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*Title:* **Acoustic Sensor for Pipeline Monitoring:  
Technology Report**

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National Energy Technology Laboratory



# **Acoustic Sensor for Pipeline Monitoring: Technology Report**

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Los Alamos National Laboratory

July 20, 2005

## **Executive Summary**

This report presents detailed information on the effort to develop acoustic sensing technologies for natural gas pipe line monitoring. It starts with a historical evolution of the project and ends with the current status. The various technical accomplishments during this effort are pointed out. The latest technique involves the use of Lamb wave propagation in the wall of a pipe generated in a stand-off manner for defect detection. The report presents data to show how various types of defects in a pipeline can be monitored using this technique. Defects (e.g., a 0.5 mm groove on 7 mm thick pipe) on the outside of a pipe can be detected using transducers inside the pipe. Various advantages and certain disadvantages of this technique are pointed out. Recommendations as to the future direction of this effort are also presented.

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# Acoustic Sensor for Pipeline Monitoring

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## Background:

It is important to provide some background information of this acoustic sensor development effort to put things in perspective. The historical evolution of the project would then become evident. In the beginning, this project was of exploratory nature and covered a lot of different aspects of pipeline monitoring. The following is a list of the tasks that were explored:

- Measure wall-thickness
- Detect gas contamination in pipeline
- Measure velocity/flow of gas
- Detect presence of gas leak
- Determine the variation in pipe cross-section (ovality)
- Determine structural defects in pipe.

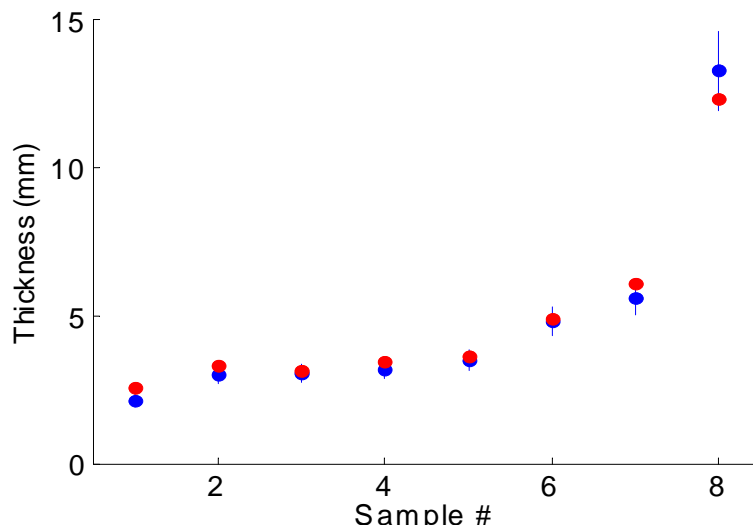
At this stage, there was no stipulation regarding adapting these techniques to an Explorer type of robot but to simply develop new techniques. The following is a brief description of what was accomplished in the spirit of technology exploration.

### *Wall Thickness Determination:*

Off-the-shelf acoustic wall thickness monitoring devices are available from a host of companies and these can provide sub-mm type of resolution quite easily. The only problem is that one needed to know the material properties exactly. For example, the thickness could be only determined if the sound speed of the material was known accurately because the measurement depended on a time-of-flight approach. The difficulty lies in the fact that knowledge of exact sound speed is not readily available, particularly for a natural gas pipeline that has degraded and aged over time. The book value of sound speed would be way off the actual value. Therefore, we proceeded to develop a technique that could provide both sound speed and wall thickness simultaneously from the same measurement and *a-priori* knowledge of wall material was not necessary. This is a major accomplishment because no such device existed anywhere. The system we developed required physical contact between the sensor-head and the wall as shown in Figures 1(a) and 1(b). This approach provided an accurate measurement of wall thickness only at the point of physical contact and not along the circumference of the pipe. In principle, this technique could be adapted for non-contact measurements using electromagnetic-acoustic transducers (EMAT).



**Figure 1.** Simultaneous measurement of sound speed and wall thickness of any container or pipe. (a) Measurement on an aluminum pipe is shown. (b) shows measurements being made on coffee mug for which there is no available sound speed data. The black sensor head needs to be in physical contact with the object as shown above.



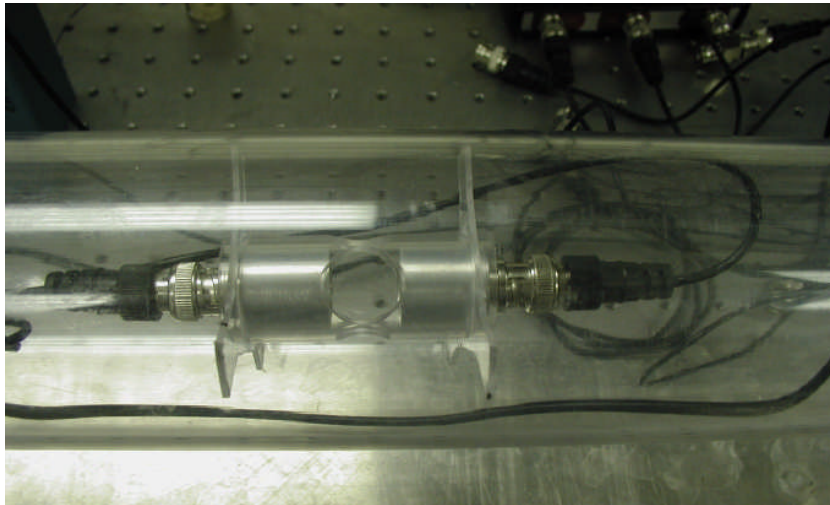
**Figure 2.** Measurements on 8 different objects are shown above. The blue dots indicate actual measurement with a digital caliper and the red dots are the thickness determined using our new approach. No *a priori* knowledge of material sound speed was used.

The accuracy of the measurement degraded for thicker objects because of the particular transducer design. It was specifically designed for thinner materials. With a properly designed transducer, the accuracy of thickness measurement can be better than 1%. This

kind of accuracy is simply not possible using existing devices in the market because those require prior knowledge of the material and that is not available for a natural gas pipeline that is degraded from use over a period of time.

*Detect gas contamination in pipeline:*

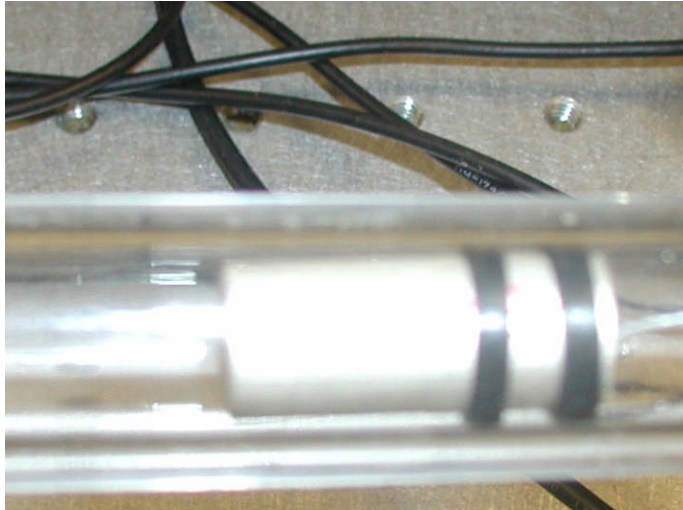
LANL has multiple patents on a technique called the Swept Frequency Acoustic Interferometry (SFAI) that is extremely sensitive in characterizing fluids (e.g., gases, mixtures, suspensions, emulsions, liquids, etc.). The technique is based on setting up standing waves in fluid-filled cavity and determining very accurately the sound speed and sound absorption as a function of frequency between 100 kHz to 5 MHz. The measurements are made in the frequency domain directly with extremely high signal-to-noise ratio. The SFAI technique can determine contamination at ppm levels. The SFAI technique was originally developed to identify chemical warfare compounds and other highly toxic materials inside sealed containers. The SFAI technique was tested on several gases and vapors to prove that this approach would be practical for contamination detection in natural gas pipeline. This task was not pursued any further at the suggestion of NETL. The following is a picture of the set up used to study this.



**Figure 3.** Picture of the SFAI set up. Standing waves are set up in the space between the two transducers facing each other. The diameter of the Plexiglas tube is 2 inches. The sensor can be built a quarter of the size shown above using the latest transducers available commercially.

*Measure velocity/flow of gas:*

We also explored a novel approach for measuring flow of gas inside a pipe using an acoustic technique. This used a simple hollow piezoelectric cylinder to produce a voltage when the gas passed through it. The voltage developed was proportional to the flow. The signal from the piezoelectric cylinder was rectified and an rms value was extracted. The signal generated could be optimized by choosing a proper size of the cylinder to obtain a resonance enhancement. Figure 4 shows a picture of the set up used.

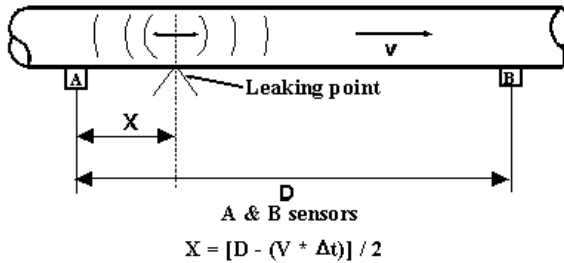


**Figure 4.** Flow measurement set up. The piezoelectric cylinder (white) is held inside a Plexiglas pipe (0.5 inch diameter) using two rubber o-rings (black).

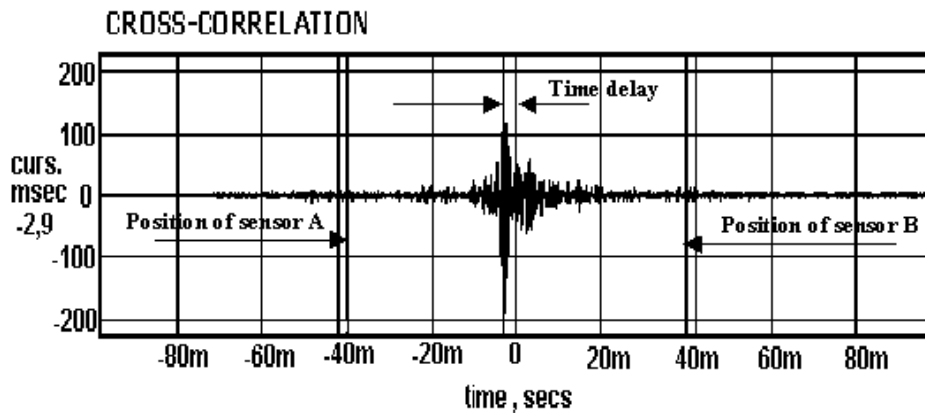
This technique was later explored for generating power from gas flow inside a pipe.

*Detect presence of gas leak*

It turned out that others have already come up with a technique to determine leaks using a cross-correlation approach based on acoustic (contact) sensing. Therefore, this task was not pursued. Just for completeness, the technique will be briefly mentioned below.



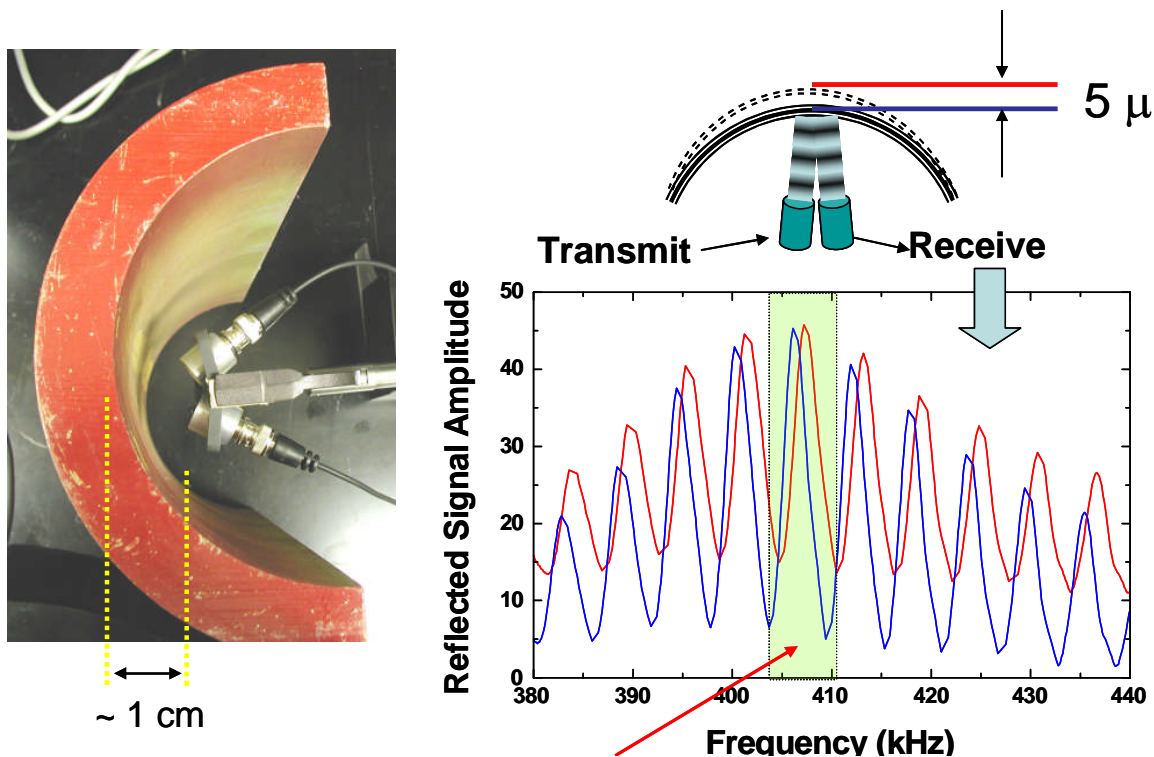
**Figure 5**



The top drawing in Fig. 5 shows the approach. Two transducers are attached to a pipe a distance apart and the signal from these transducers is cross-correlated. A leak in a pipe typically produces a high frequency noise and this noise (vibration) is detected by the transducers. By knowing the separation distance between the two transducers and the cross-correlation time delay, it is possible to pinpoint the leak. It may be possible to do this using a completely non-contact approach that can be adapted to the Explorer robot.

*Determine the variation in pipe cross-section (ovality)*

This task was quite thoroughly explored and the details are presented below.

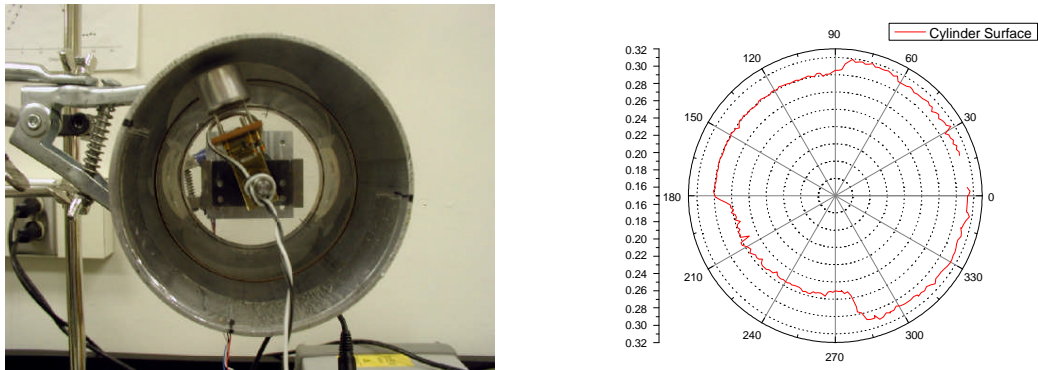


**Figure 6.** Variation in pipe cross-section and its determination

This technique used two transducers (a transmitter and a receiver) that used a frequency sweep measurement and looked for a shift in the interference pattern. Standing waves were set up between the transducers and the reflecting wall surface and these showed up as resonance peaks (see Fig. 6). This standing wave interference pattern is very sensitive to the path length and so even a very small variation in wall position change could be detected. The extreme sensitivity of the technique is shown in the top-right figure in Fig. 6 where the spectrum shift for a 5 micron variation in path length (pipe ovality) is shown. By rotating the transducer system along the circumference inside the pipe, it is possible to get an accurate representation (better than micron resolution) of the pipe wall diameter variation as a function of angle.



The above approach had the complexity of requiring two transducers. We felt that it would be better to be able to use a single transducer for this measurement which would help in the implementation of the technique. We found that certain commercially available 40-kHz air-coupled transducers provided clear access to the bare piezoelectric element. This opened up an interesting possibility that one could now monitor the acoustic pressure variation in front of the transducer (see the interference pattern in Fig. 6) through the electric impedance variation of the piezoelectric element. The sound pressure variation occurs due to setting up standing wave generation between the transducer face and the solid wall and the variation in the path length. The following figure shows an implementation of this simpler approach.

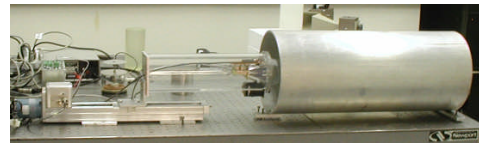
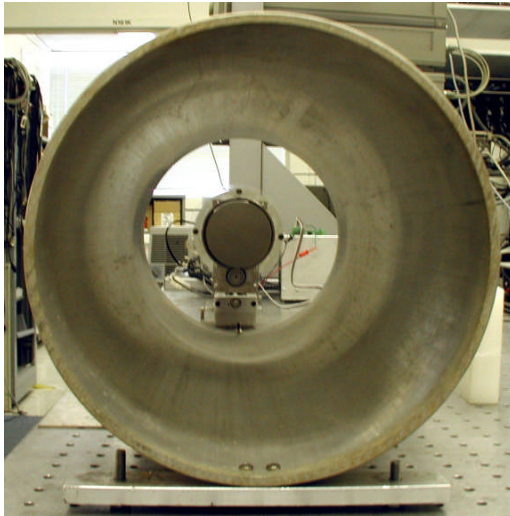


**Figure 7.** Single transducer wall variation detection. The single transducer shown on the figure (left panel) is rotated along the circumference and the resulting measurement of the wall position variation is shown on the right as a function of angle. The measurement resolution is better than 100 micron.

Figure 7 above shows the implementation of the single transducer distance tracking system inside a 3.5 inch diameter aluminum pipe. The transducer is rotated using a stepper motor and the entire 360 degree rotation takes approximately 0.1 second. We are able to detect distance variation due to the presence of even a single layer of Scotch tape. In fact, the angular data shown above are due to a single and a double layer of Scotch tape inside the pipe. This technique has the capability to detect small variation to corrosion or rust inside the pipe and the measurement is fast (<0.1 s per 360 degree sweep).

We also developed a microwave Doppler interference technique that accomplished much the same as the acoustic technique mentioned above. It used a rotary 10.5 GHz microwave Doppler head to obtain similar distance measurement inside a pipe. The main advantage of this system is that the measurements are invariant with regard to the gas or the pressure or flow in the gas inside the pipe. The microwave set up is shown in Fig. 8 on the next below.

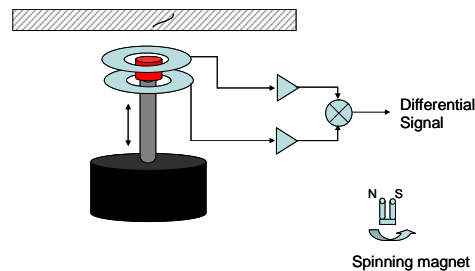
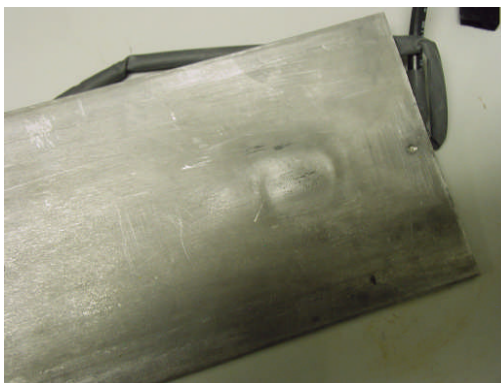




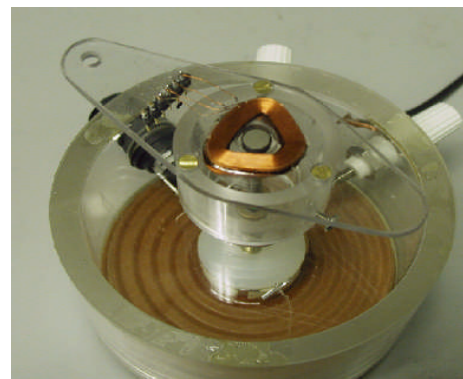
**Figure 8.** Microwave Doppler Interference System for pipe internal dimension monitoring. The rotating microwave sensor is shown at the center of the pipe. The pipe is rotated to complete a 360 degree rotation in less than 0.1 s. The measurements obtained are very similar to the one shown in Fig. 7 above.

*Determination of Structural Defects in Pipe Wall:*

Although dents in the wall and variation in wall thickness can indicate damage or presence of defect, it is important to be able to determine presence of cracks or other defects independent of that. Therefore we explored several approaches to doing so. The following is a very brief description of the various approaches attempted. The magnetic approaches (Eddy Current and AC Field Measurement) were abandoned when we learned that other labs were doing something along those lines and we did not want to duplicate what others were doing.

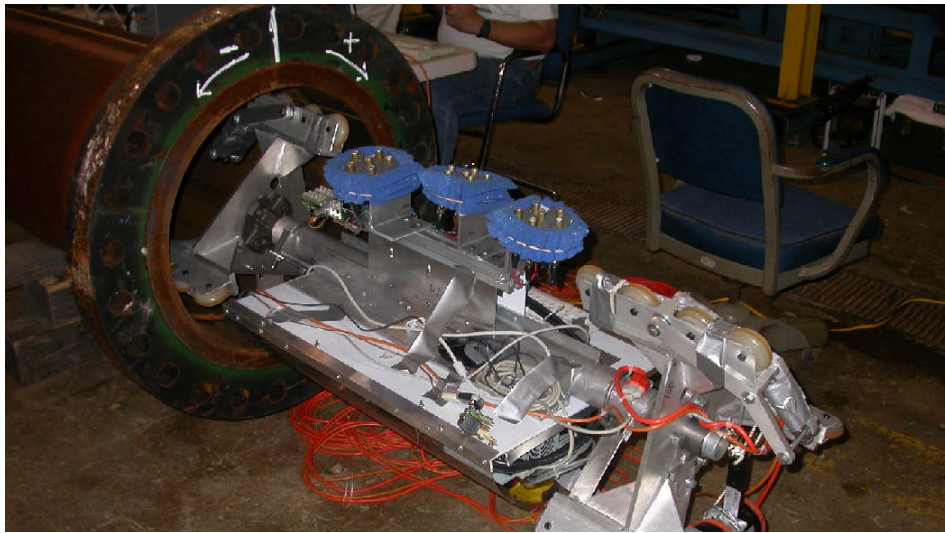


**Figure 9.** A damaged steel plate with a small Crack is shown above. The principle of the vibrating magnet differential measurement technique is shown schematically above and a photograph below. We also tried a spinning magnet technique. Both techniques appeared to be sensitive in detecting the presence of small cracks (even invisible ones) in the steel plate.

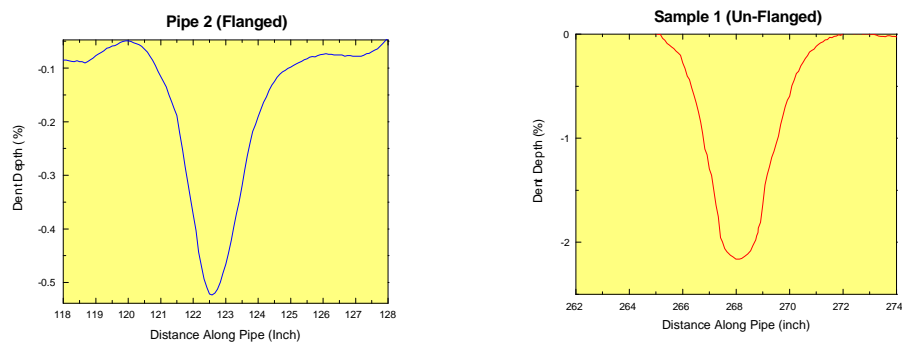


## First NDE Demonstration at Battelle Facility in 2004:

The first field demonstration of our non-contact acoustic approach was conducted in September of 2004. We were asked only to demonstrate our acoustic pipe dent detection technique on a 24-inch diameter steel pipe. The dents were all on a line across the length of the pipe within a cone of 30 degrees approximately. We were also told that no moving, rotating or spinning components were desirable and so we needed to come up with an approach that could cover the 30 degree cone without any moving sensors. Consequently, we designed an array sensor with staggered elements that covered the entire cone. The following is a picture of the sensor setup.



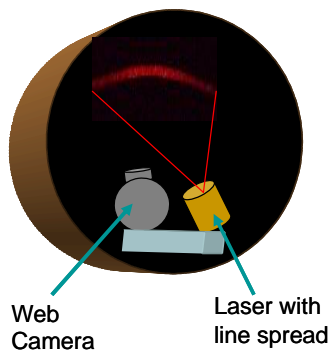
**Figure 10:** Acoustic sensor for dent detection. Three banks of staggered arrays were used to cover the 30 degree cone. There was redundancy in the number of sensors. The computers and signal processing electronics were placed underneath the transporter and are not visible in the picture. The purpose of the staggered was also to produce a 3-D image of the dents.



**Figure 11:** Example raw data from two dents – one from each pipe.

All the dents in each pipe (flanged and un-flanged) were correctly identified. Unfortunately, our original report contained erroneously higher dent-depth. Later with thorough analysis of our data-acquisition software we found our mistake to be wrong calibration. In fact, all results for dent-depths got multiplied by a factor of 1.6. This information was included in the report addendum. Figure 11 shows examples of raw data (uncorrected) obtained from our non-contact acoustic sensor shown in Fig. 10. Great profile details of any dent could be seen in the data.

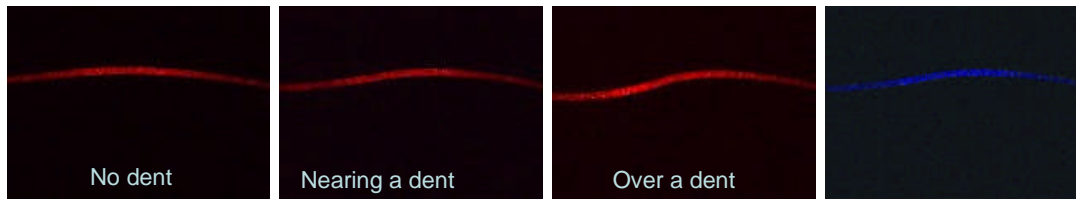
We also tried out a simple optical method for 3-dimensional dent characterization using imaging of projected laser line. For our requirement the projected laser line only covered the 30 degree cone but it can be easily made to cover the entire circumference. For each dent we could generate a movie and extract the 3-D profile of a dent.



- *Dent geometry in 3-D can be determined using this method*
- *Besides geometry, it is also easy to see corrosion, rusting and other damages*
- *Spectroscopic information on damage can be obtained using white light*
- *360 degree imaging is possible*

A sequence of line scan pictures of a dent

Movie



**Figure 12:** Laser line imaging for dent geometry determination. A simple CCD camera was used to capture the image of a projected laser beam onto the inside wall of the pipe. For a uniform geometry, the image was a symmetrical line as shown above (left). This image gets distorted as defects or dents appear as shown in the figures above.

This simple optical approach turned out to be very powerful in terms of characterizing variations on the inside wall of the pipe. Rusts and corrosions also showed up very clearly. The interesting feature of this approach was that one could essentially adapt it for spectroscopic analysis of the inside surface or defects if wanted too quite easily.

## **Current Effort (Post September 2004):**

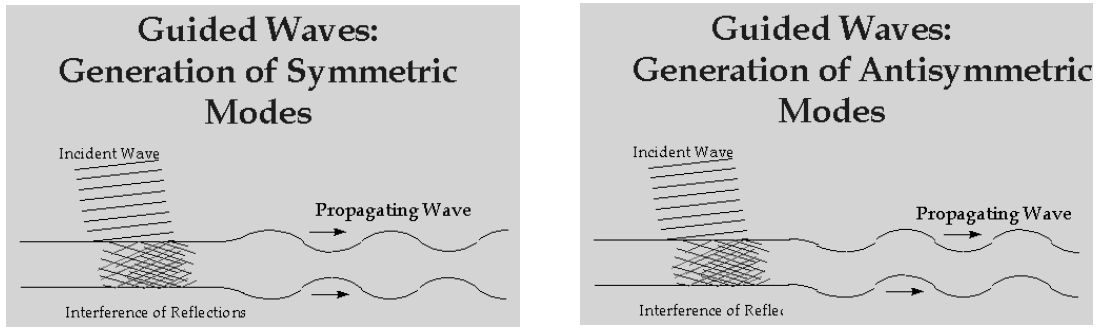
Following the September 2004 Battelle test, it was decided (based on feedback from industry folks) that there was not much value in simply determining dents and mapping these accurately. Moreover, the sensors we had developed required scanning (rotating) the inner wall of the pipe that was not desirable. The main industry interest was in determining defects in the wall, such as corrosion pits. Therefore, a new approach was pursued that could determine the presence of defects (e.g., corrosion pits etc.) anywhere along the circumference of the pipe without having to rotate the sensor head as it is transported along the pipe length. The following sections present a discussion on the new sensor design based on new physical principles.

### ***Stand-off Measurement***

We were able to obtain a new class of wide bandwidth transducers (Gas Matrix Piezoelectric) from a company that opened up new possibilities for us. These transducers are expensive (\$1200 each) and custom-made but provide measurement capabilities that were simply not possible previously. These have the highest coupling coefficient and other advantages over conventional air-coupled transducers. This combined with our patented Swept Frequency Acoustic Interferometry (SFAI) enabled us to explore completely new stand-off NDE approaches with great potential. In the SFAI technique, both amplitude and phase measurements are made simultaneously. With this technique, we can obtain excellent data from our air-coupled transducer measurements with an excitation voltage of less than 10 V, whereas the traditional pulse-echo technique would typically require voltage pulses of the order of 400 V to even be able to see any signal. The SFAI technique brings in an enormous enhancement in signal quality and enables stand-off measurement capabilities.

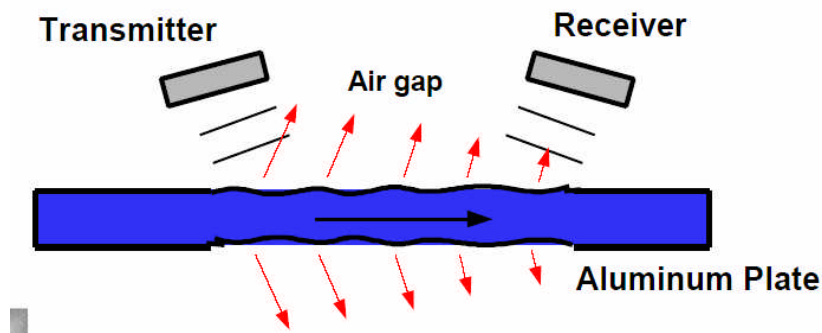
### ***Air-Coupled Lamb Wave Approach:***

Lamb waves are guided waves whose propagation characteristics depend on a structural boundary (Lots of reflections, mode conversion, hence wave superposition to form packets of energy, or modes, that depend on wave input angle and frequency) i.e. rods, pipes, and embedded layers, etc. Lamb waves are similar to longitudinal waves, with compression and rarefaction, but they are bounded by the sheet or plate surface causing a wave-guide effect. Lamb waves are a complex vibrational wave that travels through the entire thickness of a material. Propagation of Lamb waves depends on density, elastic, and material properties of a component, and they are influenced by a great deal by selected frequency and material thickness. With Lamb waves, a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical as shown below in Fig. 13.



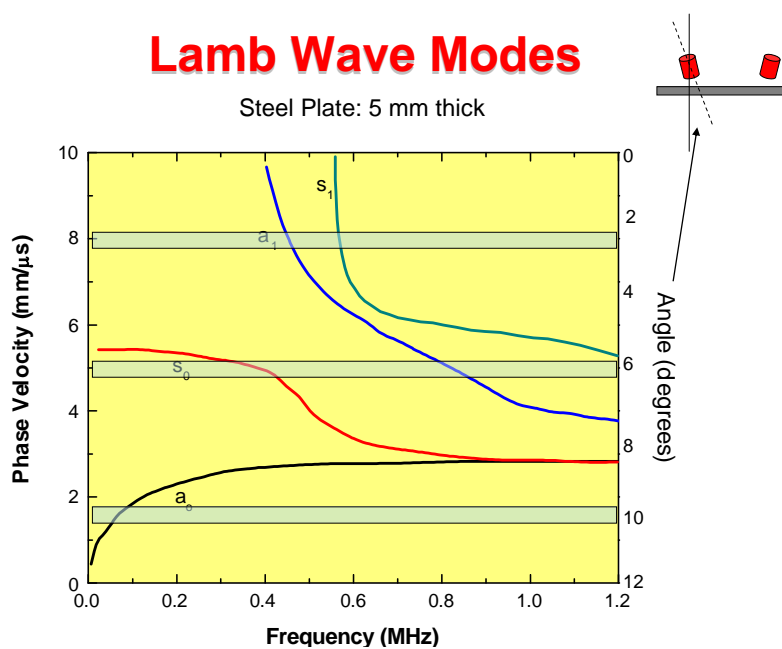
**Figure 13.** Two mode types for Guided waves in a plate. These types of vibrations can propagate along a solid plate or in the wall of a pipe quite efficiently.

Traditionally, Lamb waves are generated in a plate or a pipe using angled contact transducers. This means that the transducers are held against the plate at an angle as shown in the figure above. This angle and the transducer frequency determine the kind of vibrational mode that can be generated in the plate. Depending on the angle and the frequency, many different modes can be excited. Plate thickness mode vibrations can be generated at angles close to normal. If a plate has defects, these waves (modes) interact (e.g., reflect, scatter, etc.) with these defects and the information about the defect then can be extracted from the propagating wave. The waves slow down when encountering defect. These waves reradiate into the medium outside as they propagate and are called leaky Lamb waves. Thus a receiver transducer can pick up these propagating waves in a plate. This is shown in Fig. 14 schematically.



**Figure 14.** Generation and reception of Lamb waves in a plate using air-coupled transducer. The angle between the transducer front surface and the plate is important.

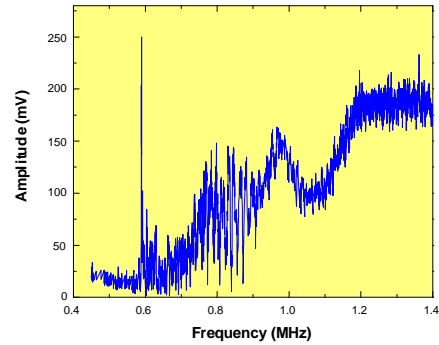
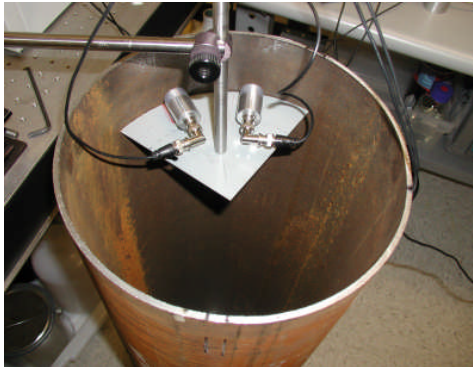
Another approach to generating Lamb waves in a metal plate is the use of electromagnetic acoustic transducers (EMAT) but that requires a lot of current, has poor signal to noise ratio, and the lift-off distance is critical. Because of these significant disadvantages, we decided to not use EMATs.



**Figure 15.** Lamb wave modes as a function of frequency and angle. The figure shows several Lamb wave modes that can be generated in the frequency range of interest. The letter ‘a’ stands for anti-symmetric mode and ‘s’ for symmetric mode. The suffixes represent the mode order.

As mentioned earlier, the Lamb waves depend on the angle of the transducer. Figure 16 shows how various modes can be generated by appropriately selecting the angle and then sweeping the frequency. The horizontal bands in the figure represent a frequency sweep. It is possible to select either a single mode or multiple modes by adjusting the angle and the frequency. At an angle that is almost normal to the plate, thickness mode vibration can be generated (see the  $a_1$  and  $s_1$  modes in Fig. 15 at angles close to 0 degrees to normal). We have been successful in determining the thickness of the pipe-wall in both transmission and reflection mode. To the best of our knowledge, no researcher has been able to measure wall thickness using air-coupled transducer in the reflection mode. It is worth pointing out that our measurements were done under ambient conditions and not under pressure. In the transmission mode, the transmitter and the receiver were on opposite sides of the pipe (one inside the pipe and one outside the pipe), whereas in the reflection mode both transducers are on the same side. Figure 16 shows the actual experimental set up for the reflection mode measurements and the thickness mode resonance data.





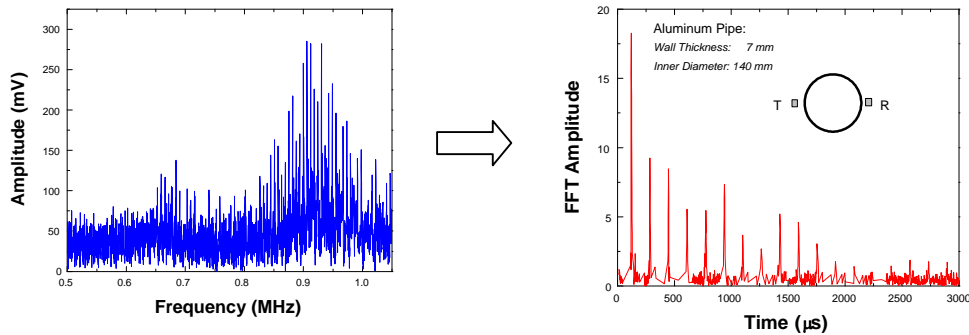
**Figure 16.** Lamb wave measurement set up. The pipe on the left is a 12-inch diameter steel pipe with a 5-mm thick wall. The two transducers are set an angle that is normal to the surface of the pipe wall. The graph on the right shows the frequency sweep measurement. The wall thickness mode resonance peak is near 0.6 MHz as expected (compare data for  $s_1$  mode in Fig 16). The resonance frequency is a direct measure of the wall thickness.

This acoustic stand-off wall thickness measurement technique can be of real value because it can provide thickness resolution down to 0.1 mm or better in a pipe that is 5 mm thick (or better than 0.2%). Unfortunately, this approach has one major shortcoming – it can only determine the thickness at a given location on the pipe at a time and to measure around the circumference of the pipe one needs to rotate (scan) the sensor head. A wall thickness profile along the circumference of the pipe can be generated his way. The need for scanning the sensor head is an undesirable aspect of this sensor. Therefore, it is better to use the Lamb wave measurements to determine defects through the interaction of such waves with defects instead of a direct measurement of wall thickness. In the following section, details of these types of Lamb wave measurements will be presented.

#### *Lamb wave detection of defects:*

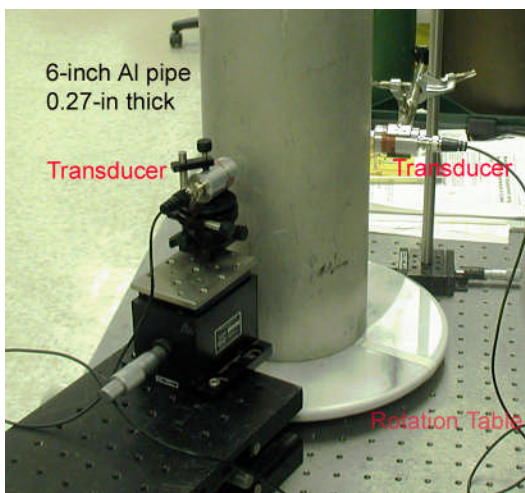
To take advantage of the SFAI technique and its unprecedented signal-to-noise ratio improvement over conventional methods, one needs to do a certain amount of signal processing. The SFAI technique gathers data in the frequency domain directly. In other words, both amplitude and the phase of the wave are measured at each frequency. The measured frequency spectrum may look very complicated but contains all the relevant information. However, the information is much easier to deal with in the time domain. This frequency domain to time conversion is made through a complex Fast Fourier Transform technique. An example of this is shown in Fig. 17.



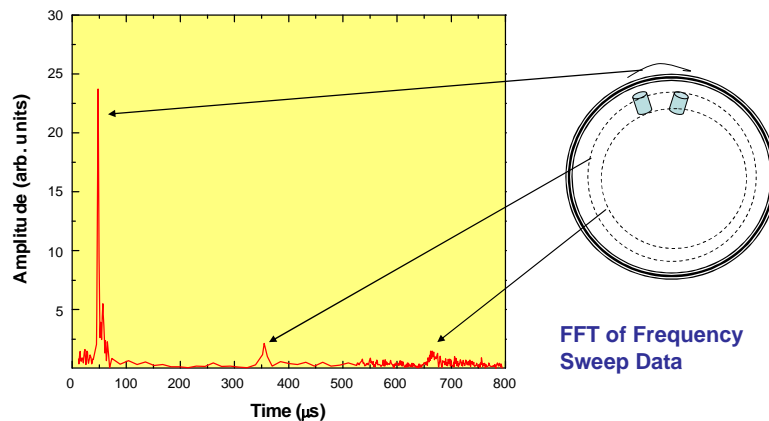


**Figure 17.** The graph on the left shows the actual measured data. The sharp lines in the data are the resonances due to the standing waves set up by the Lamb waves propagating along the circumference of the Aluminum pipe. The graph on the right shows the Fourier transformed data. This data is equivalent to a measurement where a pulse is launched and is picked up at a distance. The equi-spaced (in time) multiple peaks show that the sound pulse is going around the circumference multiple times and slowly decaying in the process.

Both form of data (frequency domain experimental data and the time-domain derived data) contain the same physical information. It is worth pointing out that this data was obtained using only a 9 V excitation. The multiple peaks in the time domain data are simply equivalent a pulse of sound going around in circles along the circumference of the aluminum pipe (14 cm inner diameter and 7 mm thick). The first peak shows the time a sound pulse takes to go from the transmitter (T) to the Receiver (R). This time includes the time of propagation through the air-gap as well. The subsequent peaks represent the propagation time for a full circle. The speed of propagation can be determined easily from this data. When such pulses interact with any defect, it reflects and scatters the signal. Typically, this shows up as extra peaks, shift in peak, splitting of peak, and damping of the peaks. Figure 19 shows the experimental setup used to obtain the data shown in Fig. 17.

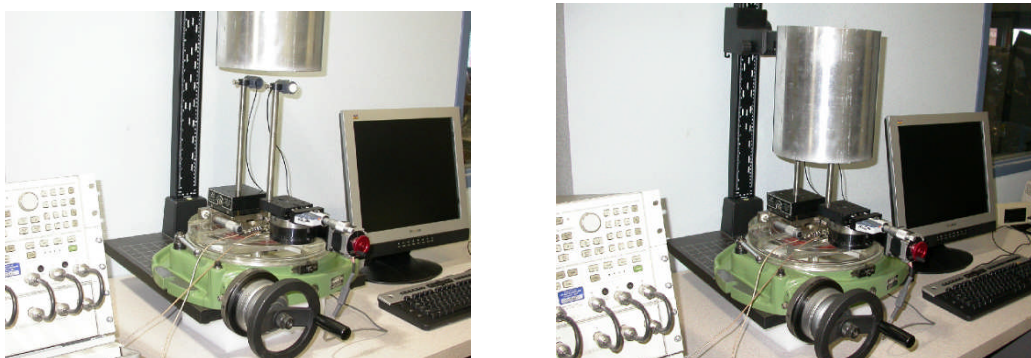


**Figure 18.** The experimental set up used for Lamb wave measurements. The air-coupled transducers are placed at a stand-off distance of 2 cm from the pipe wall. The angle adjustments are done manually using the rotary adjustments. The pipe sits on a rotation table so measurements can be made at various places on the pipe both along the circumference and along the height of the pipe. The Lamb waves propagate through the pipe wall and so both inner and outer surfaces see the wave (see Figs. 13 and 14). Therefore the measurements are equivalent whether the transducers are inside or on the outside. Both provide the same information.



**Figure 19.** Data obtained (derived from frequency sweep) from a 12-inch diameter rusted steel pipe with transducers inside the pipe (see Fig. 16 for set up picture). This points out clearly how the sound pulse propagates along the circumference of the pipe multiple times and gets detected. The small peaks indicate the extremely rusted condition of the inside of the pipe because of Lamb wave damping.

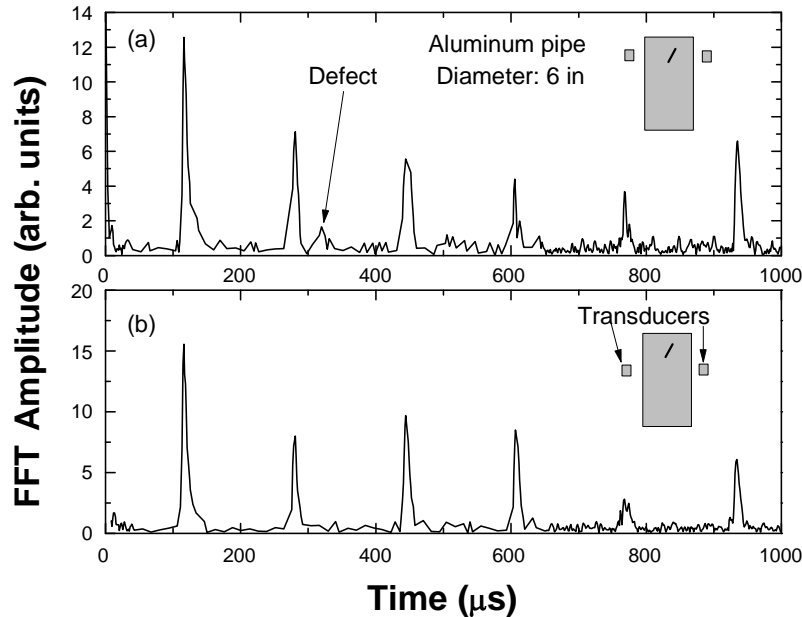
A more recent experimental set up that allows for motorized control of transducer orientation and position is shown in Fig. 20. The transducer angle can be adjusted independently and also in tandem. A computer controls all the operations through software. In this set up, the pipe is raised or lowered above the transducer system for measurements along the pipe height.



**Figure 20.** Experimental set up for motorized transducer orientation and position control. The pipe section can be raised (left) or lowered (right) over the transducer system. The transducer position and angle can be individually controlled so measurements can be made at various angles and positions along the circumference of the pipe from the inside.

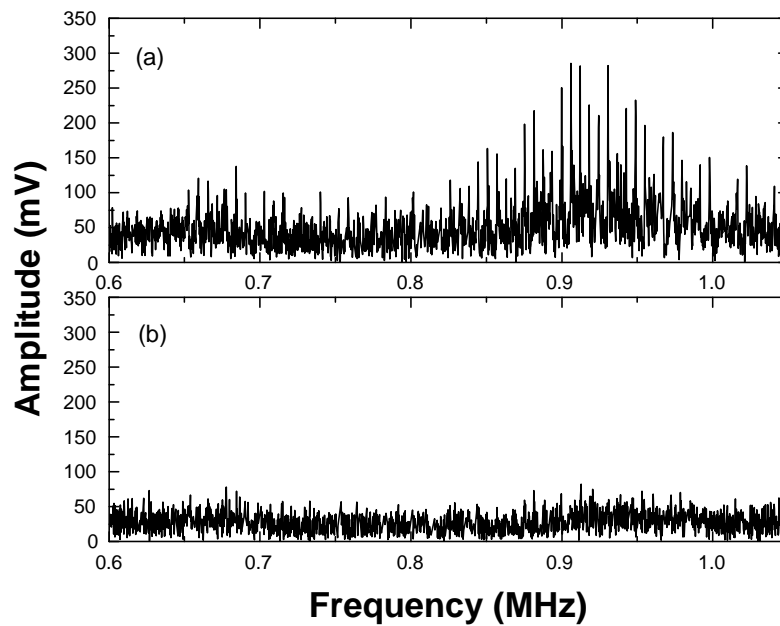
The advantage of the set up shown above is that any pipe section can be studied by simply lifting one out and substituting with another one. It also makes it easier for us to

put artificial defects both on the inside and the outside of the pipe. Besides motorized adjustment of transducers, it also allows for full manual control. In the following some results of defect detection using Lamb wave are shown.



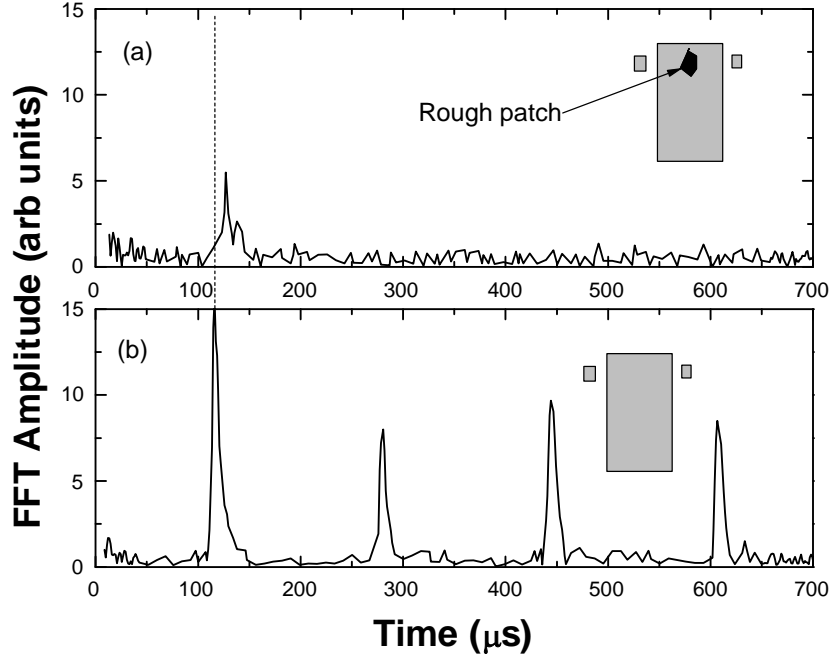
**Figure 21.** Time-domain derived data to show the detection of small 0.5 mm deep and 2 cm long defect on the inside surface of an aluminum pipe (7 mm thick). The small peak shown in (a) is due to reflection from the defect.

To detect defect using Lamb wave, we produced a deep scratch (0.5 deep) on the inside surface of an aluminum pipe (14-cm diameter, 7-mm thick) that is approximately 2 cm long and at an angle of approximately 45 degrees to the central axis of the pipe. The transducers are located on the outside (see Fig. 18 for the set up). In Fig. 21(a), a small extra peak shows up when the transducers are on the same level as that of the crack. As the transducers are moved away (either above or below) from the crack (approximately 2 cm), the peak disappears. It should be pointed out that when Lamb waves interact with defects, there can be mode conversion. This means that new vibrational modes can be generated (see Fig. 14) due to the defect that can propagate at different speeds than the original Lamb wave. Lamb waves can also slow down at a defect. Our best guess is that 0.5 mm deep (for a 7 mm thick aluminum pipe) defect may represent the resolution of this technique and it would be harder to detect cracks smaller than that. This still needs to be confirmed on various other surfaces and pipes. Again, it should be pointed out that the main point here is the ability to detect defects on the opposite side of a pipe from where the measurements are made. Otherwise, it is equivalent how the measurements are made – from inside of a pipe or outside of a pipe because the Lamb waves propagate on both sides (see Figs. 13 and 14).



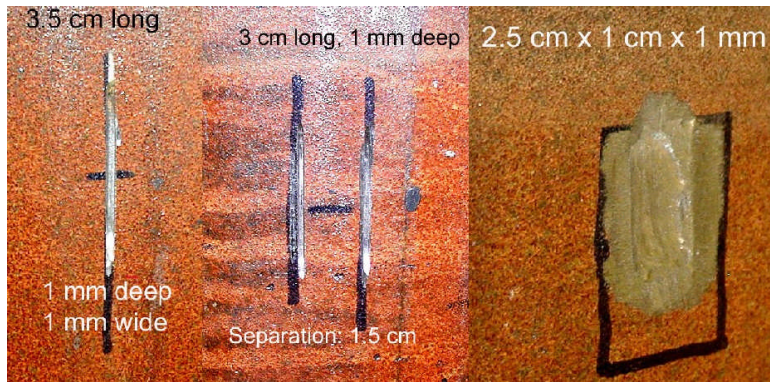
**Figure 22.** Damping of Lamb waves due to damage on surface. Frequency sweep measurements are presented to show how Lamb waves are damped when damage is present on a surface of a pipe. Figure 22(a) shows the data for the same aluminum pipe as in Fig. 21 for an undamaged pipe section. In Fig. 22(b), the data are for a section of the pipe where there is 3 cm x 3 cm area of damage made by scouring the surface. Note the significant damping of the signal.

To simulate a corroded surface, the inside surface of the aluminum pipe was scoured to produce visible damage over an area of approximately 3 cm x 3 cm. As can be seen from Fig 22(b), this damps out the Lamb waves significantly and thus can be detected.



**Figure 23.** Derived time-domain information for the frequency sweep data shown in Fig. 22. Note the following: (i) decrease of amplitude of the first peak, (ii) shift in time of the first peak indicating slowing down of the Lamb wave, and (3) disappearance of the subsequent peaks. All these factors combined indicate large area damage to the pipe.

As mentioned earlier that the time-domain data are easier to interpret and also show information that are otherwise hidden in the frequency domain information. This becomes obvious in Fig. 23 where the time-domain information is presented from the same data as in Fig. 22. In this figure one sees one additional feature – the shift of the first peak due to slowing down of the Lamb wave going through the damaged area. We have also repeated these types of measurements on a larger diameter (12 inch) steel pipe and verifying the results (see below).



**Figure 24.** Three different types of defects studied on a steel pipe of 12-inch diameter and 0.28 inch thick. The picture on the right shows a larger area damage to represent a gouge.

### **Current Status and Other Comments:**

We have shown that it is possible to detect several types of defects in a stand-off manner from inside a pipe using acoustic sensing methods. Our measurements are nowhere extensive and all possible types of defects are not studied. The following are the main advantages of our approach:

Measurements can be made from a stand-off distance of approximately 1 inch from the inside surface of a pipe.

- The technique works on all kinds of materials and sizes. We have tested pipe as small as 2-inch in diameter.
- Measurements can be made along the circumference of the pipe without scanning or rotating the sensor head.
- The SFAI technique provides outstanding signal-to-noise ration unsurpassed by the conventional pulse-echo techniques.
- The SFAI technique also allows very low power operation: less than 10V excitation for the transmitter transducer.
- Defects (small scratches) as small as 0.5 mm in depth can be detected for a pipe wall thickness of 7 mm, approximately 7%. The ultimate resolution is not known yet. By the way, this sensitivity is for detection on the opposite side of a pipe from the measurement side. It can be better if the defect is on the same side.
- 3-D image of a defect may be possible to obtain as the sensor head is moved along the axis of a pipe.
- The technique works even under ambient pressure but the quality of the data can improve by an order of magnitude if the pressure is even 50 psi.
- Based on experimental simulation, corrosion areas on a pipe surface can also be detected.
- It is possible to include dent detection capability in the same system.
- The electronics used can be miniaturized. All components are commercially available. The entire system can be accommodated within two modules of the Explorer robot.

The following are the disadvantages of our approach:

- Proper orientation of the transducers with reference to the pipe wall is very important.

- The measurements currently are slow and the Lamb wave measurements cannot be made at a very high speed, such as the proposed 4 inch per second movement of the Explorer. It is best designed to go back to a suspect area and do a thorough examination (see recommendations later). In contrast, the dent detection can be done in real-time.
- At present, we can only detect various types of defects and cannot provide quantitative answers about the actual dimensions of the defects from a single measurement. However, it may be possible to provide a 3-D image of the defect.
- We do not have a good way to distinguish between defects on the front surface as compared to on the back surface. The dent detection scheme combined with the Lamb wave approach should be able to distinguish the two. The front surface information is stronger than the back surface and may swamp the back surface (i.e. on the outer surface of a pipe) information. This needs further thorough study.

#### **Difficulties faced:**

Most of our design and studies were done prior to having any detailed operational information about the Explorer system. This information became available only at the PDR in June 2005. We found that the Explorer module can sag as much as ½ inch inside a 6-inch diameter pipe. Moreover, the modules will sway as much as 20 degrees and oscillate as they move. These introduce significant amount of difficulties in our design and our original design have to be modified to be workable in practice. In the short term, we will try to develop extensive feedback systems to counter the sag and oscillation of the modules but it will not be very fast because these will be motor driven. Extensive amount of algorithms need to be tested and refined. The electronics also needs to be modified significantly. These are all doable but will take additional efforts. The project has suddenly become a lot more challenging based on the new realities of the Explorer design.

#### **Future Recommendations:**

We would like to propose two stages of this development effort. One is geared toward a field demonstration in October-November 2005 time frame of the current technology and the other one is moving onward from there. For the field demonstration, with some additional efforts we should be able to demonstrate the technology described in this report. This information will be helpful in refining the deployable design presented at the PDR because the new information presented about Explorer II will require significant refinement of the electronics that we currently have. We can speed up the measurement technique by at least an order of magnitude so that our Lamb wave system can make real-time measurements while being transported at a speed of 4 inch per second. This will involve switching from our present frequency sweep system to a chirp correlation technique but maintaining the same advantages regarding signal-to-noise etc. It will be



possible to implement this new electronics in the October-November field demonstration with some additional cost. We have actually proven the new concept but do not have the electronics package as it is somewhat expensive. Further down the road, it will be advisable to use electronic beam steering technique instead of mechanical orientation using feedback. Electronic beam steering is similar to phased array radar where there is no physical movement of the sensor and the beam is steered in any direction electronically. Ultrasonic beam steering is used in ultrasonic fetal monitoring where 3-D images are produced of a baby inside the womb. Similarly, 3-D images of defects can be produced on the fly because there is no mechanical inertia involved in adjusting the angle of the sound beam from a transducer. This is a longer term project and is meant for a future improvement of the design presented at the PDR and not for the current design.

**Summary:**

This report presents detailed information on the effort to develop acoustic sensing technologies for natural gas pipe line monitoring. It starts with a historical evolution of the project and ends with the current status. The various technical accomplishments during this effort are pointed out. The latest technique involves the use of Lamb wave propagation in the wall of a pipe generated in a stand-off manner for defect detection. The report presents data to show how various types of defects in a pipeline can be monitored using this technique. Defects (e.g., a 0.5 mm groove on 7 mm thick pipe) on the outside of a pipe can be detected using transducers inside the pipe. Various advantages and certain disadvantages of this technique are pointed out. Recommendations as to the future direction of this effort are also presented.