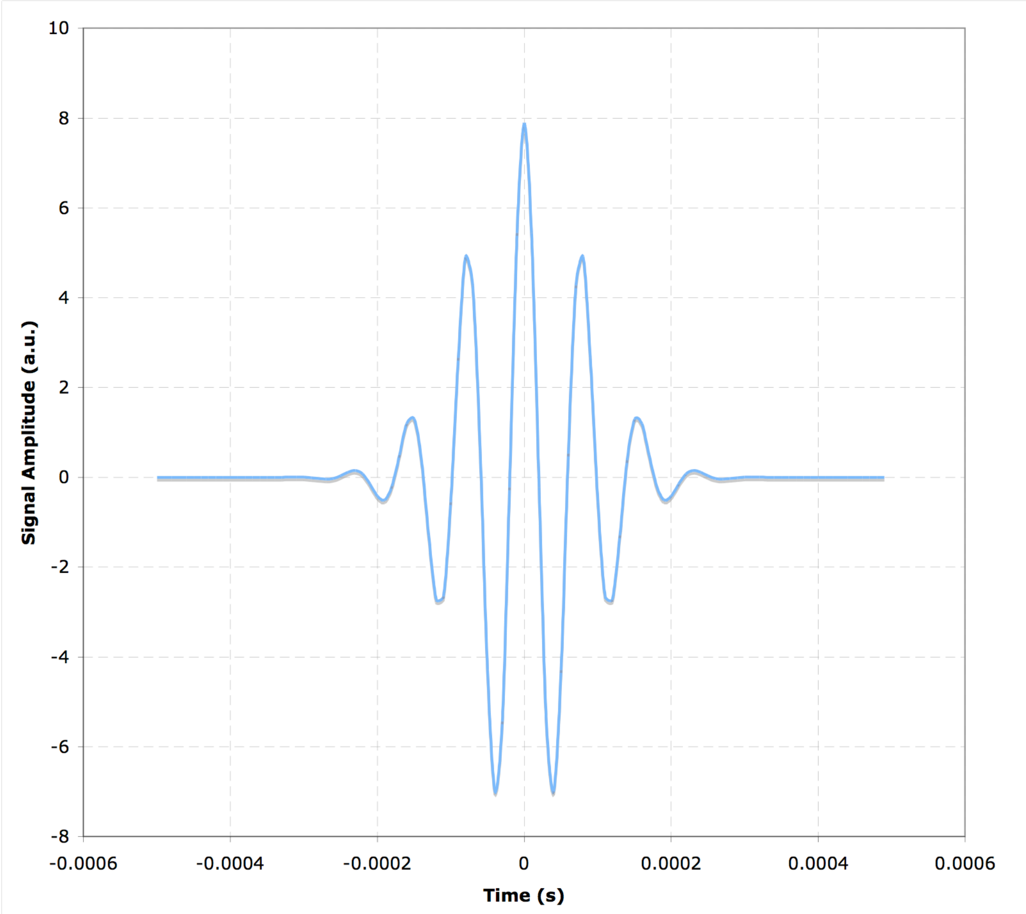


Figure 3—Typical Electrical Drive Pulse For Magnetostrictive Transducer

Prior ultrasonic level measurement systems have typically been excited using impulse signals. While this has the virtue of exciting all of the system mechanical modes and is conceptually simple, it has two practical difficulties. First, exciting all of the possible mechanical modes is energetically inefficient. This means that more energy (higher voltages) has to be transferred to the drive coil for a given amount of returned signal. It is advantageous to reduce the cable peak voltage for in-vessel deployments. More importantly, however, an impulse function reflection is more difficult to separate from system noise through signal processing. The fundamental torsional mode of the waveguide should be non-dispersive, so a reflected wave shape will be the same as the excitation wave shape. Signal filtering can be employed to recognize the specific wave shape and to extract signals with this characteristic from a noisy measurement. Impulses can also be recognized by a similar filtering technique but their bandwidths are much greater than the shaped sinusoidal pulses and, as a result more noise must be passed through the filter resulting in a poorer signal-to-noise ratio.

The excitation signal is generated using a computer controlled arbitrary waveform generator coupled into a power amplifier and an impedance matching transformer to maximize the energy transfer into the signal drive coil.

3 SIGNAL MEASUREMENT TECHNIQUE

The reflected stress waves dynamically change the length of the magnetostrictive stripes within the drive/signal coil. Changing the length of the magnetostrictive material changes the shape of its magnetic field which in-turn induces a voltage on the solenoidally wound drive/signal coil surrounding the stripes. The reflected signal is measured using the same coil as was used to drive the signal. A reed relay is employed to switch the amplifier out of the measurement signal loop when a drive pulse is not required. The induced voltage is amplified with a band limited, low-noise amplifier and then digitized. Details of the electrical and mechanical drive and probe configuration will be provided in the next project letter report.

4 SIGNAL PROCESSING ALGORITHMS

Using the same coil to excite the transmitted pulse and to detect the reflected pulse causes one practical problem. The excitation voltage is typically orders of magnitude greater in amplitude than the detected-reflection voltage. If the receiving amplifier gain is set appropriately for the reflected pulse it is driven into deep saturation by the excitation pulse. This causes the receiver amplifier to be inoperative for a short period of time. If the first reflected pulse arrives during this saturation time, it will not be detected. In preliminary tests with typical drive voltages, the receiver amplifier saturates but is recovering when the first reflection arrives. This means the reflected pulse shape is “riding” on a decaying exponential (Figure 4). A bandpass digital filter can effectively remove this added decaying exponential with minimal impact on the accuracy of detection of the reflected pulse shape as shown in Figure 5.

Figure 4—Typical preamplifier output signal

Figure 5—Typical bandpass-filtered preamplifier output signal

The bandpass filter used is a 6^{th} order Butterworth bandpass.

The optimal filter for detecting any known wave shape in the presence of wideband additive noise is the matched filter. Another name for the matched filter is “correlation filter” because correlation is effectively what the matched filter does. Its impulse response is chosen to be the time inverse of the signal shape to be detected. Then, when the signal is convolved with the impulse response, the result is the cross correlation between the signal and the pulse shape to be detected. The arrival time of a pulse can be found by finding a strong peak in the matched filter output signal. Figure 6 shows this graphically. The top trace is the total recorded signal and the lower trace is the same signal after suppressing the large initial driving pulse and expanding the vertical scale.

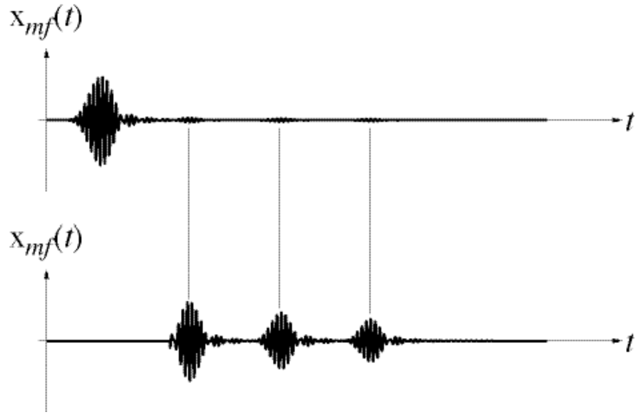


Figure 6—Matched-filter output signal - Top plot is the total signal and bottom plot is the same signal after suppressing the driving pulse and expanding the vertical scale

The next step in signal processing is to locate the peaks of the reflected signals. This is done by a technique that is well known in communication system design, a square-law detector followed by a low pass filter. The technique is demonstrated in Figure 7 wherein the top signal trace displays the matched filter output signal squared and the lower trace displays a low pass filter of the resultant signal.

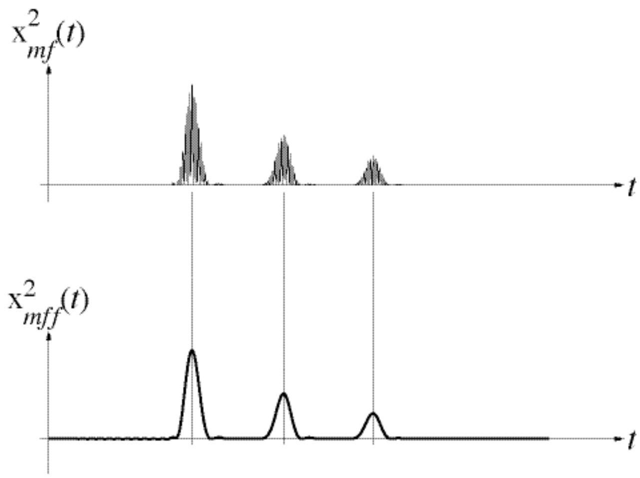


Figure 7—Matched filter output signal squared (top) and then low pass filtered (bottom)

The square-law detector creates a pulse signal that has a non-zero average value and the low pass filter then takes out the double-frequency ripple on the signal, leaving only the smooth underlying pulse shape. The peak of that pulse indicates the time of arrival of the reflected pulse.

All the illustrations in Figure 4-Figure 7are simulated signals without noise. The following figures are the same except with a typical level of noise added to the preamplifier output signal.

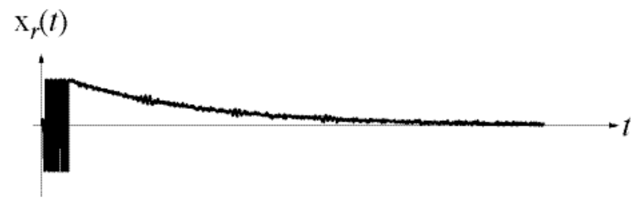


Figure 8—Typical preamplifier output signal in the presence of broadband additive noise

Figure 9—Typical bandpass-filtered preamplifier output signal in the presence of broadband additive noise

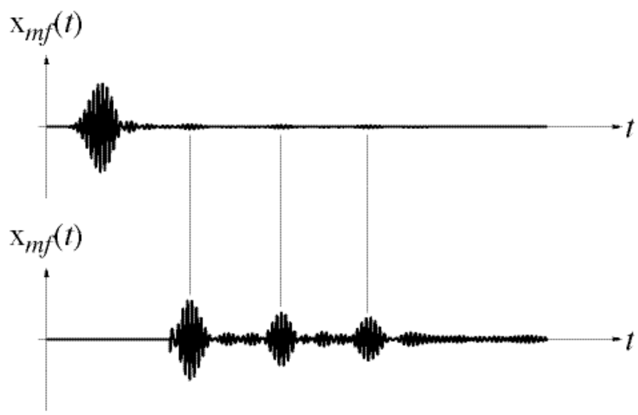


Figure 10—Matched-filter output signal in the presence of broadband additive noise - Top plot is the total signal and bottom plot is the same signal after suppressing the driving pulse and expanding the vertical scale

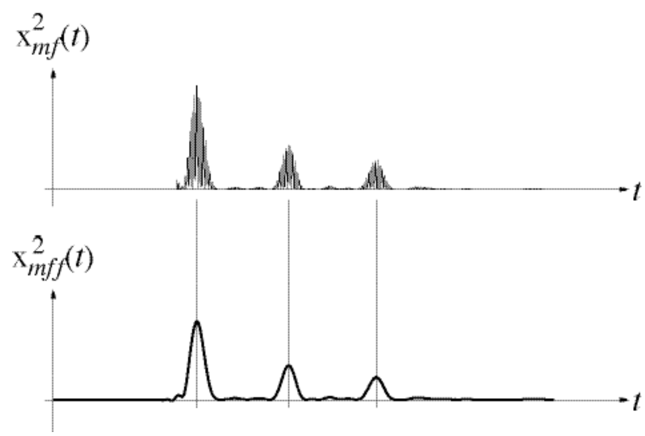


Figure 11—Matched filter output signal squared (top) and then low pass filtered (bottom) in the presence of broadband additive noise

5 MEASURED SIGNALS

The signal processing technique and overall measurement apparatus has successfully been employed to measure water level at room temperature. The basic experimental technique was to pulse the transducer with a particular frequency windowed sine wave and then to observe the timing of the reflected wave. The frequency of the driving sine wave was varied over the range of frequencies for which the blade is likely to be mechanically responsive (from about 40 kHz to 170 kHz). Results of the measurements are shown in the following series of graphs.

Figure 12 shows a typical measurement result. In this case the drive frequency was stepped from 40 kHz to 165 kHz and the signal was acquired and processed according to the sequence of steps outlined in the signal processing section of this report. For short periods of time (100 μs range) at higher frequencies (above 100 kHz) the measurement result is very high likely representing local reflections (non guided) of the drive signal. Thus it appears that no energy is coupling into the waveguide at these frequencies and as expected no return signal is observed. The signals of interest are those at ~350 microseconds and 400 microseconds, which represent the reflection from the distal end of the blade returning to the drive/receive coil and those that first pass to the proximal end of the waveguide from the drive coil, return and the transmit to the distal end of the wave guide and back.

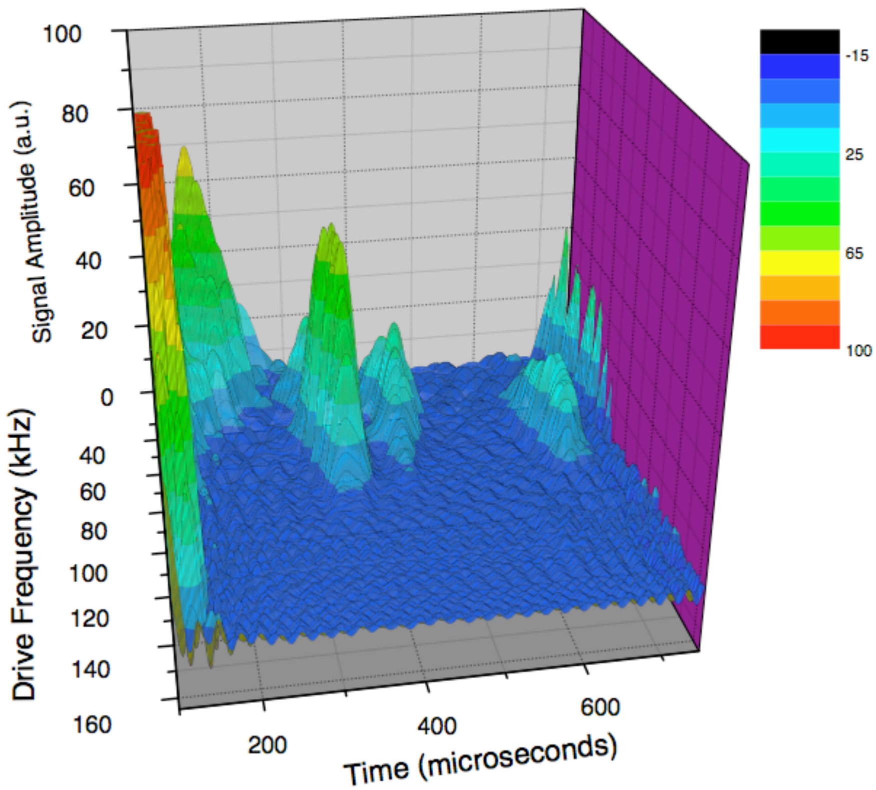


Figure 12—Processed measured signal for wave guide in air scanning over wide frequency range

While these results are useful for determining the allowed range of the drive signal, measuring only the signal return from a wave-guide in a single fluid does not indicate the water level. It is necessary to subtract measurements from a water-immersed waveguide from an air-immersed waveguide to demonstrate measurement sensitivity. This is shown in Figure 13. Figure 13 further demonstrates that the measurement system has a fairly narrow range of measurement frequency sensitivity between 80 kHz and 90 kHz.

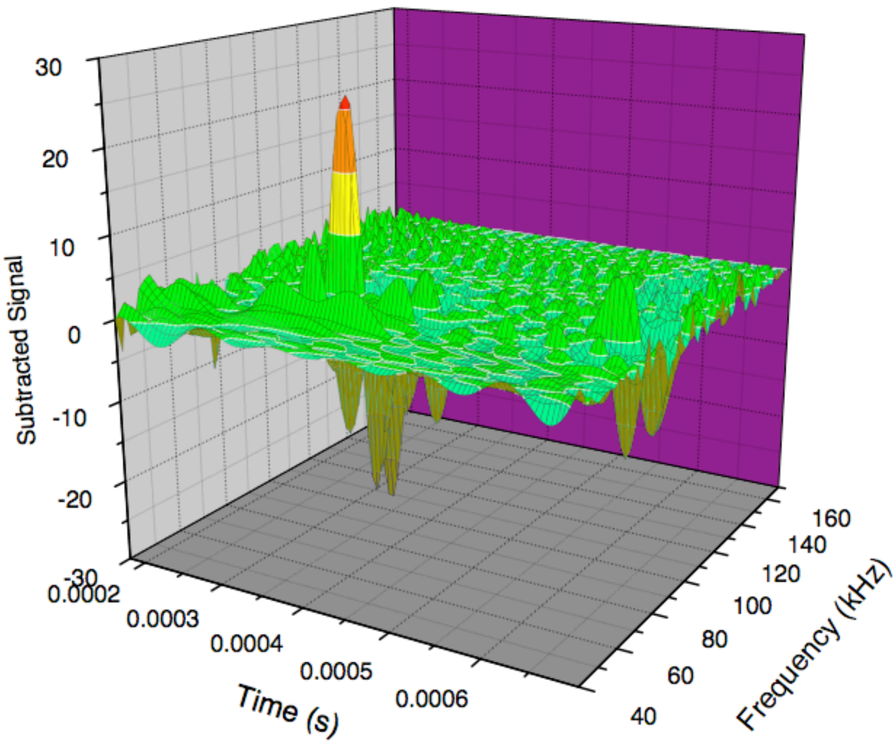
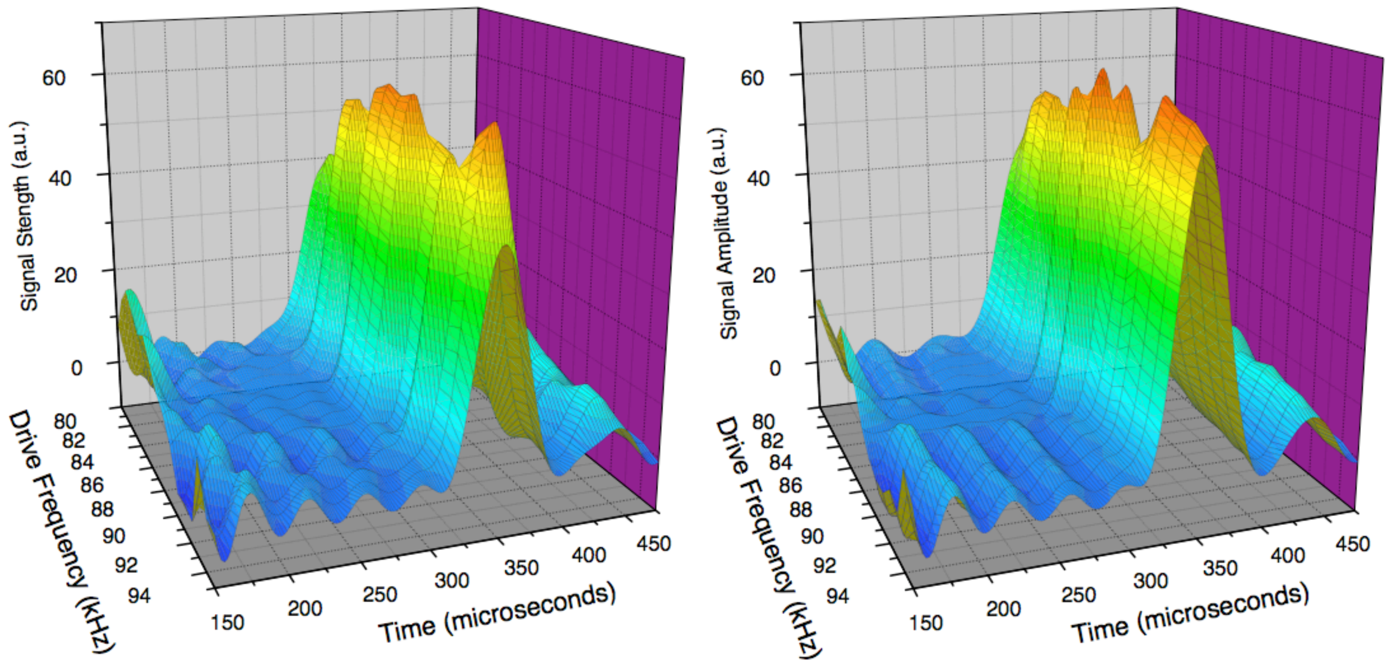


Figure 13—Resultant signal from subtracting water immersed peak signal from an air immersed measurement

Zooming in on the sensitive area of the signal shows that both the water-immersed and air-immersed waveguides provide strong and visually similar signals (Figure 14).



(a) (b)

Figure 14 (a)—Air immersed waveguide reflection and (b) Water immersed waveguide reflection

Subtracting the air immersed waveguide signal from the water immersed waveguide signal yields Figure 15 that definitively demonstrates the sensitivity of the measurement to water level. Specifically at 82 kHz the water immersed signal reflection is delayed relative to the air immersed reflected signal. This is shown in the single trace plot Figure 16. Note, however, that the measurements demonstrate high finesse (frequency sensitivity) and that at some frequencies the measurement does not appear to be sensitive to the presence of water and at others exhibiting an as yet unexplained inversion of the relative timing of the water and air immersed signals (87, 89, and 92 kHz).

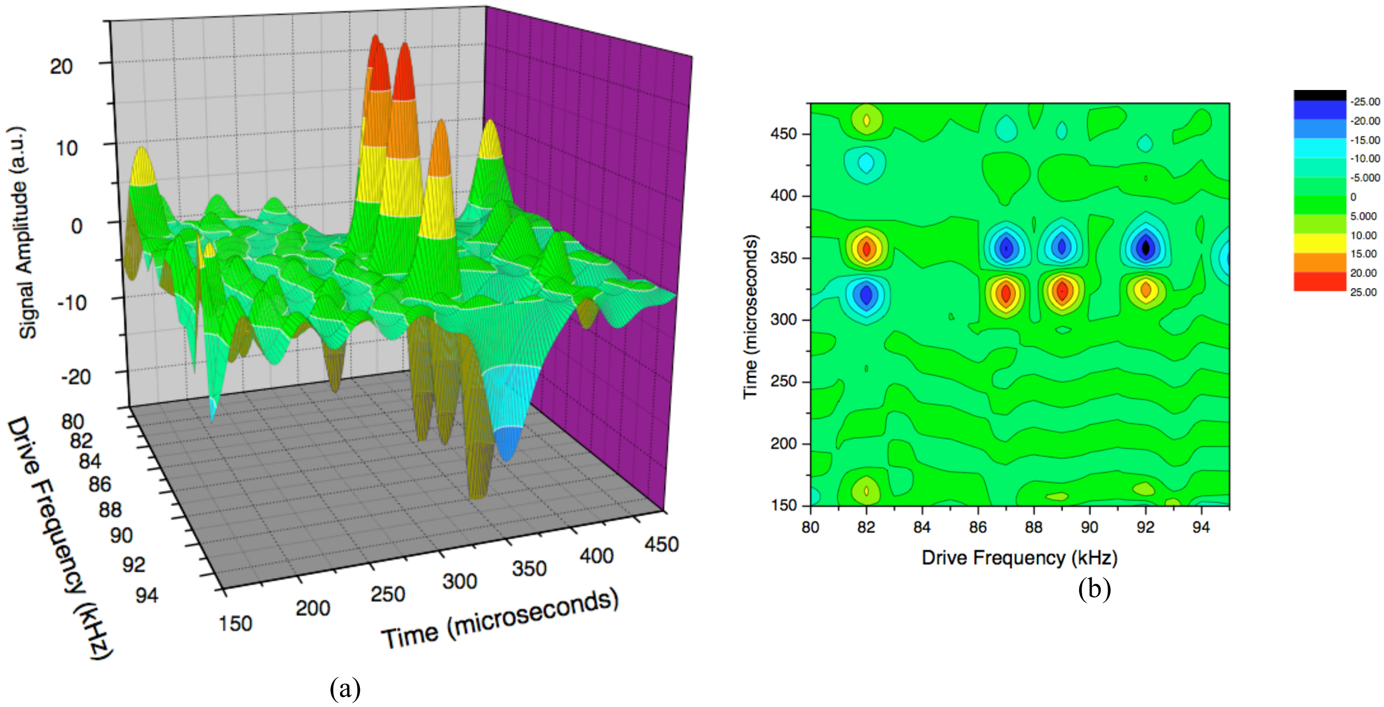


Figure 15—Subtracted signal from water and air immersed waveguide signals (a) 3D surface plot and (b) contour plot

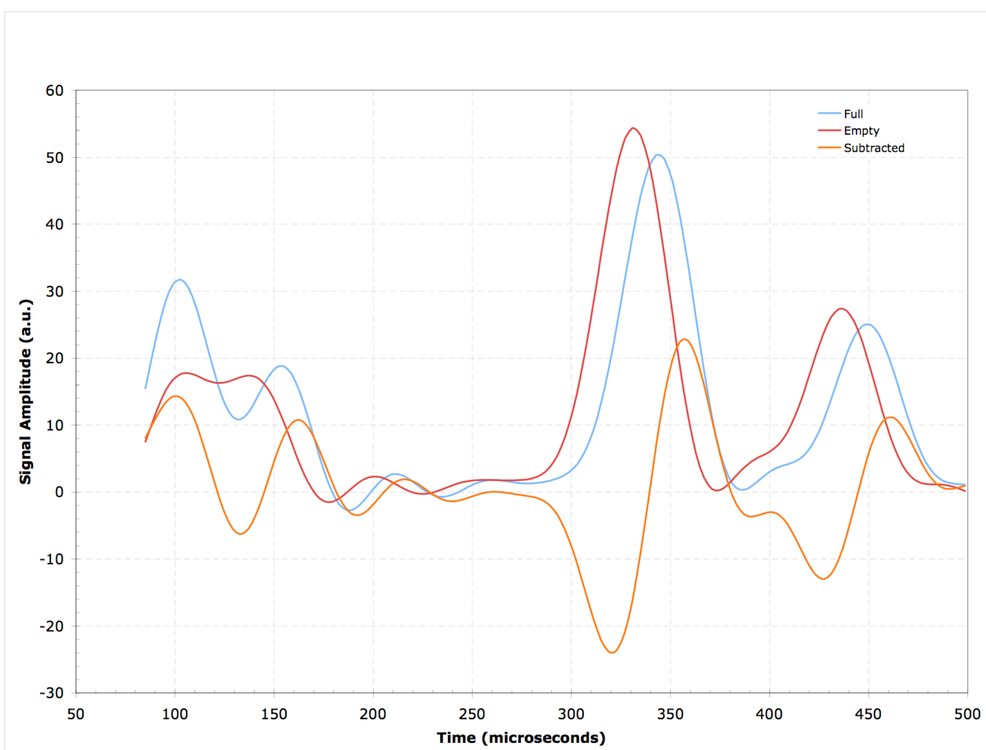


Figure 16—Reflected waveform from a water immersed (full) and air immersed (empty) waveguide with drive frequency of 82 kHz

6 CONCLUSIONS

The experimental system is functional and does measure the water level. The signal processing algorithms do allow extraction of the reflected signal from the noisy return signal.

We have only recently managed to get the entire measurement system functioning. The measured signals are quite complicated and contain a significant number of features that we cannot yet explain. Further, fabricating the transducers and actually making the measurements has strongly suggested a series of refinements to make in the final, high temperature and pressure tolerant version of the system to be fabricated and demonstrated during FY2007.

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[2] Jin O. Kim and H. Bau, *On-Line, Real-time densimeter—Theory and optimization*, Journal of the Acoustic Society of America, 85(1) January 1989, pp 432-9

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[6] L. C. Lynnworth, R. Cohen and T. H. Nguyen, *Clamp-On Shear Transducers Simplify Torsional and Extensional Investigations*, Ultrasonics Symposium, 2004 IEEE, 3, August 2004, pp. 1603-7