RPSEA

Technologies of the Future for Pipeline Monitoring and Inspection

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Abstract

This report describes an initial research effort into an inexpensive alternative method of pipeline inspection. This method utilizes small-scale (capsule sized) sensors mounted either in conventional "dumb" pigs or in free-floating packages to continuously measure temperature, pressure, and other quantities inside the pipeline.

Existing technologies for inspecting pipelines and other things, such as the human body, are surveyed. A sensor that could record multiple data types, such as temperature, pressure, and acceleration, and store them on the unit was selected and adapted for use in pipelines. The sensor was mounted in a variety of off-the-shelf pigs and in several different custom-designed free-floating packages. Thus packaged, the sensor made more than thirty runs in a twelve-inch steel pipeline loop owned by T.D. Williamson Co. Temperature, pressure, tilt, and acceleration were measured continuously in each run. These results are presented, described, and analyzed.

The results show the potential of the small sensor to locate bends in the pipeline as well as areas with increased or decreased wall thickness and temperature and pressure profiles. There are differences in results depending on which type of package the sensor is deployed in, as well as differences in repeatability. These differences are described and discussed.

Directions for future research are outlined. The results herein are quite promising, and it is concluded that this technology holds great promise to revolutionize the way pipelines are inspected.

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Dr. Michael Volk **Date**

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Executive Summary

This report describes an initial research effort into an inexpensive alternative method of pipeline inspection. This method utilizes small-scale (capsule sized) sensors mounted either in conventional "dumb" pigs or in free-floating packages to continuously measure temperature, pressure, and other quantities inside the pipeline.

Existing technologies for inspecting pipelines and other things, such as the human body, are surveyed. A sensor that could record multiple data types, such as temperature, pressure, and acceleration, and store them on the unit was selected and adapted for use in pipelines. The sensor was mounted in a variety of off-the-shelf pigs and in several different custom-designed free-floating packages. Thus packaged, the sensor made more than thirty runs in a twelve-inch steel pipeline loop owned by T.D. Williamson Co. Temperature, pressure, tilt, and acceleration were measured continuously in each run. These results are presented, described, and analyzed.

The results show the potential of the small sensor to locate bends in the pipeline as well as areas with increased or decreased wall thickness and temperature and pressure profiles. There are differences in results depending on which type of package the sensor is deployed in, as well as differences in repeatability. These differences are described and discussed.

Directions for future research are outlined. The results herein are quite promising, and it is concluded that this technology holds great promise to revolutionize the way pipelines are inspected.

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CHAPTER 1 Introduction

By its very nature, it is difficult to know exactly what is going on inside, or even outside, a pipeline. The consequences of not knowing, however, can be catastrophic. The technologies available to measure the precise location of a pipe, the conditions inside it, and the integrity of the pipe structure itself have remarkably improved, alongside similar advances in instrumentation for inspecting, for example, the human body.

This report assesses the technologies available for pipeline inspection, with emphasis on the particular challenges faced when inspecting deepwater pipelines. These challenges include the excessive costs associated with conventional inspection (smart pigs) of deepwater lines and the associated long intervals between inspections. Another challenge is the need, unique to deepwater lines, to measure pipeline location, since lines on the sea floor can be inadvertently dragged around by ship anchors or moved by severe weather. The potential for stuck pigs is a challenge in all types of pipe inspection, but particularly in deepwater lines, where the costs associated with locating and removing a stuck pig are generally much greater than for onshore lines. The costs associated with the failure of a deepwater line are also generally much greater than for a similar line onshore – thus underscoring the need for reliable, effective, and economical techniques for inspecting deepwater lines and thus preventing their failure.

Chapter 2 Literature Search

2.1 This chapter surveys technologies for existing pipeline inspection. It covers current methods of inspection to technologies that could be applied to pipeline inspection.

For most pipeline inspection tasks, the pig remains the state of the art. Pigs, typically torpedo-shaped devices, were originally developed simply to clean deposits from the surfaces of pipes. "Smart" or instrumented pigs have been around for decades, and they have become quite sophisticated and capable, as described later in this paper. They are not without their limitations, however.

Deepwater pipelines have many challenges when it comes to in line inspection. The pigging of deepwater lines presents particular difficulties. For deepwater pipelines, pigs can be launched from platforms, from surface vessels, or from remote subsea pigging units. Due to the economics of offshore exploration and production, many pipelines are being tied together, like branches on a tree, before being sent to the shore. These lines are often miles from shore, and many of them are connected using flexible pipe for jumpers, risers, and flow lines. This can make these lines very difficult to pig since flexible pipe is usually sized differently from rigid steel pipe [Lochte]. These lines may also change diameter from one section to another. Inspecting and maintaining these lines is both expensive and technologically challenging since the pipelines lie on the ocean floor, often several thousand feet below the surface. Another difficulty in deepwater can be what to do with the information obtained through inspection. To intervene at every anomaly indicated by pigging is unrealistic, since each deepwater intervention is likely a million dollar plus event [Lochte]. It is perhaps better to gather quality information and determine what trends need to be addressed. Sea bottom intervention on a pipeline requiring surface vessels is a very expensive operation [Lochte], due to the rising costs to rent vessels and equipment and keep them staffed with technicians. As a result, a new technique is being used to pig and maintain deepwater pipelines.

A subsea pigging unit (SPU) is specifically designed for deepwater and it is a remote unit that can be deployed from and recovered to a smaller survey type vessel [EngineerLive]. An SPU can be connected to the pipeline and activated by divers or a remote operated vehicle (ROV). One of the major design goals was to keep the unit small and light enough so that vessels that can launch and recover ROVs that can handle the subsea pigging unit. ROV operators were also heavily involved with the design of SPUs to ensure a minimum of ROV interface issues. SPUs have an on board emergency release system that makes sure the ROV has no risk of getting stuck on the SPU. SPUs have the ability to inject corrosion inhibitors and other chemicals as well as launching pigs. SPUs operate independently of a host or support vessel to both filter and chemically treat flooding water while continuously regulating and monitoring flooding and pigging operations [Halliburton]. Once a SPU has been activated the vessel can then be redeployed for other activities.

The corrosion inhibitors are injected by using a pressure differential. The lines are usually made up at atmospheric pressure, so when they are lowered to the seafloor, the onboard controls of the SPU allow incoming seawater to be filtered to a desired level and then injected along with the corrosion inhibitors. The SPU compensates for the diminishing differential pressure as the pipeline progressively fills with the filtered mixture of seawater and induced chemicals at a preset controlled rate. Chemicals are stored in a flexible bag in the unit's base and are introduced at the desired dosage via a venturi system [Graves]. When the hydrostatic head pressure eventually equals the pressure differential required to drive the pig, flooding and the pig will momentarily cease, and a skid-based subsea pump will finish the job [Graves]. The pump is powered by either a hydraulic power pack or a ROV. The SPU controls the flow rate and thus the pig speed or flooding rate.

Future subsea pigging units will be designed to handle 24 inch and larger pig launcher assemblies. Other technical developments will concentrate on instrumentation, enhanced boost pump, and chemical injections systems. Improvements with ROV systems will also greatly increase the ease of use of SPU systems in deepwater environments.

2.1.1 Biomedical

With advances in materials, electronics, and computers, medical devices are getting smaller, faster, lighter, and more versatile. Lower costs have in many cases rendered inspection devices disposable. Smart sensors, which are created by combining sensing materials with integrated circuitry [Schwiebert], are being developed for use in the biomedical industry. These smart sensors can monitor physical, biological, and chemical reactions within the body. A single smart sensor pill could measure ECG, EEG, EMG, and/or heart rate. It is not uncommon to place multiple sensors on a single chip, with integrated circuitry of the chip controlling all of these sensors [Schwiebert]. Such sensors generally have to be able to communicate with an external computer system to log and record the transmitted data through a wireless interface. These sensors have several other limitations as well, which include: limited on-board energy storage, biocompatibility issues, other safety issues, reliability, and issues related to patient comfort.

2.1.2 Capsule endoscopy

Capsule endoscopy started because there was a need to bridge the gap between a gastroscopy and a colonoscopy. The average adult digestive tract is approximately 30 feet in length [ASGE]. A gastroscopy can inspect the first four feet of digestive tract, which includes the esophagus (food pipe), stomach, and a small first part of the intestine. A colonoscopy can inspect the last six feet of digestive tract that includes the colon and rectum. In between where those two procedures operate lies the 20 or so feet of small intestine where the process of digestion actually occurs. The majority of digestive problems happen in the first four or last six feet and manufacturers in the last ten years have been making longer instruments, up to 275 cm, or approximately 9 feet [Mylonaki]. Tools of this size, however, tend to give patients extreme discomfort and the time required for this size of tool to be used has cleared the path for a new technology to emerge - capsule endoscopy.

The idea for capsule endoscopy is credited to Dr. Graviel Iddan in 1981 [GI Health], but it was not until 2001 when the technology was finally available to make his idea a reality. The original device was named the M2A (mouth to anus) [Mylonaki], which was a 11x 26 mm capsule that only weighed four grams and contained a color video camera, four LED lights, wireless radiofrequency transmitter, and enough battery power to take 50,000 color images during the eight-hour journey through the digestive tract [GI Health]. The relative size of the capsule was about the size of a large vitamin and the shell was made of a specially sealed biocompatible material that was resistant to stomach acid and powerful digestive enzymes [GI Health]. To retrieve the pictures eight specially placed antenna pads captured the wireless signal that was released and stored it on a device the size of a Walkman on the patient's waist.

In 2003 a study was done comparing the M2A to the longer reaching conventional tools. The study showed a 55% improvement over a push enteroscopy, but some technical problems did arise. One patient's capsule remained in the esophagus for seven hours, and another patient's battery ran out after two hours and only acquired 22 minutes of images. Overall, however, no serious complications occurred [Mylonaki].

Today Sayaka has introduced a new redesigned pill that captures 870,000 images and has a side camera instead of a front located one. In the front of the pill is a permanent magnet with an electromagnet located directly behind the permanent one. This pill automatically rotates the capsule 60 degrees every two seconds allowing for a more complete picture of the intestines. Software allows doctors to compile the data and relay the images as a video that gives them the ability to magnify problem areas up to 75 times [Mone]. This pill does require more power than the previous designs, however. It takes 50 milliwatts to run the camera, lights, computing power, and data transmission. To power this little dynamo, a vest is worn by the patient that contains a coil that continuously transmits power to the capsule through inductive charging. The vest also collects the data and stores it on a standard SD memory card [Pink Tentacle].

Since the Sayaka capsules cost approximately $100 [Mone], patients are not required to retrieve and return the video capsule to the physician. It is disposable and expelled normally and effortlessly with the next bowel movement [GI Health]

2.2 Smart sensors

The technology that allows the M2A to withstand the acidity of stomach acid and forces of the digestive system can be applied to devices that need to withstand the pressures and hydrocarbon fluids that are transported in pipelines. Proteus Technology is one of the leading companies that manufacture digestible sensors. Their sensors can monitor heart rate, respiratory rate, and other body responses of a digesting pill [Proteus]. The way that the sensors are manufactured allows for an extremely thin and durable protective layer that ensures long-term survival and performance of micro sensors.

Smart Sensors are already being used to monitor the conditions of organs. More then one third of heart and liver transplants go unused because of the very short window of time the organs have; four to six hours for the heart and twelve to twenty-four for the liver, before the transplant is no longer viable [Schwiebert]. To have a better and more accurate understanding of the time the organ has to be transplanted, some researchers are working on a gas monitor system that has smart sensors to monitor the levels of in vitro heart carbon dioxide and oxygen so that the viability of the heart can be determined.

In the United States, the second leading cause of death is cancer, and for many cancers early detection can be the difference between survival and death. Wireless biomedical sensors will play a key role in early detection. Studies have shown that cancer cells emit nitric oxide, which affects the blood flow around the damaged cells [Schwiebert]. Sensors can be placed near the suspect areas to help detect abnormalities. NASA has proposed smart sensors to be used on astronauts for space flights and ground-based missions that will monitor biotelemetry and bioinstrumentation to support life sciences research. Technology like this could also prove to be useful for soldiers on the battlefield or for fire fighters, allowing real-time health monitoring of the biometrics and thus rapid knowledge of when an individual needs medical attention. The use of biomedical monitoring can help reduce the risk of injury or operator error due to fatigue or the inattention of the operator in safety critical and restrictive environments like aviation, space, and industrial machinery operators. [Hippokratio]

Temperature sensors are not typically used as a primary measurement tool in pipeline inspection, although there are some newer tools that use temperature and pressure (and vibration) to characterize the pipeline. There are a wide variety of temperature sensors commercially available. Temperature sensors can basically be broken down into 2 types, contact and non contact type [Temperature].

Contact temperature sensors essentially measure their own temperature, assuming that there is no heat flow between the sensor and the object that it is attached to. Temperatures of surfaces using contact probes can be difficult to measure, especially if the surface is moving. Understandably, their usefulness on an inspection tool traveling at typical pigging speeds is questionable. However, contact sensors may be deployed within the electronics housing to monitor the temperature of the housing [Temperature]. Most commercial and scientific non-contact temperature sensors measure the thermal radiation (typically infrared) that they receive from a known or calculated area on its surface, or a known or calculated volume within it.

Pressure sensors can be divided into five categories: Absolute, gauge, vacuum, differential, and sealed but the theory of operation is basically the same for all of them: the measurement of the deflection of a diaphragm converted to some type of electrical output.

An absolute pressure sensor measures the pressure relative to perfect vacuum pressure (0 psi or no pressure). Gauge pressure sensors can be calibrated to measure the pressure relative to a given atmospheric pressure at a given location. Vacuum pressure sensors are used to measure pressure, minus the atmospheric pressure at a given location. Differential pressure sensors measure the difference between two or more pressures. Sealed pressure sensors are the same as the gauge pressure sensor except that they are calibrated by manufacturers to measure pressure relative to sea level pressure.

There are several methods of measuring pressure. Piezoresistive sensors are a resistive element printed onto a diaphragm. When the diaphragm is deflected due to an external pressure, the resistance changes and that voltage is then recorded. Another type of pressure sensor is capacitance based. Two conductive plates will have a specific capacitance between them, as a function of the distance between the plates. One of the plates may be attached to a diaphragm, when pressure is placed on the diaphragm, the diaphragm deflects and then capacitance increases or decreases. Yet another type is electromagnetic which measures the displacement of a diaphragm by means of changes in inductance. All these pressure sensors can be microprocessor controlled or they can simply output an analog voltage.

Displacement sensors are used on caliper type tools. By attaching the actuator of a potentiometer to a spring loaded arm, the displacement of the arms results in a change of resistance, which can be measured and its value stored. There are 2 basic types of potentiometers, rotary and linear. There are many different types of resistive elements including, carbon, conductive plastic, cermet (metal ceramic composite), and wire wound.

An accelerometer is an electromechanical device that will measure acceleration forces. These forces may be static, like the constant force induced on a motionless mass by gravity, or they could be dynamic - caused by moving or vibrating the accelerometer. There are single axis and multi-axis accelerometers commercially available. Single axis accelerometers measure forces in one direction of movement; multi-axis accelerometers measure forces in multiple directions.

There are several types of accelerometers. Piezoresistive and piezoelectric accelerometers contain microscopic crystals that, when stressed by accelerative forces, cause a voltage to be generated, or a resistance to change. Another type is capacitance based. Two conductive plates will have a specific capacitance between them. If an accelerative force moves one of the plates, then the capacitance will increase or decrease proportionally. They are usually microprocessor controlled which provides either an analog (0-5V) or digital output (pulses or serial data) [Analog].

Power restrictions play a huge role in the development of a smart sensor. In options such as biomedical or pipeline inspection, energy generally must be stored on board the sensor (note the exception of the inductive charging system mentioned above). Batteries for such devices require exceptional autonomy for biomedical applications, since changing batteries is impractical for implanted devices. In addition, the heat generated by the sensor has to be dissipated without damaging the surrounding tissue [Battery Pack].

Sensors require a wide range of input voltages and varying current requirements. The operating range of the tool, CPU Speed, and storage capacity are directly affected by the battery capacity. When all these are factored together it is easy to see that the power supply is a critical part of the inspection tool [Battery Pack]. Power supply circuits must be designed to minimize power consumption yet provide enough power for the data acquisition and storage systems.

In order to preserve as much battery life as possible, sensors, storage, and CPUs must be chosen carefully with attention to power requirements. Battery packs must be custom designed to provide the necessary power within the packaging constraints of the housing. There are many different battery chemistries from which a selection must be made according to power requirements and rate of discharge. Choice of materials for the sensors is also critical.

2.3 Pipeline inspection technology

Pipeline inspection tools or smart pigs typically contain an electronics system through which data are captured and stored or transmitted. In the case of un-tethered tools the data must be stored, as the technology to transmit data through the steel wall of a pipe does not yet exist. Given the need to store data, the smart pig must contain the following: a CPU or data logger, data storage media, software, and power supply. Depending on the complexity of the tool and the type of sensing these systems may also include wire, connectors, and custom circuit boards. Almost none of the aforementioned components are available that have been designed specifically for pipeline inspection. In many cases components designed for other applications are adapted for use in pipelines and are accompanied by custom designed electronics systems. The development of an electronics system for pipeline inspection usually begins with the sensors. The following technologies have been successfully developed and are routinely used in pipelines 6" and up. Electronics systems in larger inspection tools are naturally easier to integrate as more space is available in larger pipes. Nevertheless, there are components of any system that are exposed to the environment within the pipeline. Not only must the sensors be rugged enough to withstand the harsh conditions, but the wiring and interconnections as well. The smaller the pipeline diameter, the more modules may be required to house the CPU, data storage and power systems whereas in larger tools, these systems may fit in as few as one module.

2.3.1 Inspection hardware

Single Board Computers (embedded PCs) are widely used in inspection tools. An SBC is a miniaturized PC that has the necessary memory and peripherals to host an operating system and custom application software. Some SBCs actually have onboard data storage as well. These systems vary in size from standard PC footprint down to credit card size. SBCs continue to improve in speed as they shrink in size [Gavrichenkov].

Field Programmable Gate Arrays (FPGA) and microcontrollers can also being used for data processing. An FPGA is an array of transistors on a chip that can be configured through software to replicate the functions of what might take hundreds of conventional ICs and passive components. Microcontrollers are single chip computer systems that are not as powerful as SBCs but are very flexible. Using custom firmware these microcontrollers can be programmed to do a variety of tasks that would normally take dozens of ICs and passive components [Gavrichenkov].

2.3.2 Data storage

Data collected from sensors can be stored in a variety of ways depending on the quantity and acquisition speed of the data. Some common methods are hard disk drives, flash drives, solid-state drives and data loggers. More sophisticated inspection tools (MFL and ULT) may be travelling through the pipe at 5-9 mph, sampling (potentially) hundreds of sensors every quarter inch or less. Obviously, under those conditions, a lot of fast storage is required. For these tools hard disk drives and flash drives have been used successfully for years. As hard drive and flash drive technology improves, the speed and distance inspection tools can travel in one deployment also improves [Jackson].

Data loggers have also been used for caliper tools and work very well with simple linear measurements, caliper tools being a good example. Data loggers are different from PC based systems in that they simply record values directly from the sensors whereas PC systems may actually do some data processing such as compression, interpolation, and so on.

2.4 Emerging inspection technology

Pig tracking can be very difficult. One company has created a device that is used to track the passage of a pig and pinpoint its location in a pipeline [Pipeline Inspection Company]. Sensors are placed on the outside of the line at regular intervals, and a portable wand-based system is then utilized to precisely locate a stuck pig. The stationary system runs on replaceable batteries. The lifespan of these depend on the output signal.

A new pig from General Electric is modernizing magnetic flux leakage technology. The new smart pig can move up to five meters per second. The new smart pig has the ability to articulate and is considered one of the smallest tools in the industry. Its flexibility will allow for back-to-back bends of 1.5 times the diameter of the line [GE]. This will allow them access to over 80% of existing pipelines without modification. The eight-foot overall length will allow for launch systems shorter than the standard nine foot length. The new smart pig will also accommodate a combination caliper. This will allow them to simultaneously record dents with (corrosion) metal loss allowing the operator to prioritize problem areas for action.

In addition to those features an integrated fiber optic gyroscope inertial measurement system can accurately map the pipeline in real time during the run of the pig. An inertial measurement unit is an electromechanical module that contains three accelerometers and three gyroscopes. The accelerometers are placed such that their measuring axes are orthogonal. They measure inertial acceleration, or g-forces. Three gyroscopes are placed in a similar orthogonal pattern, measuring rotational position in reference to an arbitrarily chosen coordinate system. These are used in inspection tools to ascertain the tool's location in a pipe, particularly so that the operator may know where detected anomalies are located. This will allow an accurate measure of the bending of the pipe and monitor pipeline movements, of particular interest for deepwater pipelines.

Another system of monitoring cracks and degradation simply clamps onto the side of the pipe and allows for an inspection up to 40 meters in either direction of the band. This system uses an acoustic transducer to create torsion waves that propagate down pipes and reflect off features like welds, supports, and areas of wall loss. This system is non-intrusive and easily accessed by an inspector by allowing them to simply plug into the band monitor the section. The benefit of this is that it allows the line to be monitored past an obstruction like a road, on an offshore platform, or in another remote, usually inaccessible sites, without having to dig up the ground around it to inspect it. This also keeps the inspector from having to go into hazardous areas to inspect [G-Wave].

Remote field technology (RFT) is starting to become more common in the pipeline inspection tool industry, replacing to some extent magnetic flux leakage.

RFT uses a low frequency AC signal and measures the magnitude of the change of the wave and the frequency of the AC, as induced by anomalies in the pipe [Queens University]. This is different from MFL, because MFL relies on the magnetic saturation of the material to gather data, whereas RTF simply relies on the rate of change of the magnetic field. One of the benefits is the fact that RFT doesn't need contact with the pipe surface to operate. This allows it to test through the buildup of scale, coatings, wax deposits, and liners with approximately equal sensitivity to outer diameter and inner diameter wall loss [Russel]. This allows an RFT tool to go through without first utilizing a cleaning tool, thus cutting down on inspection time and the tools required to inspect. RFT also allows the measurement of stress in a pipeline, which will give an indication as to whether the pipeline has been moved. Also because of the stress measurement it has the potential to determine if the soil under a pipe has eroded away and a sort of pipe bridge has occurred or that the top of the pipe is being over loaded. In addition to this, RFT tools have shown enough sensitivity to measure machined defects as shallow as a 10% loss in wall thickness. [GTI]. As with other inspection tools, RFT pigs can be either tethered or free swimming. Pipelines as small as 50 mm and as large as 1981mm have been successfully inspected [Russell]. RFT pigs have been able to deal with diameter changes, short radius elbows, offsets, changes in pipe diameter, reduced port valves, plug valves, and small pressure differentials that are too low to push a conventional pig through the line [GTI].

Eddy current sensors that are used in pipeline inspection are usually custom-made by the tool manufacturer using copper wire and a ferrous core. Eddy current probes are available from a variety of manufacturers. There is no definitive guide to designing eddy current sensors for pipeline inspection but often they are as simple as a coil of wire around a core, and encapsulated in some type of carrier. Eddy current probes induce a magnetic field in conductive materials and measure changes in that field – such changes can be caused by cracks and other defects in the material.

Ultrasonic sensors come in a wide variety of configurations. In a pipeline inspection application, a transmitter emits a high frequency sound that is bounced off the pipe wall and then picked up by a receiver. The time and intensity of the returning pulse is compared to the original signal. Ultrasonic sensors may take the form of discrete transmitters and receivers or integrated transceivers. There is not a particular advantage to either type of sensor other than one orientation may better suit the mechanics of the tool. Ultrasonic measurement systems may include microprocessor interfaces, which can easily be integrated with other computer systems, or the basic transmitter, receiver, transceiver modules that would require additional electronics to interface the sensors with a CPU [Birks].

A new small ultrasonic sensor is being developed that is still in the laboratory test phase. It uses an ultrasonic cylindrical guided wave that will measure three types mechanical defects: gouges, removed material, and dents [Na]. Right now the testing is being done in water with an aluminum pipe. The pipe being used is only 22.22 mm in diameter and the device can change the angle of the incident beam from perpendicular (0 degrees) to 51 degrees allowing a sweeping motion to be employed as the device travels down the line.

Pure Technologies has developed an acoustic emission sensor that fits into a ball and has the ability to detect leaks. This system is called a Smart Ball Pipeline Leak Detection System [Smartball]. This is a free swimming device that is much smaller then the inside diameter of the pipe, allowing the ball to roll along the bottom of the pipe. Pipelines that are already set up for conventional pigs do not need to be modified. The ball can simply be launched and retrieved through the existing facilities. Smart pigs usually cannot distinguish the difference between a deep crack or other defect that is leaking and one that is not yet leaking. The ball's design allows it to silently roll along the bottom of the pipe so that it does not present its own acoustic interference with its sensors. Rolling also allows it to pass by leaks where conventional sensors could not go. The Smart Ball uses on board accelerometers to measure its progress down the pipeline. The accelerometer output is synced with GPS readings taken at the beginning and end of each run, when the ball is outside the pipeline. This allows leak locations to be pinpointed within a claimed accuracy of plus or minus one meter. The device is fully sealed so that its sensitive internal electronics are not exposed to the pipeline fluids, allowing application in a wide range of hostile environments. This device is also relatively inexpensive, allowing for multiple devices to be run to pinpoint a leak location. However, the device only detects leaks, and is not capable of identifying areas of metal loss, cracks, and other anomalies that could later become leaks.

Laser inspection systems are another emerging pipeline inspection technology. Two ways of using laser inspection systems to map the inside of a pipeline are currently under development. One technique uses a laser beam that is focused on an area of the pipe wall and is simultaneously photographed by a high-speed camera. The other laser technique for mapping the inside of the pipe utilizes a laser-profiling tool that travels down a pipeline while rotating 360 degrees and reads all the surface characteristics of the pipe in the same manner as a CD-ROM drive reads a CD [Dettmer]. This technology is replacing the use of closed-circuit TV inspection systems. Laser mapping technology is currently only being used in newly laid pipelines since the pipelines must be empty for the device to properly work. Both ways can operate in pipeline diameters from six inches to eighty-eight inches in diameter and can be utilized on steel, plastic, clay, and cast iron pipes, concrete cavities, and epoxy coated structures. This device can inspect at a rate of thirty feet per minute [Bennett].

2.5 Development of smaller, smarter inspection tools

Over the past 10 years, CPUs have increased from 10 million transistors in the AMD K6 processer, to 2 billion transistors on the Pentium dual core processors, yet the physical size has remained relatively the same. The computing power has increased by a factor of 200 but commercially available IC packaging is practically unchanged. There really hasn't been a need to make smaller ICs when humans would not be capable of handling them (keyboard-driven devices, for example). Though there are assembly systems that can attach nano-sized components to printed circuit boards, the manufacture of circuit boards themselves has also reached a practical size threshold.

Given those limitations, the designers of inspection tools must look for new and innovative ways of developing smaller and smarter tools using electronic components that are increasing in performance but not likely to get any smaller. One way designers have approached these constraints is by taking advantage of increased processor speeds to develop more advanced software. For example, one tool that has recently been built and deployed very successfully uses a simple complement of sensors (temperature, pressure, and vibration) along with a sophisticated software algorithm and a Figureical user interface, to produce corrosion profiles with resolution rivaling high resolution MFL and ULT tools. Not only is this tool smaller and easier to deploy than MFL or ULT, it is more easily scalable to larger sizes as well. Housed in a 3" diameter cylinder, it will easily deploy in pipelines as small as 4".

2.6 Miniaturizing technologies for the next generation of tools

Gordon Moore, the founder of Intel, famously claimed in a 1965 paper that the number of components that could be economically placed in an integrated circuit had doubled every year since the IC was developed in 1958 and would continue to do so for at least ten years. This prediction came to be known as Moore's Law. In 2005, Intel predicted that the trend would continue until 2029. The capabilities of many digital electronic devices are linked to Moore's law including processing speed, memory capacity, sensor capability, and even the number and size of pixels in digital cameras for example [Moore].

Given the apparent 3" glass ceiling where conventional electronics packaging currently resides, the desire to develop smaller electronics systems leads to a higher-level strategy. Systems could be designed and deposited directly onto the silicon wafer. By custom designing the ICs themselves, the designer would have the ability to embed the functions of multiple systems on one IC, which could reduce size considerably. Custom ICs provide the designer with the ability to dictate the size of the package as well as the pinouts.

Of course solid-state circuits can't do everything. For example, pressure sensors, in the traditional sense, have a moving diaphragm. Mechanical systems with moving parts can also be etched on silicon. MEMS and NEMS technology, (micro electromechanical systems, or nano electromechanical systems) are just as their name implies, mechanical systems on a chip. MEMS and NEMS technology have been used to fabricate microscopic pressure sensors, motors, gyroscopes, and hydro-generators, and other mechanical devices.

By combining custom ICs with MEMS and NEMS technology it is conceivable that a sub 3" inspection tool could be developed that might provide operators with more information, faster and more reliably than ever before. These next generation tools may not even require a pig to carry them.

2.7 Research path forward

The smart pig is likely to remain the state of the art for pipeline inspection for years to come. However, a main conclusion of this research is that the needs of deepwater pipeline inspection, combined with the advances in sensors, software, and computing technology have created opportunities for researching new approaches to pipeline inspection. Pipeline inspection tools much smaller than conventional pigs are attractive for several reasons. Their small size means they cannot become stuck like a conventional pig. Their (potential) low cost offers several advantages. First, lines can be inspected much more frequently, providing pipeline operators with a much better picture of changing conditions inside their equipment. (A medical analogy is instructive here. There was a time when diabetics had to visit their doctors to have their blood sugar measured. Nowadays, inexpensive instruments allow diabetics to measure their own blood sugar many times a day, resulting in vastly improved management of this disease.) Another advantage of small, low cost inspection tools is the minimal impact if they are lost or damaged. The challenges with small inspection tools are many. The technology exists for tools that can measure things like temperature, pressure, and salinity. A small tool that can measure wall thickness, detect cracks, and measure the thickness of internal deposits remains a dream at this point, however. As noted earlier in this paper, there is future potential for sensors that can do all of these things in a small package, and without requiring contact with the pipe wall. Our research goal is to explore the capabilities of small tool packages. Small tools that utilize today's technology to provide useful information to pipeline operators will build a strong foundation for future research on small tools capable of replacing the smart pig.

Having completed this literature survey, this research now focuses on the next major technical task, sensor development. Subtasks include testing in flow loops, development of improved (smaller, more capable) sensors, and work on packaging schemes. This latter will include the exploration of both neutrally buoyant small sensor packages and small sensors packages that are more dense than the pipeline fluid, and thus travel along the bottom of the line.

2.8 Technology readiness

It is often useful to consider research and development efforts in terms of the technology readiness levels (TRLs) of various aspects of the research. In this scheme, projects proceed from paper concepts (TRL 0), to the proof of concept stage (TRL 1-2), to prototyping work (TRL 3-5), and finally to field-qualified hardware (TRL 6-7). The ongoing sensor development work in this research is currently in the proof of concept stage. Within the proof of concept stage, TRL 1 refers to a proven concept with functionality demonstrated by analysis or testing, whereas TRL 2 requires a validated system concept, tested in a realistic environment.

The goal of this research is to push the technology in the small sensor package forward to TRL 3, which requires a functional prototype developed and tested.

Chapter 3 – Experimental Apparatus

3.1 Chapter Summary:

In this chapter we outline the goal of the "package." This part of the project was dedicated to designing and testing a device that would hold a sensor, be able to traverse a pipeline, gather data, and be recoverable. All testing would be done in The University of Tulsa 2" jumper loop and in TD Williams 12" Test Facility.

The smart pig is likely to remain the state of the art for pipeline inspection for years to come. However the needs of deep water pipeline inspection, combined with the advances in sensors, software, and computing technology have created opportunities for developing new techniques of pipeline inspection. Pipeline inspection tools much smaller than conventional pigs are attractive for several reasons. Their small size means they cannot become stuck like a conventional pig. Another advantage of small low cost package is the minimal cost if the device is lost or damaged.

Initially, a package was required that would be able to hold a sensor, travel through a pipeline, and be recoverable. This broad set of guidelines with few restrictions. In the beginning it was not clear which of the direction the project would go, and what other requirements or capabilities the package would also need to include. The very first idea was some sort of neutrally buoyant device that would not be much bigger than the sensor itself and could take the pressure and temperature of deep water pipelines. This idea would eventually be what the project would strive for. This idea however proved to be a very complex task.

3.1 University Of Tulsa North Campus Test Facility

The University of Tulsa North Campus test facility utilized in this research included a two-inch jumper loop, a hydrostatic pressure center, a glycol temperature bath, and a three axis orientation tester. These facilities were used to do preliminary testing on the sensor and packages before use in the TD Williamson 12 inch test facility, which is described in Chapter 5.

The two-inch jumper line was initially used for slow motion visual testing of the initial prototype to prove that it would travel down a pipeline. This facility allowed the use of multi phase testing along with slug testing of the fluid.

The hydrostatic pressure center was used to verify the pressure readings on that the sensor was outputting and to test the structural integrity of the free floating prototypes.

The glycol temperature bath allowed verification of the sensor temperature readings. This also allowed the time it took between the temperature change of the fluid and the recorded sensor temperature to be measured.

The three axis orientation testing allowed verification and a deeper understanding of what the tilt sensor was reading. During the runs in the flow loops the sensor would give data that was difficult to interpret as its orientation was varied about the X, Y, or Z axis as it went through turns, dips, and spins. This bench top testing opened the path to understand how the sensor could jump, for example, from +180° to -179° almost instantaneously.

3.2 – TD Williamson Flow Loop

In this section the test facility that was used and the test procedure for the pigs is described.

3.2.1 TDW 12” Flow Loop.

The TD Williamson Flow loop is a 12” diameter, approximately 1200 feet long test facility, with a standard pig launcher and receiver. This flow loop is able to run both air and water. The loop has 400 feet of exposed pipe with the rest located underground. The facility is outfitted with intrusive type pig passage detectors and in some cases a portable non-intrusive detector was also used. Two main types of pig signals (“pig sigs”) are used, two pig sig 4’s and four pig sig 5’s. The pig sig 5’s have a small magnet in them and are located at the launch, the receiver and then through turns 2, 3, and 5. Figure 6.1 shows the location of the turns and the change in wall thickness. The facility is capable of launching and receiving pigs with water or compressed air at pressures up to 275 PSI.

The pig types that were used included foam and cup type pigs as well as a high resolution Magnetic Flux Leakage inline inspection tool (MFL), and a low resolution caliper tool.

The miniature sensor was mounted onto various types of pigs and other packages and deployed at a speed of 2 to 3 feet per second. Each pig type produced roughly similar results with respect to temperature, pressure, acceleration and orientation inside the pipe and provided a baseline for evaluating the data collected from pig-less carriers.

The miniature sensors were mounted to either the front or the back of the foam pig, and on to the body of the MFL tool, cup pig, and caliper tools. The pigs were loaded into the TDW pig launcher and the system was charged. Each pig run was tracked using the permanently installed pig passage detectors (pig sigs), and manually timed, so that data could be correlated to these known locations. Miniature sensors are equipped with a real time clock and data is collected at one second intervals. After each run, the sensors were removed from the pigs and data was downloaded and analyzed. Free floating or pig-less runs were also made and data was compared to the known data collected from sensors attached to pig. These results are presented in Chapter 5.

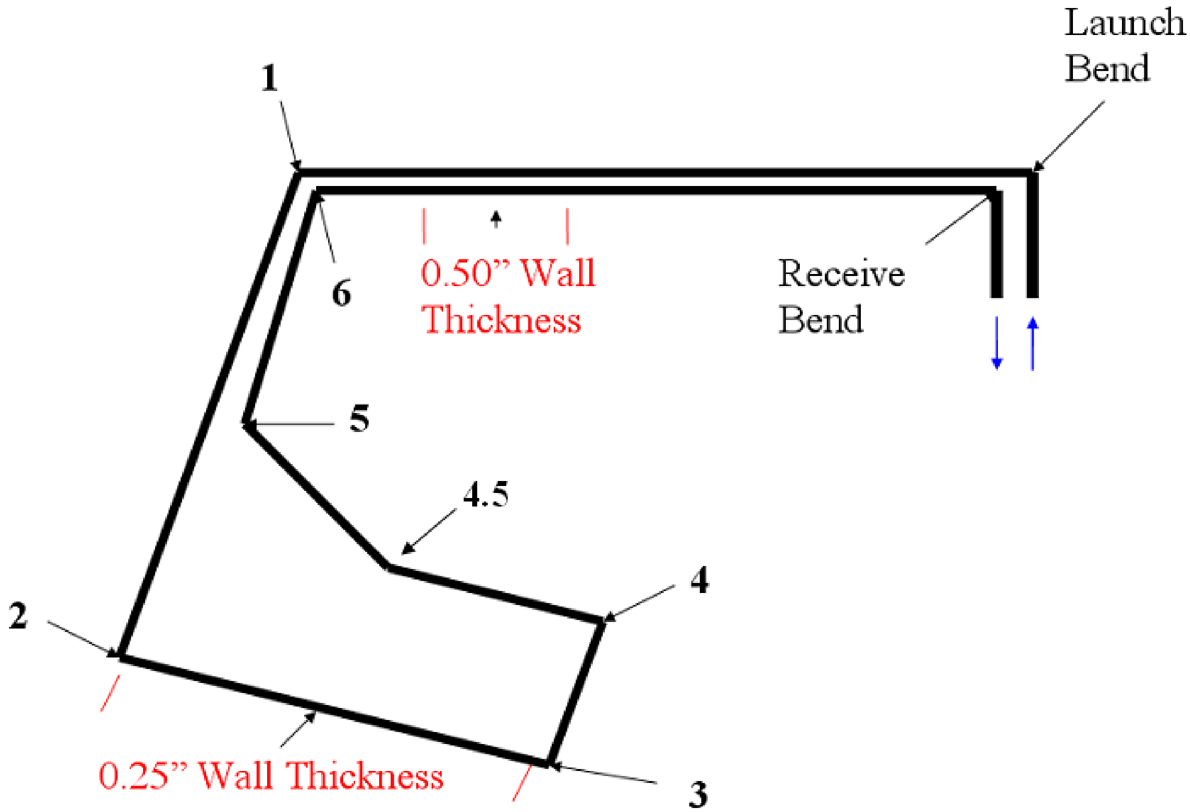

Figure 3.1 TDW Test Facility Simple Map

3.2.2 Sensor Testing in Pigs

The objective of tests conducted at the T. D. Williamson, Inc (TDW) Test Loop Facility in Tulsa, Oklahoma, was confirmation of the feasibility of a miniature pig-less monitoring and inspection system. In order to establish a baseline to compare the results of a pig-less system, initial testing was performed by inserting a miniature sensor into a variety of standard pigs.

The miniature sensor was mounted onto various types of pigs and deployed at a speed of 2 to 3 feet per second. Each pig type produced similar results with respect to temperature, pressure, acceleration and orientation inside the pipe and provided a baseline for evaluating the data collected from pig-less carriers.

The miniature sensors were mounted to either the front or the back of the foam pig and on to the body of the MFL tool, cup pig and caliper tools. The pigs were loaded into the TDW pig launcher and the system was charged. Each pig run was tracked using the permanently installed pig passage detectors and manually timed, so that data could be correlated to these known locations. Miniature sensors are equipped with a real time clock and data is collected at one-second intervals. After each run, the sensors were removed from the pigs and data was downloaded and analyzed. Free floating or pig-less runs were also made and data was compared to the known data collected from sensors attached to pigs.

A gimbal device was fashioned and utilized for some test runs. The gimbal was attached to the back of a cup pig and an additional sensor was attached to the side of the pig, to allow the orientation data from the two sensors with and without gimbal to be compared.

3.2.3 Sensor Testing in Free-Floating Packages

Free float design

A goal of this research is to develop a free-floating device that can travel down the pipeline collecting data. Many ideas have been tested but the designs that have been the most promising have been ones that have positive buoyancy, or ones that want to float rather than sink. Three options were tested that have this characteristic, the peapod, the barbell, and the bullet. Of these three the bullet is the only one that will withstand 2000+psi. All of the above were tested in the TDW 12" test facility in Tulsa, Oklahoma.

To test these designs the initial test would require the use of a placebo sensor, meaning that an aluminum slug of the same dimensions and weight as the actual sensor would be placed in the location where the sensor would go. Then it would be loaded into the launcher, the launcher would then be pressurized, and roughly 7-15 minutes would be allowed for each run. After the allotted time the receiver would be checked and it would be recorded whether or not the device was recovered. Actual sensors would then be placed in the free floaters for further testing. After each test the sensor data would be recovered and analyzed. Further design modifications will focus on making the three designs neutrally buoyant.

3.3 Prototype Progression

The smart pig is likely to remain the state of the art for pipeline inspection for years to come. However, the needs of deep water pipeline inspection, combined with the advances in sensors, software, and computing technology have created opportunities for researching new techniques of pipeline inspection. Pipeline inspection tools much smaller than conventional pigs are attractive for several reasons. Their small size means they cannot become stuck like a conventional pig, and another advantage of a small, low cost package is the minimal cost if the device is lost or damaged.

The first idea was some sort of neutrally buoyant device that would not be much bigger then the sensor itself and could record the pressure and temperature inside deep water pipelines. This idea would eventually be what the project would strive for. However, this concept proved to be difficult to realize.

3.3.1 Ball tether system

As a result, an alternative idea was posed of a heavy ball that would drag on the bottom of the pipeline tethered to a positive buoyant ball floating at the top of the pipeline. Sensors would then be attached at the top, middle, and bottom giving a profile for data the sensors would be gathering, such as temperature and pressure. This concept was initially tested in the 2" jumper loop at TU north campus. Due to the size of the test loop, a scaled down version was built. This was to allow us to test the hydrodynamics of the device, and see if it the top ball would float and the bottom would sink allowing the profile of the flow to be recorded. The materials chosen were small wooden balls and fishing line. These were chosen because of the high tensile strength to weight ratio of the fishing line and the ability of wood to float in water and be easily shaped. To prevent damage or loss the sensors, aluminum slugs were cut to the size of the sensors. Initial tests were promising so a prototype that would fit in TD Williams 12" diameter test facility was built.

In this prototype the braided high tensile strength fishing line would still be used but it was determined that wood would not be a very suitable material to act as the buoyant ball. Plastic balls were procured and used to offset the weight of the "heavy" ball. This prototype required several plastic balls to off set the wood "heavy" ball and the prototype ended up being two feet in length, but only two inches in diameter at its thickest part. During flow loop testing these prototypes proved to be very difficult to recover at the end of a run. The prototype is shown in Figure 3.2 in the pre-launch condition.

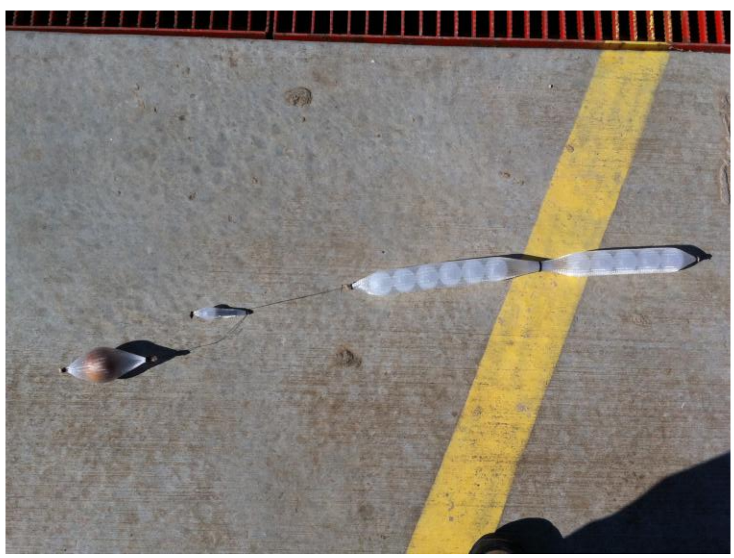

Figure 3.2 Original Design of tethered prototype

After several runs in the TD Williams 12" diameter test facility, the prototypes would have to be "pigged" out and came back disconnected, with the heavy wood ball being either lost or extremely difficult to recover. Since the heavy end proved to be the part of the design that was providing the most trouble, it was decided that it should be removed.

3.3.2 Peapod

Figure 3.3 Peapod

The tether idea was simplified to just a floating sensor. With only a single sensor, it would not allow the characteristic profile to be recorded but it would allow for the device to be simpler. This would allow easy launch and recovery and a smaller package. Since the excess plastic balls were not needed to offset the heavy wood ball, the initial "peapod" was less then five inches in length and 1.25 inches in diameter. This package allowed the sensor to traverse the pipeline easily. Because of the small size, previously un-piggable pipelines would now be able to have a sensor traverse them. Results are contained in Chapter 5.

3.3.3 Barbell

Figure 3.4 Barbell

Similar to the peapod another prototype, called the barbell, was created. This design used the same plastic balls as the peapod but a hole was cut in one of the balls to allow the sensor to be inserted in it. At the other end of the sensor, a hole was drilled through another plastic ball allowing the diaphragm of the sensor to be touching the fluid. Then around the sensor polyethylene foam was used to provide buoyancy.

3.3.4 Kayak

Analysis of the tilt data (Chapter 5) for the peapod and the barbell showed that the device might be tumbling. The idea of building a type of gimbaled device that would always allow the sensor to maintain a specific orientation and attaching it to the sensor was conceived. This prototype would however be much larger in diameter then the peapod and barbell. The gimbal concept would also be attached to a pig to validate the orientation data. Chapter 5 describes the results.

3.4 –Sensor Description

This section describes the type of sensor used in this research.

3.4.1 Tilt Sensor

The Tilt Sensor measures temperature, pressure, and orientation. The sensor has the ability to sample at rates up to 1 Hz. The current capabilities of the sensor allow us to record data for several days, but to meet the requirements for field-testing a new sensor with increased memory storage is required. The current sensor can store up to 512 kilobytes of data. An increase in storage to at least several megabytes is recommended. As well, the sample rate of the sensor also will need to be increased from 1 Hz to 60Hz. Current sample rate results in unacceptably large gaps in the data. Sampling at 1Hz is adequate for temperature and pressure but the acceleration data will require a higher rate. The temperature sensor is an internal microprocessor that measures ambient temperature of the microprocessor itself. Since the unit is small, thermal lag is negligible which allows relatively accurate measure of temperature, within ±1 C.

The pressure sensor use a diaphragm located at the end of the sensor and a measure of hoop stress that is placed on the outside of the casing. This is then computed in the built in software to give an overall pressure reading.

The tilt sensor measures angular changes in the sensor's orientation in the three dimensions with earth's gravity as the reference. Because of the three-axis tilt the sensor can be placed horizontally or vertically. The sensor has an orientation mark at the end of it, just above the diaphragm. When this is pointing straight up the axis should give a x and y reading of zero with a z axis reading of 90°. The tilt accuracy is better than ±3°.

Chapter 4 – Bench scale Testing of Prototypes

Chapter Summary - This chapter contains the results of sensor testing in three different formats. The first format is benchmark testing, the prototypes described in Chapter 3 were tested in several different ways. In this chapter the results of bench scale testing are described wherein the sensor was tested in carefully controlled settings designed to determine exactly what the sensor was measuring when subjected to known inputs. The results are described in Chapter 5. The second format is pig testing, wherein the sensor was installed on various types of pipeline pigs and run through the TDW test facility in west Tulsa. With the results are described in chapter 5. The third format is testing the sensor when it is mounted in any of a variety of free-floating packages that were developed as part of this research and tested in the TDW test facility. The results are described in Chapter 5.

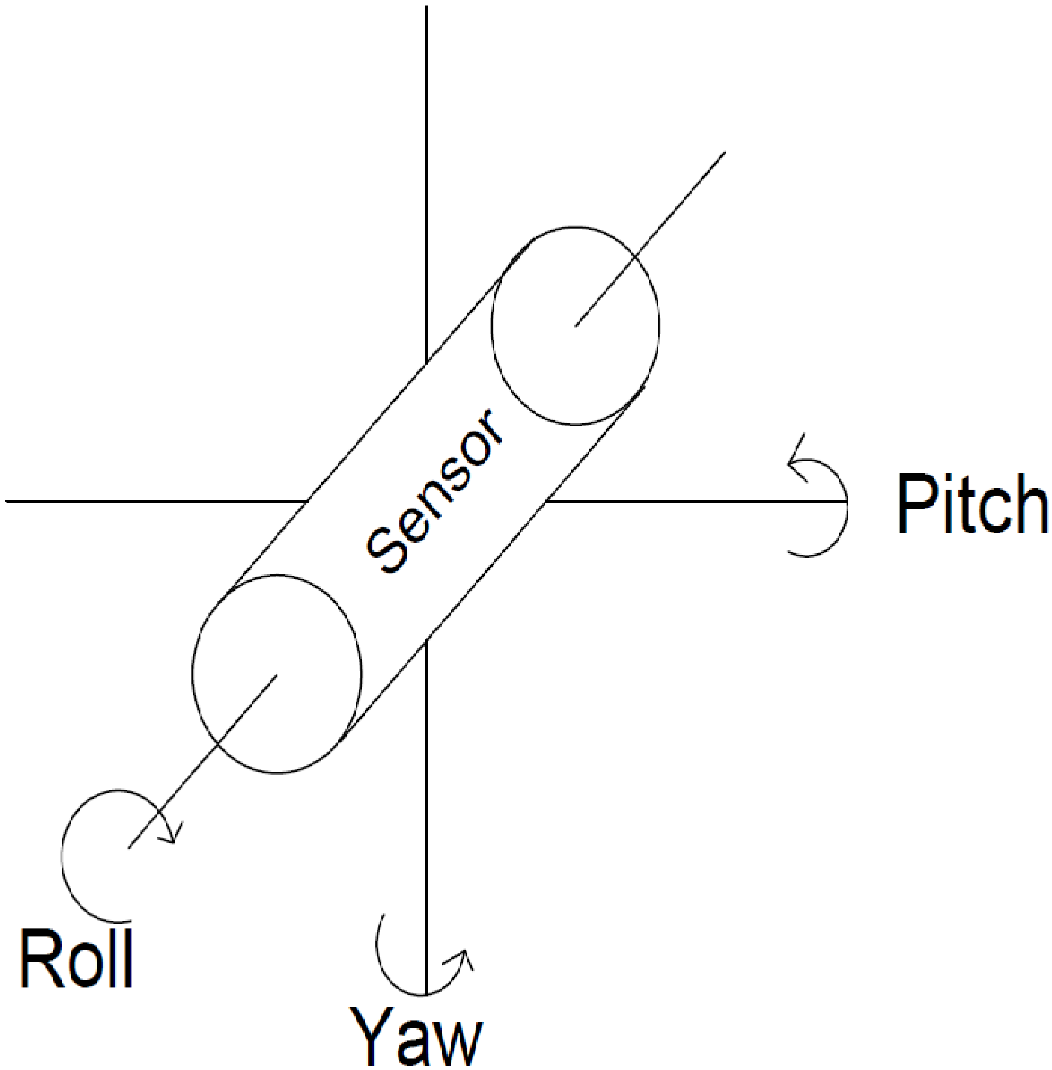

Figure 4.1 Geometry of Bench Top Test

4.1 Sensor Benchmark Testing

4.1.1Tilt Roll and Yaw test

To measure what each of the X,Y,&Z sensors were recording, we devised three tests to measure pitch, roll, and yaw. All tests were run on a simple pivot apparatus that would only allow motion about one axis to eliminate variables. The pitch, roll, and yaw tests had four trials each to show repeatability. The pitch test was run placing the sensor with the orientation mark facing completely vertical. This is the reference point from which all angles were measured. The sensor would be placed in the 0 degree or starting position and the time was recorded. Then the sensor was rotated to the 90, 180, 360 and back from 360, to 180, 90, and 0. At each position the angle was held for 60 seconds to allow the time to be recorded accurately. The geometry of the test is shown in Figure 4.1.

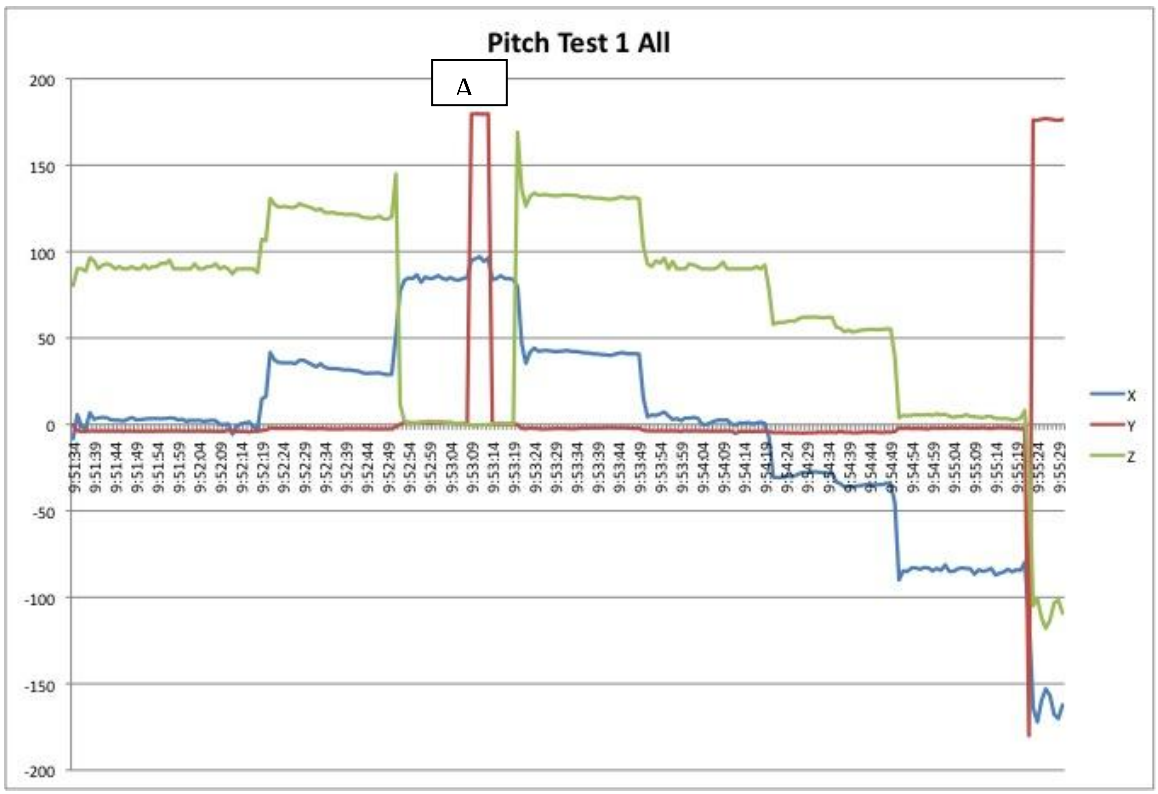

Figure 4.2 Pitch Test, XYZ data test 1

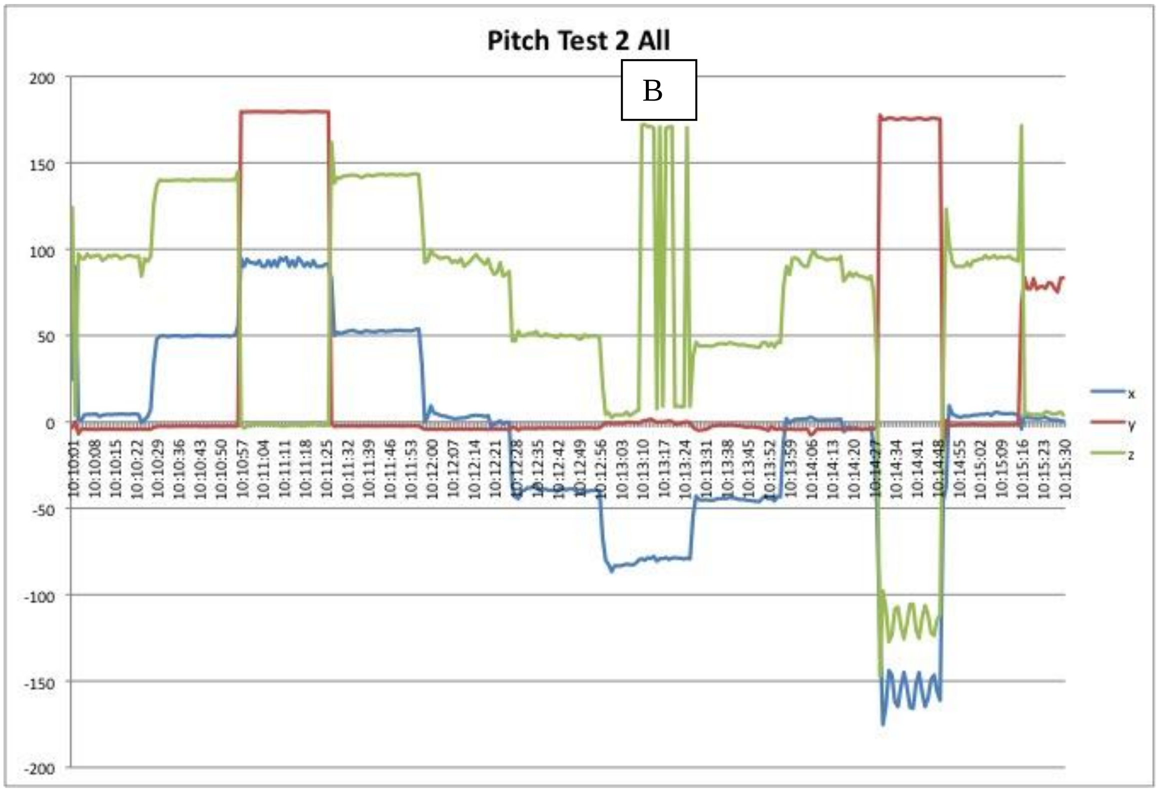

Figure 4.3 Pitch Test, XYZ data test 2

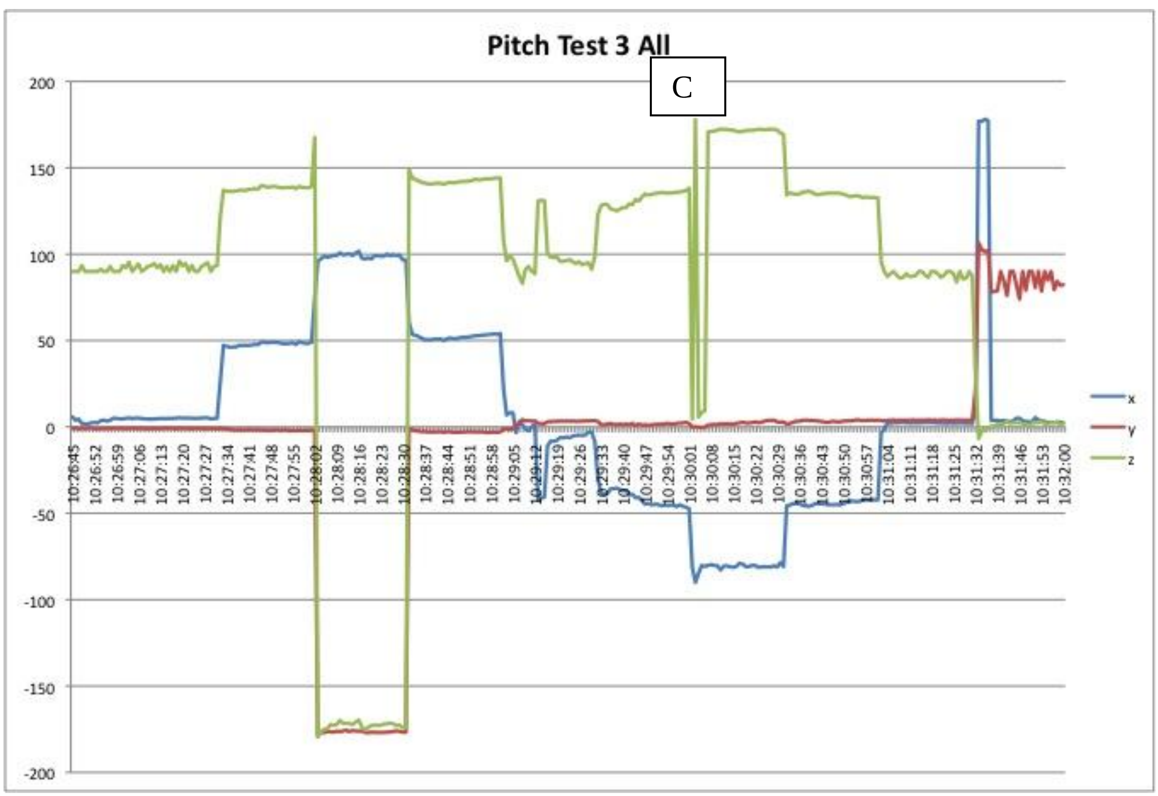

Figure 4.4 Pitch Test, XYZ data test 3

Figures 4.2, 4.3, and 4.4 show the pitch test described earlier. In Figure 4.2 a small angle change happened at the point marked “A”. The sensor was placed at an angle greater than 90°. In Figures 4.3 and 4.4 the sensor was inadvertently taken from 0° to 90° then back to 0° and then to -90°. In Figure 4.3at 10:13:03 you can see that the Z-axis is unstable at “B” when X and Y aren’t showing changes in the signal. This is because the Z component is calculated from X and Y and the slightest change in either one causes Z to be unstable. A similar thing happens in Figure 4.4 at point “C”. At 10:29:19 the test apparatus was disturbed causing the sensor to be moved and the alignment to be thrown off. The Z component is calculated using the software provided with the sensor. The sensors were not initially designed to go upside down so the software does not account for that.

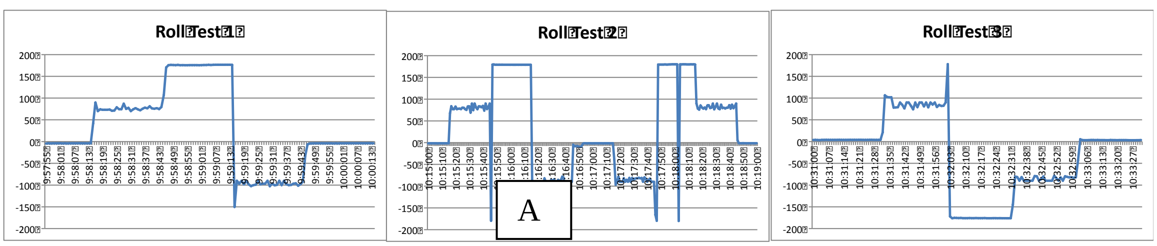

Figure 4.5 Roll Test

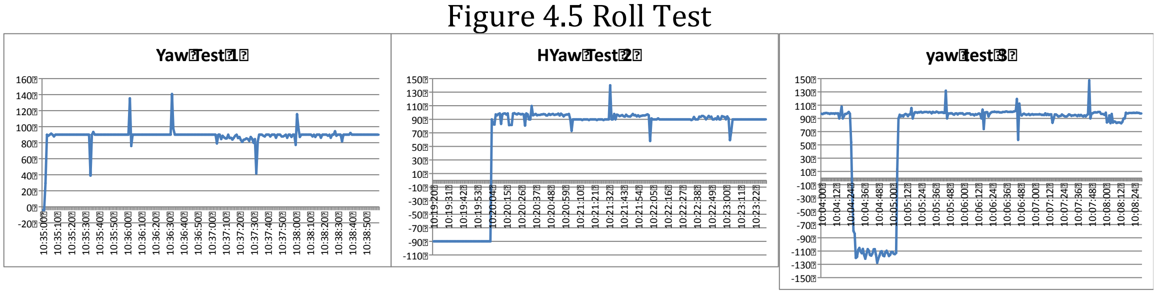

Figure 4.6 Yaw Test

In figure 4.5 the Y axis component of the sensor was tested. This was done by rotating the bullet shaped sensor about its longitudinal axis. In this test we found out that at some point the sensor decides to flip from +180° to -180°, as shown for example in point “A”. This is important knowledge of the limitations of the device, although the cause is uncertain.

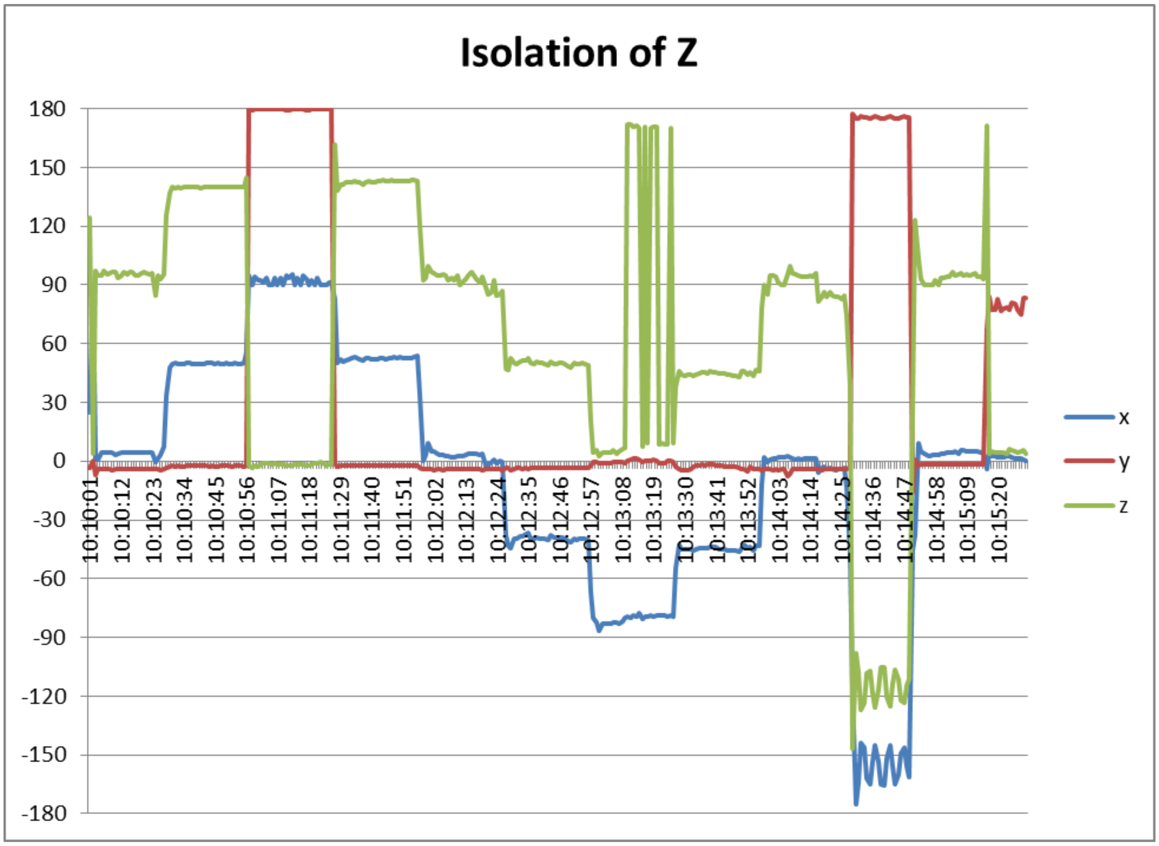

Figure 4.7 Isolation of Z Component

In Figure 4.7 we tried to isolate the Z axis by rotating it about the vertical axis, as shown in Figure 4.1. This test was successful in showing that the Z component was just a 90°offset of the X axis.

4.2 Pressure test

The goal was to test the accuracy of the pressure readings of the pressure sensor. To do this a pressure vessel was built to withstand 3000 psi, using a 3” schedule 80 pipe pressurized with tap water using a spregue pump.

The pressure was ramped up in a stair step fashion. Originally the increment of pressure change was going to be 50 psi but due to the large interval on the analog pressure gauges and inconsistency of the pump, pressure control was not as accurate as it could have been. The pressure recorded did correspond to the pressure from the sensor and the general stair step profile was achieved as shown in Figure 4.8

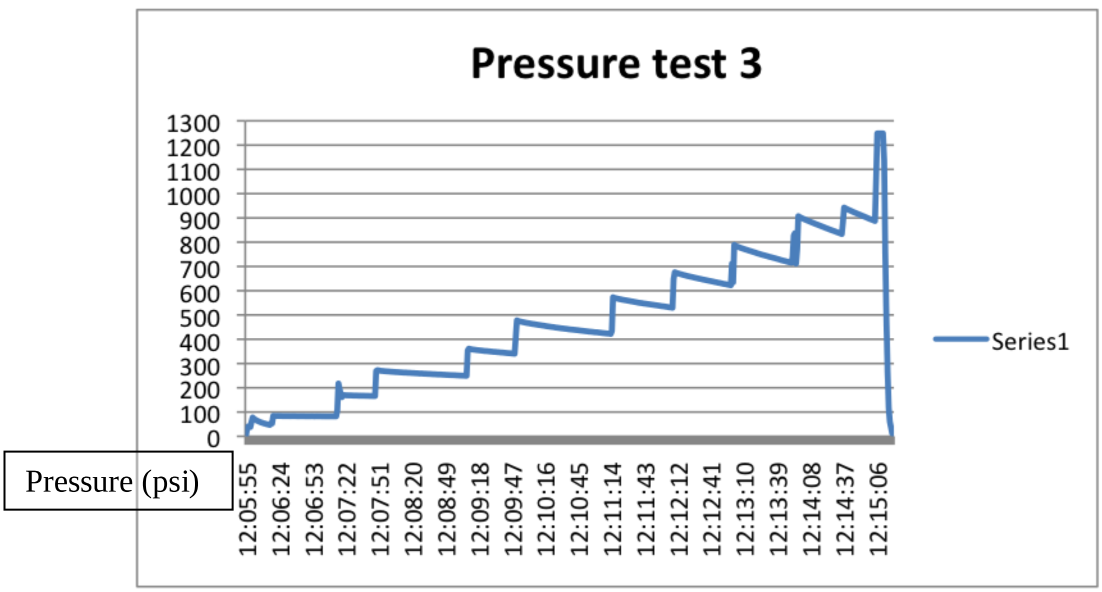

Figure 4.8 Pressure test

4.3 Temperature test

As with the pressure test we were trying to ensure that the temperature sensor was recording accurately. To do this we used an ethylene glycol bath. To verify what the sensor was reading a k type thermocouple and the digital setting of the bath were used and compared to the sensor data. To allow for thermal lag the temperature would be set on the bath then when the thermocouple read the desired temperature a 20 second interval was used before changing to the next temperature. The temperature started at zero degrees Celsius and then increased till the max temperature limit of the sensor was reached, 40 degrees Celsius. Then the temperature was brought back down to zero from the limit. The goal was to make sure that the temperature curve of the sensor was similar to the recorded temperature. As shown in Figure 4.9, there was a good agreement between sensors and bath temperature.

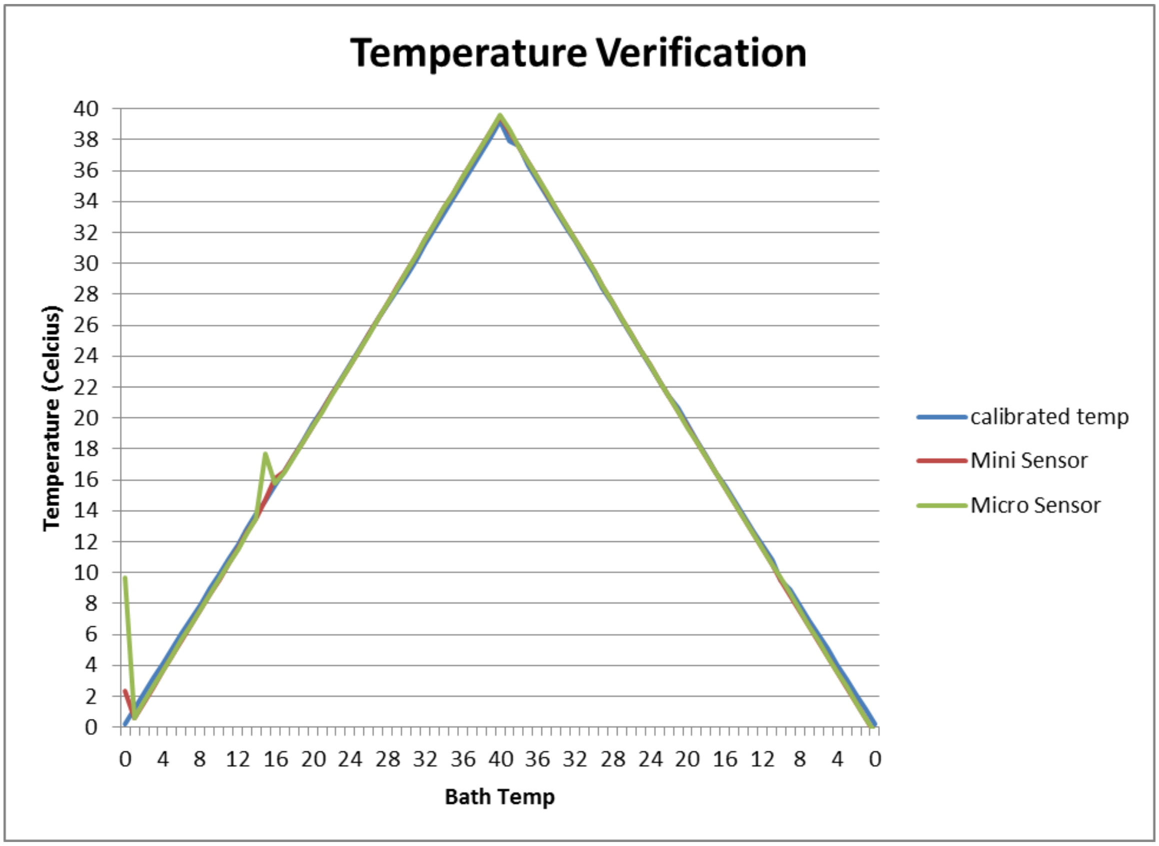

Figure 4.9 Temperature Verification

Chapter 5 - Results of Flow Loop Testing

5.1 - Chapter Summary

In this chapter (and the next) the results from the flow loop testing of the sensor in various packages are shown and discussed. More than 25 total runs were performed throughout the duration of this research project. Some runs resulted in better data than others, and consequently, not all of the runs have their results included in this report. The purpose of this chapter is to describe and discuss the results of the flow loop testing.

Chapter 5 includes results for sensors mounted in a variety of pigs as well as results for the sensor mounted in various free-floating packages. All runs were done in the TDW 12" diameter flow loop in west Tulsa that was described in Chapter 3. Various types of pigs were used, as described below.

The TDW test loop was described in detail in Chapter 3.5.1, along with the basic testing conditions (pressures, temperatures, and so on). The TDW flow loop can be operated with water (nominal pressure of 60 psi) or air. The vast majority of the testing described herein was performed in water, although some air testing is also described.

Chapter 5 describes results in which the sensor was mounted in either a foam pig, a cupped pig, or on inline inspection tool pig. There are some differences among the results from the various pigs – these are described in this chapter.

5.2 - Description of a run that yielded excellent data

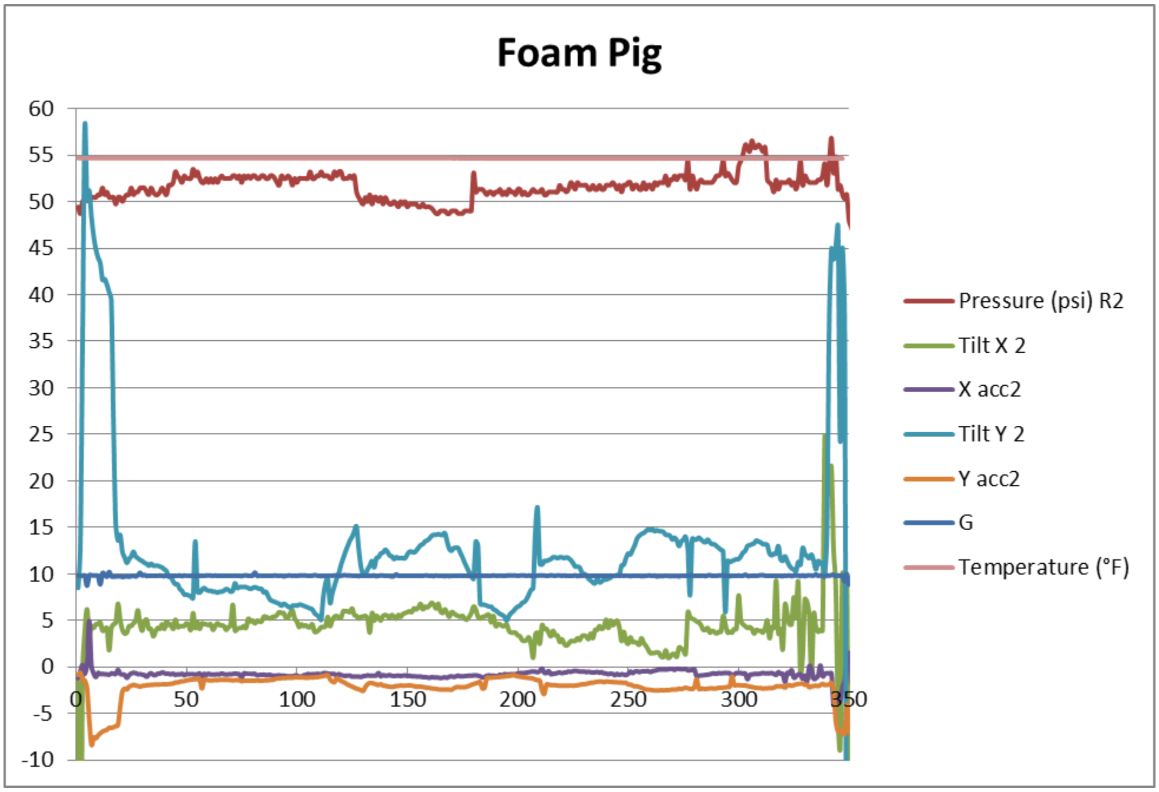

Figure 5.1 Ideal Foam Pig Results

Figure 5.1 is from a foam pig run done on April 1, 2011. The X-axis is time in seconds. The units for the y-axis vary depending on the curve. There are curves for pressure in psi, temperature in °F, tilt, and acceleration. Figure 5.2 shows only pressure and y tilt from this same run. Pressure drop associated with changes in the pipe wall thickness are apparent in both Figure 5.1 and 5.2. The temperature remains constant. In the tilt data the X-axis tells when there is a change in elevation, which is seen at the 5 second and 340 second mark. The Y and Z-axis are 90° out of phase with each other and tell when a turn is made. On this run the right hand turns are pointed down on the Y-axis and the left hand turns are pointed up.

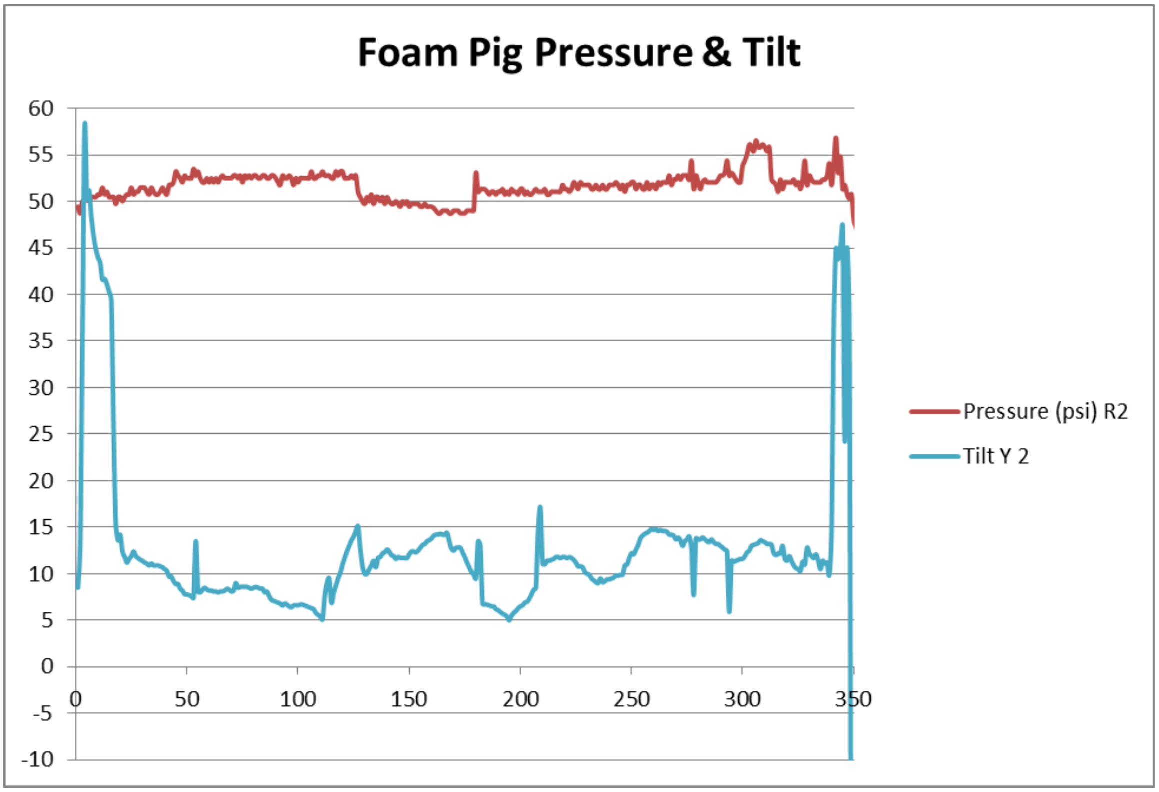

Figure 5.2 Acceleration and Orientation data for foam pig run, showing turns in flow loop

The run depicted in Figures 5.1 and 5.2 is an example of a good run - this is what the data ideally look like. This is the benchmark against which we determined what was "good" data versus what was "bad" data. Figure 5.2 shows only the pressure results from Figure 5.1. We can see the pressure change as pipe wall thicknesses changes. As shown in Figure 5.1, the pig did not rotate while it traveled down the pipe. This is seen from the x,y, and z data since there are no rapid swings from +180 to -180.

5.3 - Description of a run that yielded less than optimal data

Figure 5.5 shows an example of a run in which the data are much more difficult to understand and interpret than the data described above in 5.2. For this run, on March 15, 2011, the sensor was mounted on a special magnetic flux leakage pig, as shown in Figure 5.4. Figure 5.3 shows the results of this run versus time. The vertical axis in Figure 5.3 depicts either pressure or x, y, and z orientation data.

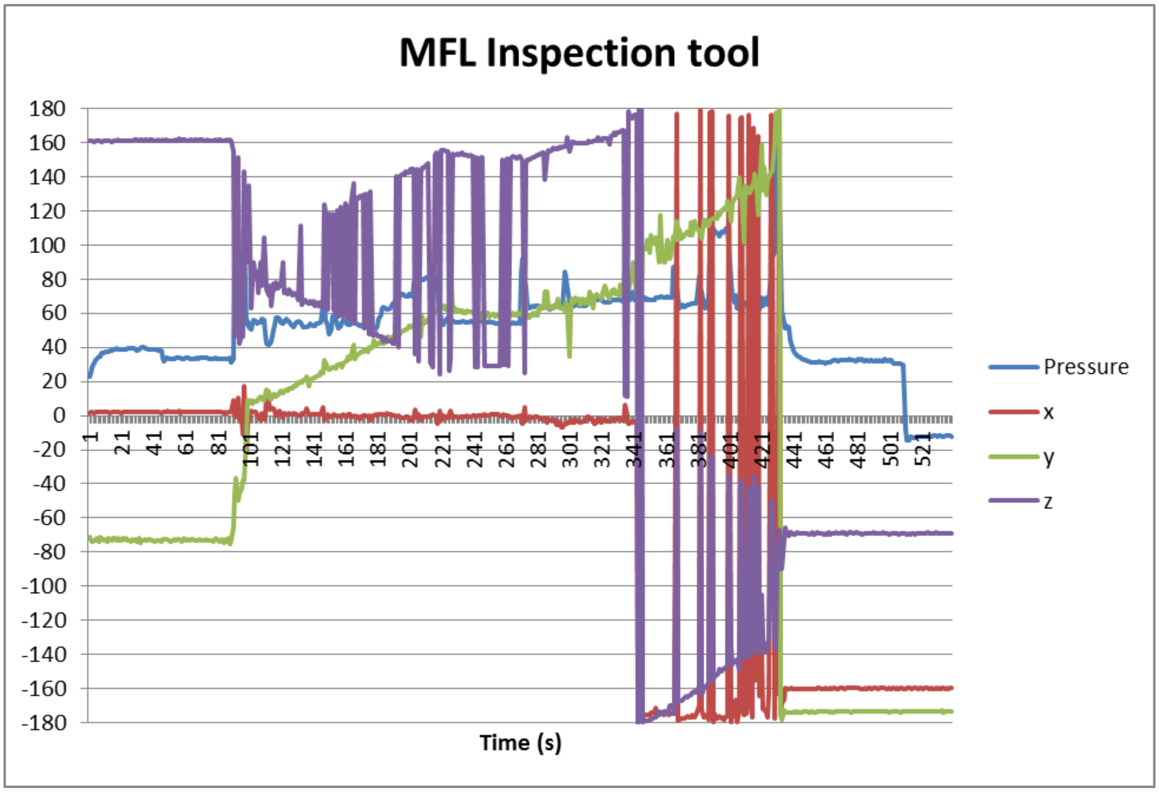

Figure 5.3 – Magnetic Flux Leakage Pig Run 3-15-2011

Figure 5.4 Location of sensor on MFL Pig

The data in Figure 5.3 show that the pig was rotating throughout the run, and that it achieved about one full rotation during the 15 minute run. This can be seen with the y data.

Also we can see that the sensor was bouncing or oscillating vertically inside the pipe. This is demonstrated by the rapid direction change associated with the two different axes: x and y. On this run the pressure data gave noticeable spikes at the turns. This happened because the pig would get stuck in the turns allowing the pressure to build before it was able to make the turn, at which point the pressure rapidly decreased. This also made a distinct sound as the pig travelled down the pipeline.

The pressure data for this particular run are reasonable, even though the rest of the data (as described above) are not. Figure 5.5 shows only the pressure data from this run. The bends and wall thickness changes are labeled.

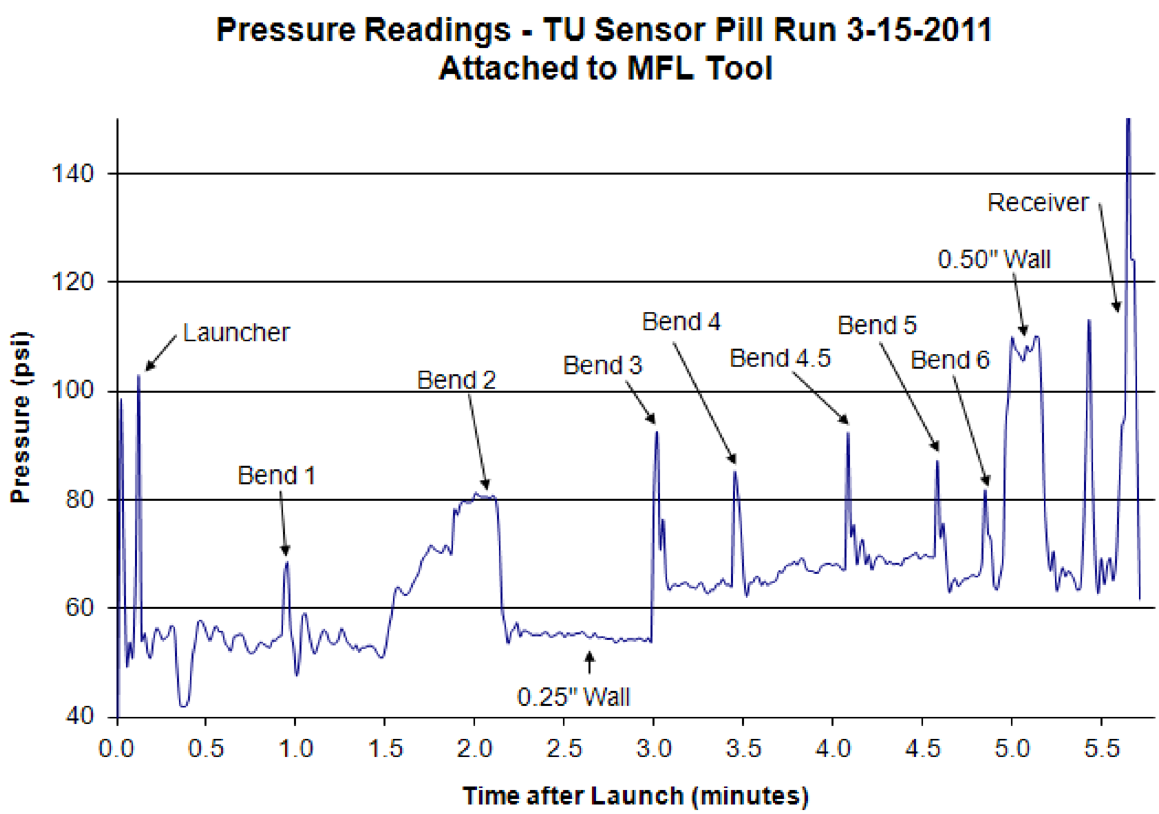

Figure 5.5 – MFL run pressure only

During most pig runs only the wall thickness changes are really pronounced - as shown by pressure data. The turns are usually revealed by a combination of pressure and X, Y, & Z-axis data as shown in Figure 5.3.

5.4 - Comparison of results from three different types of pigs

In this section, results from three different types of pigs containing sensors are compared. The three types of pigs are cup pigs, caliper pigs, and the magnetic flux leakage pig.

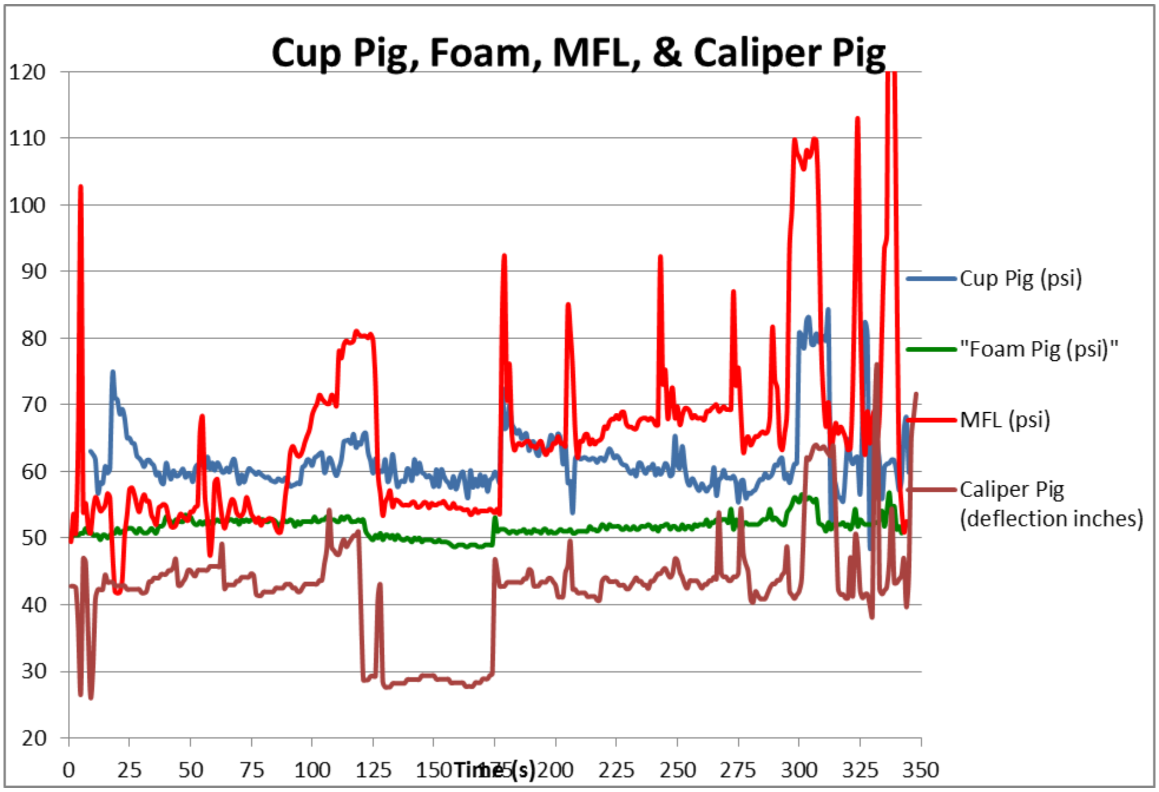

Figure 5.6 – Comparison of pressure results from different types of pigs

Figure 5.6 shows pressure versus time data for sensors mounted in three different types of pigs. Also shown in Figure 5.6 are deflection data from a caliper pig. The data are for separate runs from various dates in 2010 and 2011.

Figure 5.6 shows that when the sensor is mounted on different kinds of pigs, the results are not always the same. In Figure 5.6, the cup, foam, and magnetic flux leakage pig all give similar pressure data. But the cup and inline inspection pig have a tendency to build more pressure during the turns therefore giving more indication that there was a turn. However all pigs showed the wall thickness changes in the pipe that go from 0.375” to 0.25” back to 0.375” and then to 0.50” and back down to 0.375”. This is because the pressure would drop at the 0.25” walled section of pipe because there was less inner diameter thus allowing the pig to expand. The opposite happened when it would reach the 0.50” section. The slightly smaller inside diameter caused the pig to compress allowing pressure to build. The changes from one pipe wall thickness to another were no more then 3 psi. This result leads to the conclusion that a more sensitive pressure sensor would be better able to identify small changes in wall thickness and other anomalies in the pipe. To confirm the wall thickness changes the pressure data was paired with caliper pig data. The caliper pig measures deflection allowing us to make a comparison with the pressure data.

5.5 – Comparison of Multiple Runs Using the Same Type of Pig

In this section, multiple runs using the same type of pig (foam pig), done on the same date, using the same sensor module, are compared. This allowed the effectiveness of each type to pig to be compared.

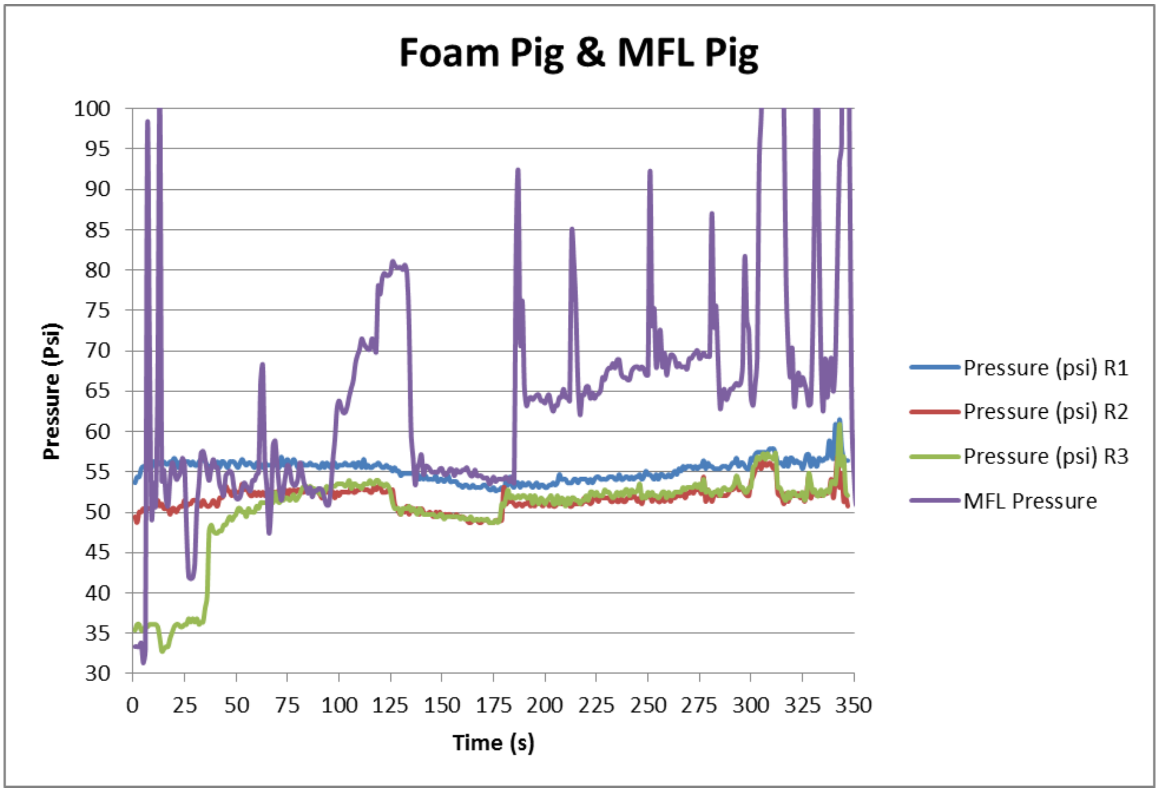

Figure 5.7 Foam Pig Repeatability

Multiple runs were done with the same pig for all pigs except for the magnetic flux leakage pig, which was only run once due to time constraints. The foam pig results in Figure 5.7 shows that even with the same pig the data can still vary significantly with the exception of the beginning of the third run, all of the tests were set up and run the same way. The low pressure in the beginning of the third run was due to a valve being only half open. Other than that the data shows that runs two and three, the red and green lines respectively, have very similar pressure signatures. Run one showed a slightly increased pressure that did not give as much definition for the wall thickness changes as the other two runs with the same pig did. There were several theories as to why this happened. For example, it is possible that since the pig was brand new on the first run it needed to be "broken in", or perhaps that the pig needed to be saturated with water before it could give more accurate readings, or there was some sort of biological growth on the inside of the pipeline that prevented a good seal to form and this was scraped away on the first run, allowing better results on runs 2 and 3.

5.6 – Comparison of Water versus Air

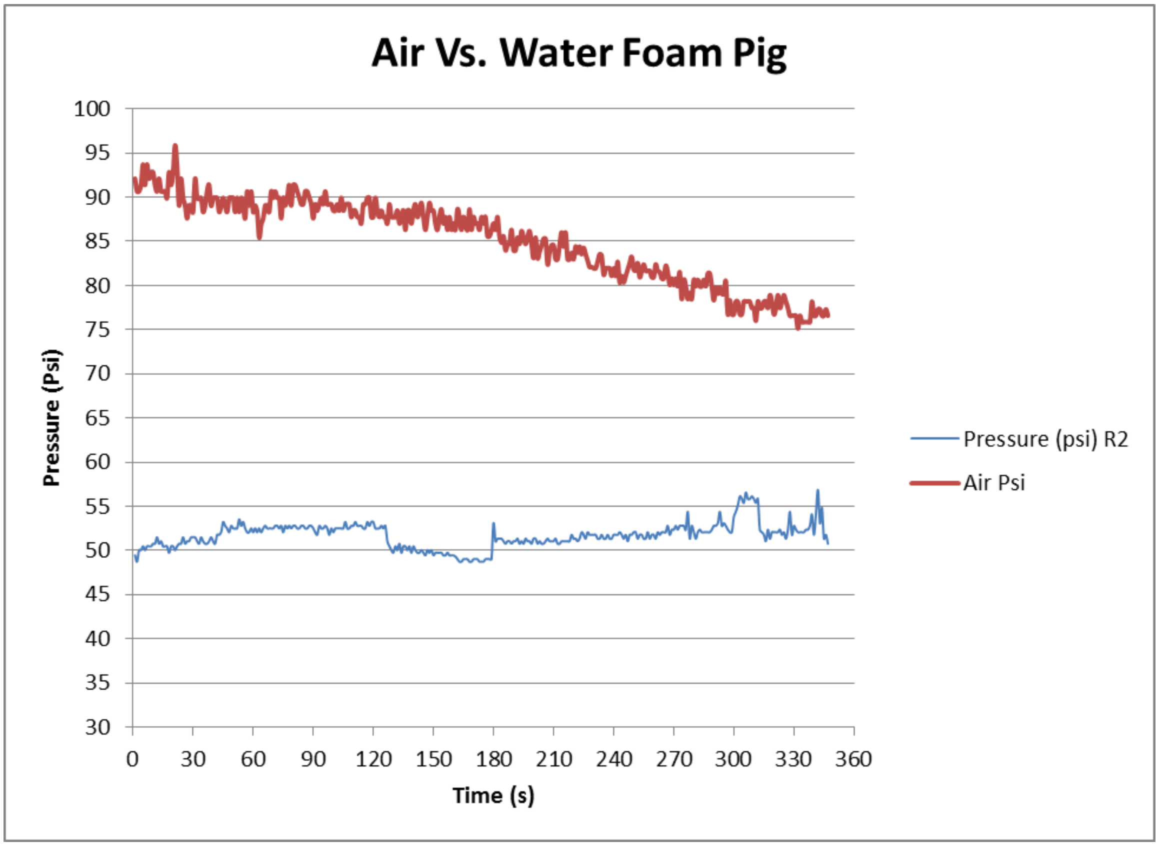

Figure 5.8 Air Vs. Water Run

In Figure 5.8 we can see that the choice of fluid is more important then the type of pig. Figure 5.8 shows that the air pressure needed to drive the pig starts high and ends much lower. This trend is not seen in water testing where the pressure is very consistent. Note also that the changes in wall thickness are easily seen in the water run but not in the air test.

5.7 – Test runs in which sensor location was varied

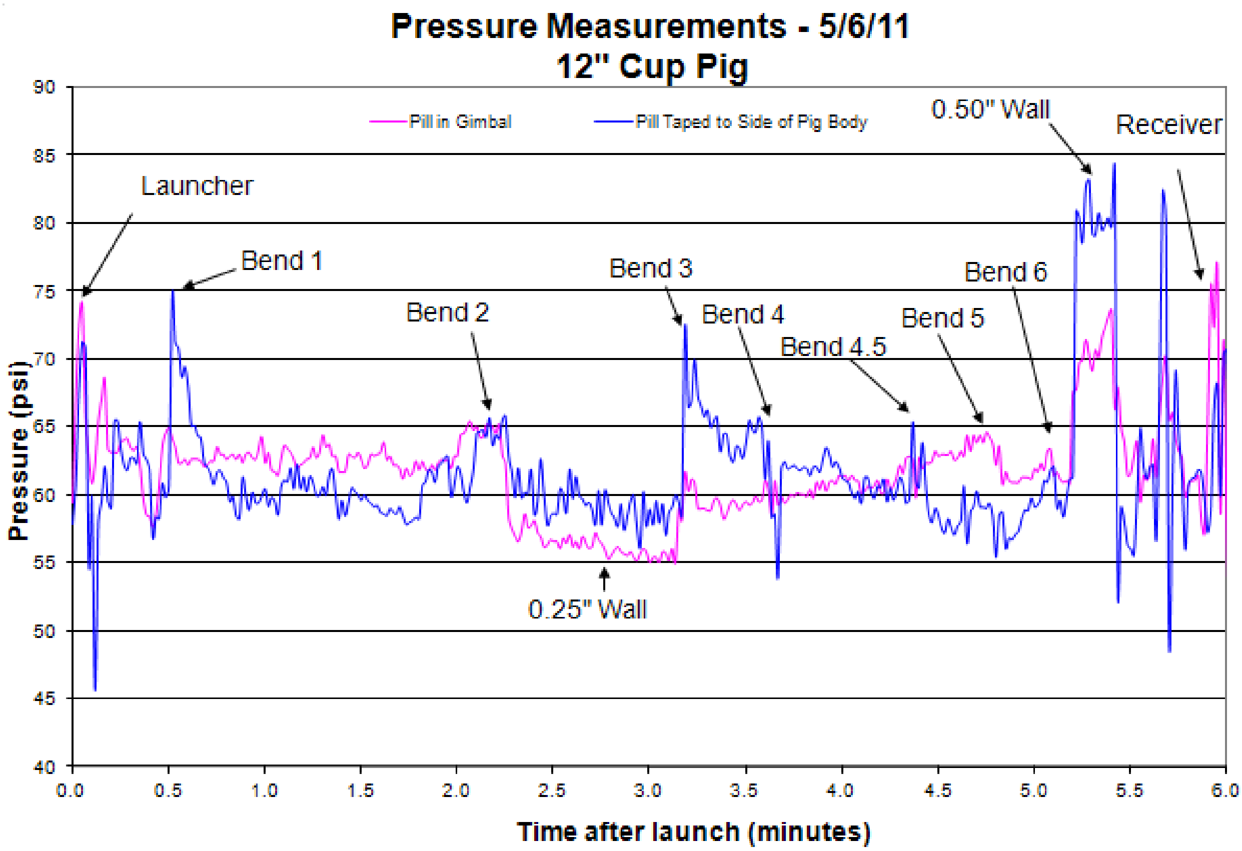

Figure 5.9 – Sensor Location

The location where the sensor was placed on the pig also had an influence in the pressure signature. In Figure 5.9 on a cup pig, two sensors were attached, one at the side and one in the back. The sensor taped to the side showed a pressure increase over the sensor placed in the back. The sensors themselves had a tolerance of ± 2 psi, which could account for some of the difference in the results

5.7 – X, Y, and Z Axes Sensor Data

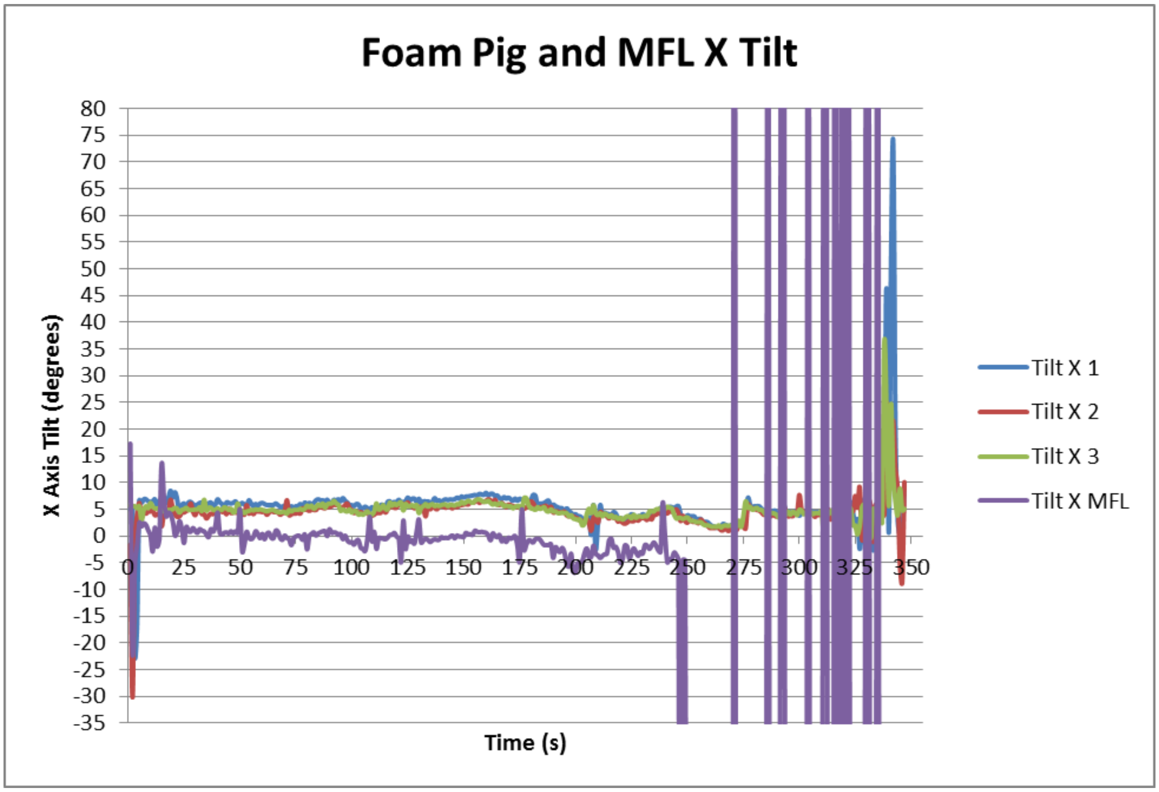

Figure 5.10 – X-Axis Data

With the X-axis data we were able to see elevation changes in the pig's motion. Most of the elevation changes in the test facility were gradual except for the launcher and receiver. Figure 5.10 shows two different types of pigs, the magnetic flux leakage pig and three foam pig runs. Comparing the two different pigs shows that the foam pig is a fairly repeatable consistent ride, that is also relatively smooth, whereas the MFL pig having a much more difficult or "rocky" ride. This has been attributed to the fact that the inline inspection pig would get stuck and took longer to complete the run and the foam pig being able to sail through rather quickly.

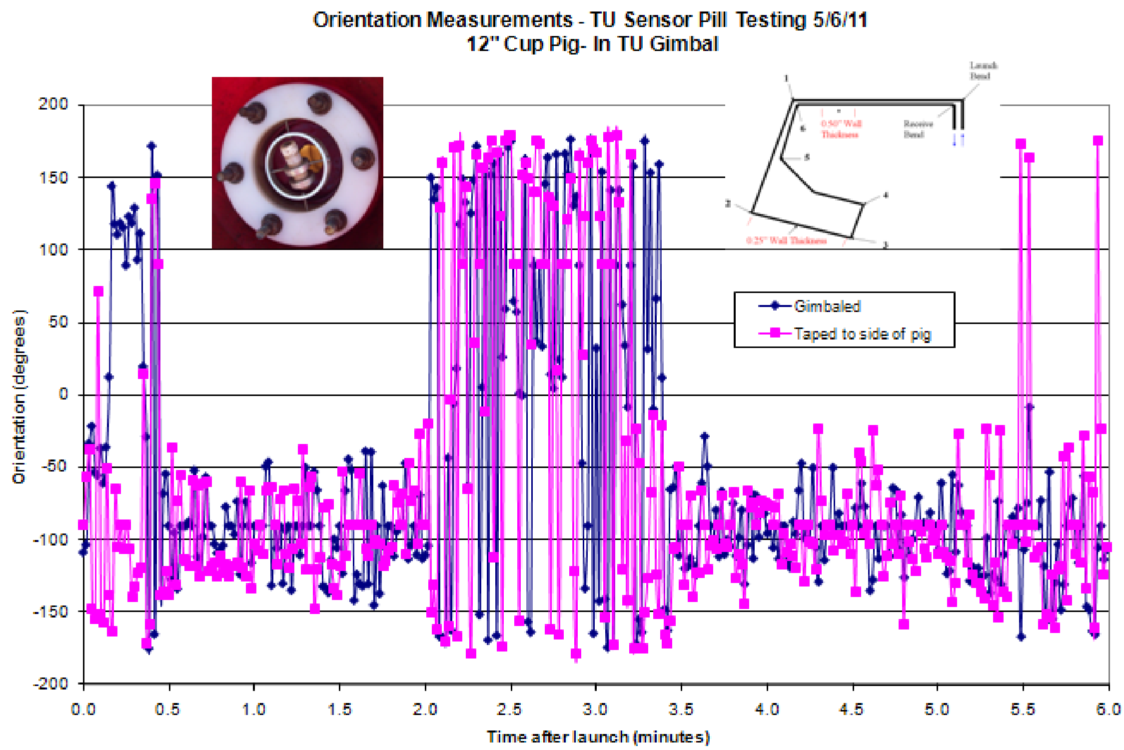

Figure 5.11 – Cup Pig X Axis Data

Figure 5.11 is another example of different pigs giving different data. In this run a cup pig was used with two sensors attached. A sensor attached to the side and the other sensor was attached to the back of the pig in a gimbal device to eliminate small vibrations, and to allow the sensor to always go back to the same position regardless of if whether pig was rotating. For the most part the gimbal did help with some of the excess noise and gave a similar reading to previous pigs entering the thin walled section of the flow loop when it looked like the pig started to move around at about the two minute mark. This correlates with the fact that the pig was in the thin walled section of the pipe and had more freedom to move.

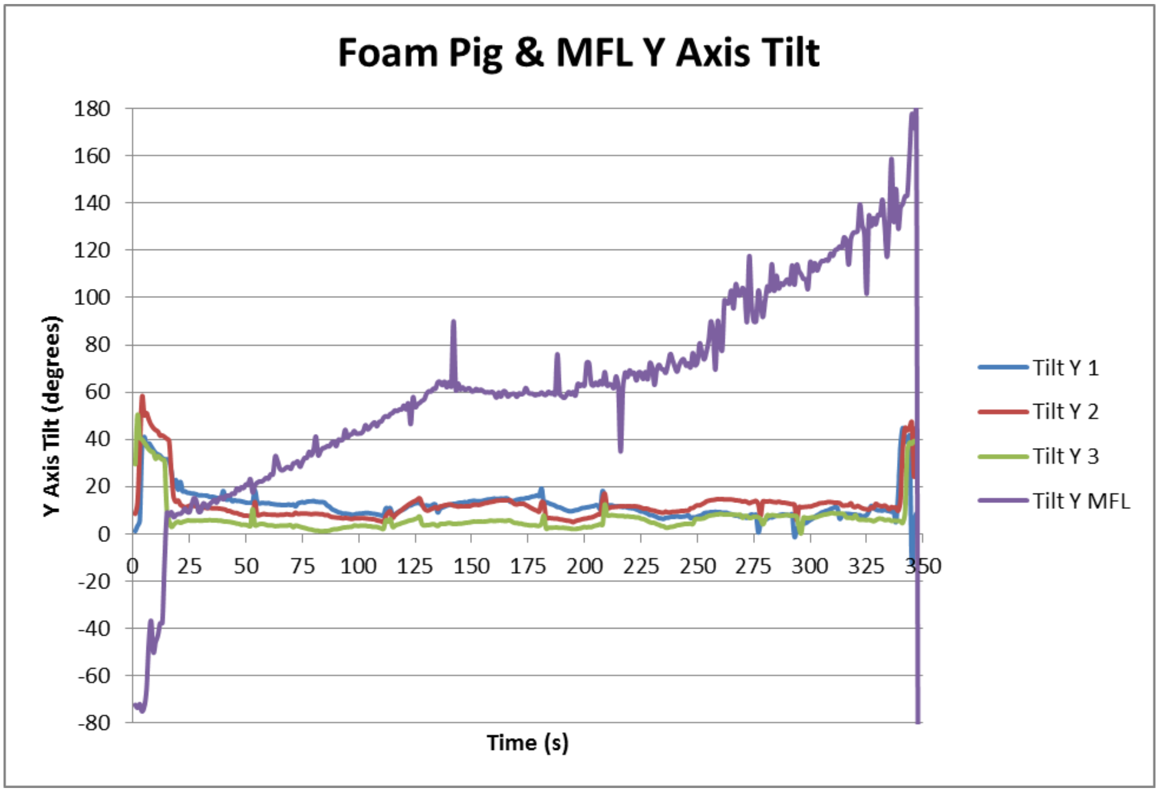

Figure5.12 – Y Axis Data

Figure 5.12 shows the data from the magnetic flux leakage pig and the foam pig. The Y and Z-axis data are used to determine when the pig goes through a turn in the pipe. The data from the pig run does show that when turns happen we get a small spike in the data. This was possible because the pig did not rotate during the run as it did with the magnetic flux leakage pig. For the MFL run, Figure 5.12 shows that the pig was constantly rotating through the run. This was also confirmed because the sensor was placed in the 9 o'clock or 270 degree position when launched and was received in the 6 o'clock or 180 degree position. The spikes on the MFL run do not correspond with the pipe turns as do those on the foam pig. The data shows that the sensor goes from -80 degrees to a positive 180 degrees. This coincides with the launch/receiver positions.

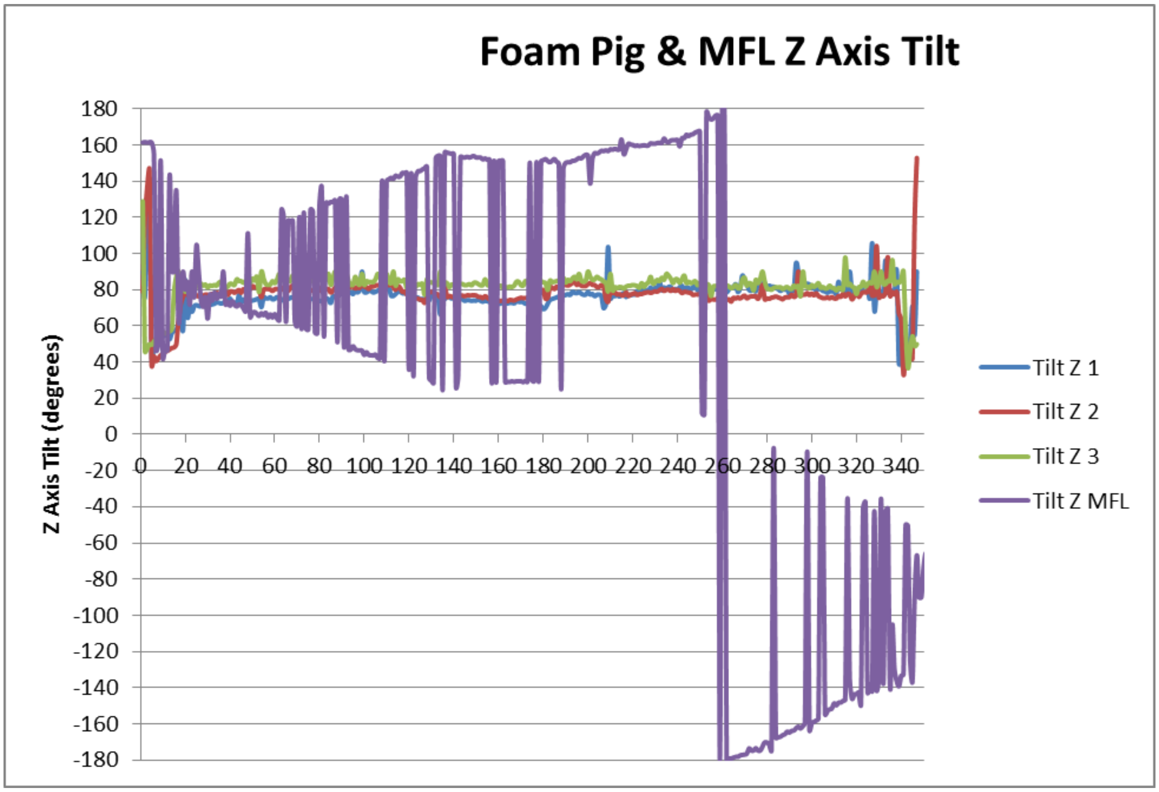

Figure 5.13 Z Axis Data

From the software specifications and the benchmark testing we did, we have concluded that the Z-axis tilt data are not actually measured but rather calculated from the X and Y-axis data. This led us to start focusing more on the X and Y-axis data while largely ignoring the Z-axis. In Figure 5.13 is the same data set as Figures 5.6 and 5.8. These show that the foam pig runs were consistent and didn't move around too much therefore giving relatively consistent results. In contrast the Z-axis from the magnetic flux leakage pig data is constantly moving in what appears to be an oscillating fashion and then somehow turning upside down and repeating the oscillation. From the other data we have determined this to be false, and that the Z-axis will give an inaccurate reading during runs where the pig rotates.

5.8 – Typical Free Floating Prototype Data

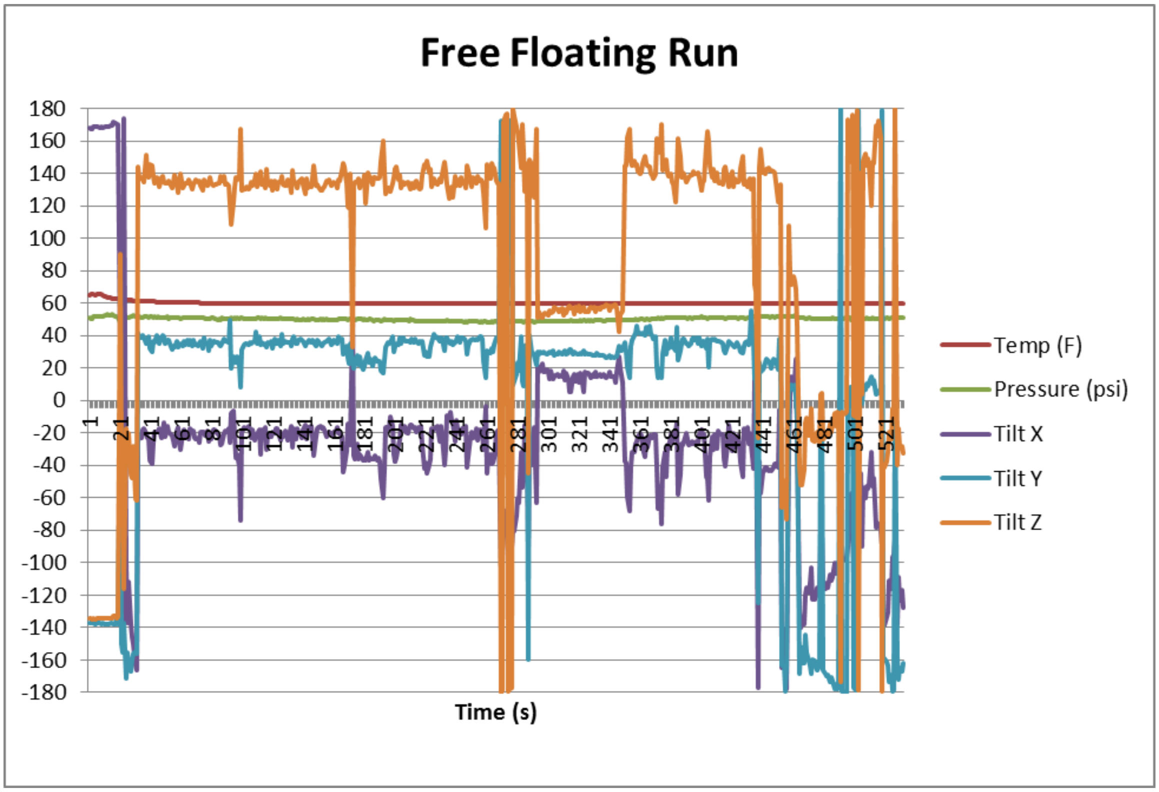

Figure 5.14 Typical Free Floating Run, Barbell

Figure 5.14 shows typical data from a free-floating run. When compared to Figure 5.1, the data look dramatically different. Because the sensor is not geometrically constrained as it is on a pig, its orientation is not as clearly defined.

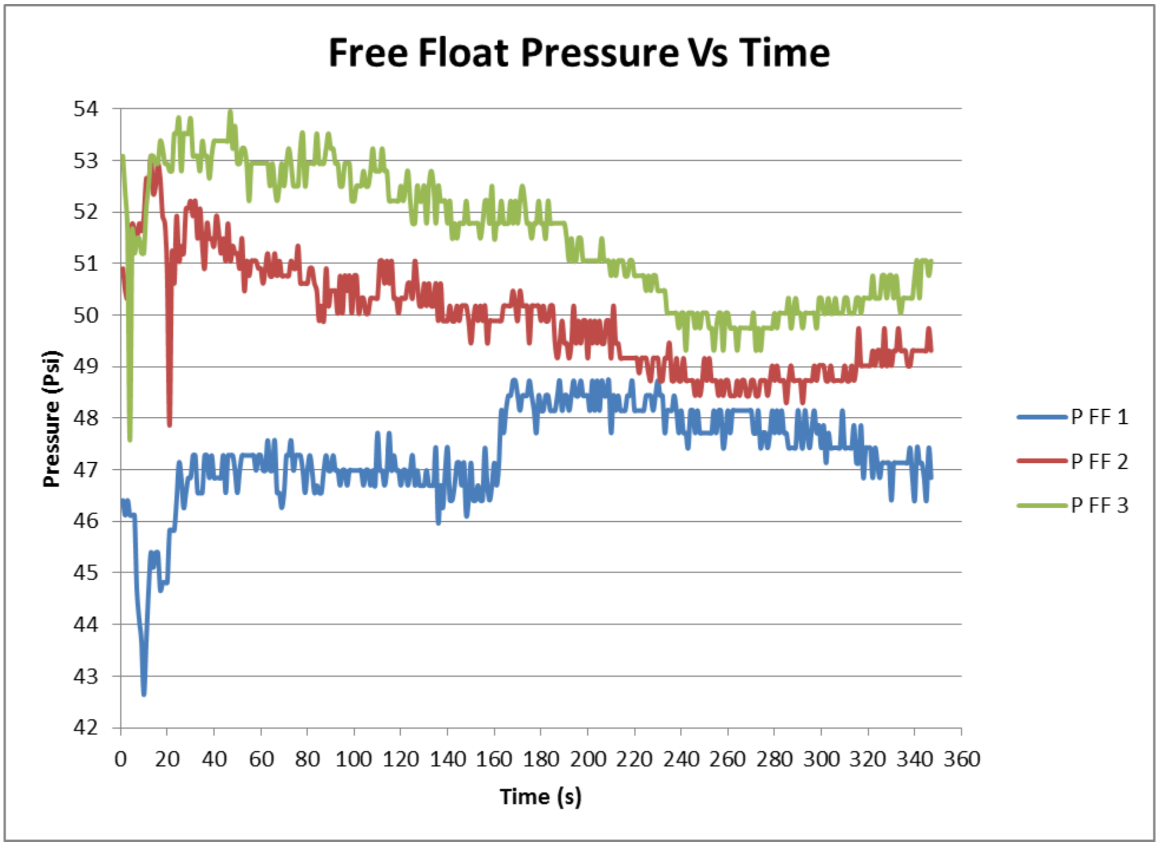

Figure 5.15 Repeatability of Free Floating Runs

Figure 5.15 shows pressure results the same free-floating prototype as Figure 5.14 (barbell) in three different runs from that day. The first run does not follow the same trend line as the other two runs. It is also reading a lower pressure even though the flow loop pressure was not adjusted in between runs. Run 2 and run 3 have similar characteristics but are offset by approximately 2 psi. Even though this is not a large difference, all runs were repeated under the same conditions to ensure the best data possible. When the free floating runs are compared to the foam pig run in Figure 5.16, the foam pig has a noticeable trend, and we are able to pick out the wall thickness changes, as seen in Figure 5.9. The pressure profiles among the 4 different runs do not show that the free-floating device can detect wall thickness through pressure change.

5.9 – Different Types Of Free Floating Prototypes

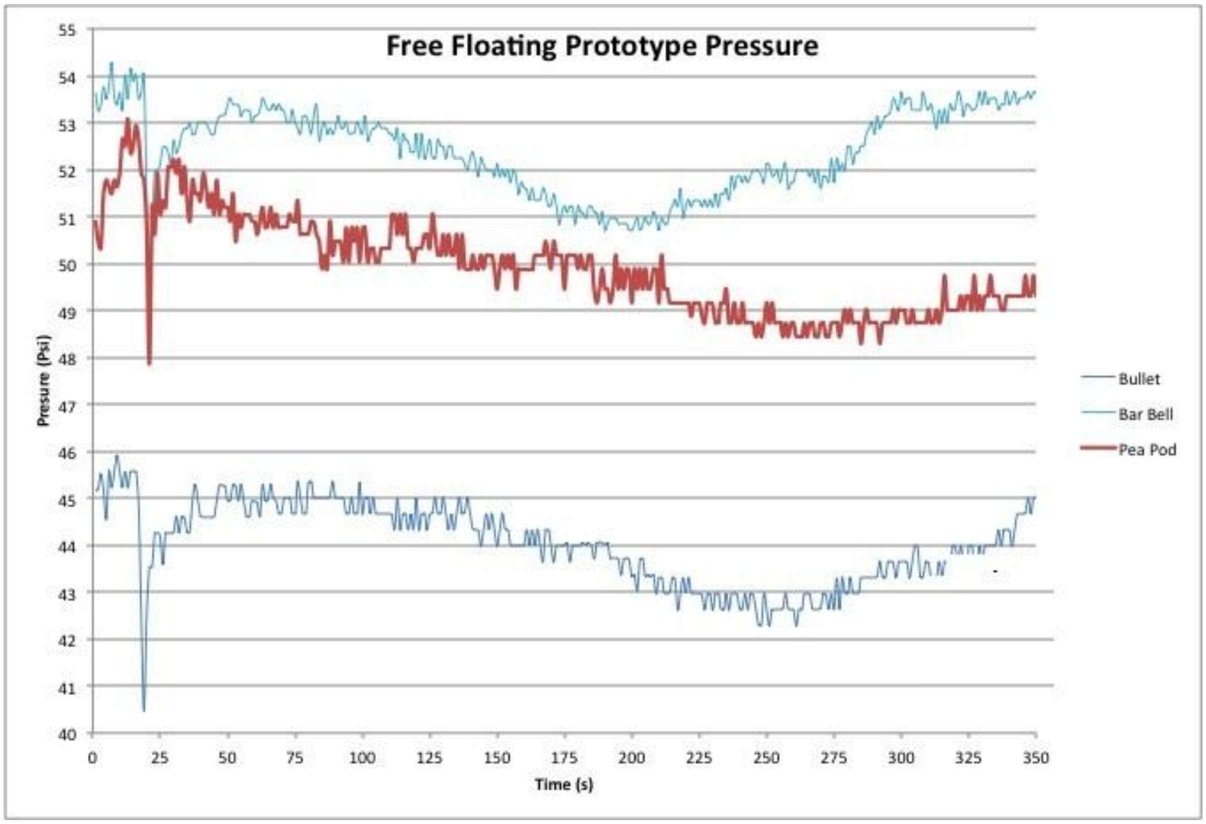

Figure 5.16 Three Different Free Floating Prototypes

In Figure 5.16 the three different free-floating prototypes are shown to have similar pressure profiles. This means that the type of free-floating carrier doesn't have much influence on the nature of the data.

Chapter 6 Field Test

Summary: In July 2011 a field test was done in a working natural gas pipeline. The run was 22,451 feet long and took 3 hours 35 minutes and 09 seconds to complete. The average run speed was 1.7391 feet per second. Two sensors were mounted on a caliper pig.

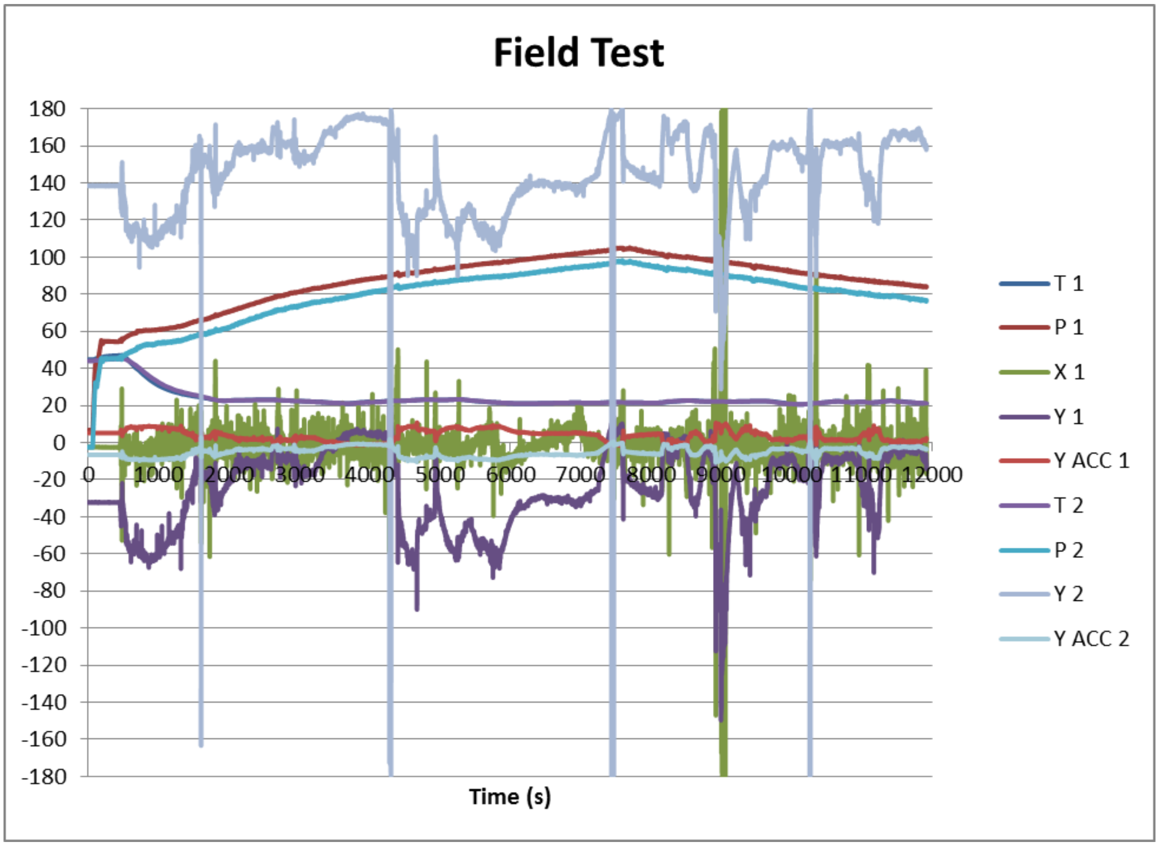

Figure 6.1 Field Test, Both Sensors mounted on pig

Figure 6.1 shows the data from both mounted sensors on the calipar pig. It shows the pressure increasing until the operator started releasing the pressure at 7500 seconds. The operator did this because the pig did not arrive as expected. These results are similar to the run done at TDW with air as shown in Figure 5.9.

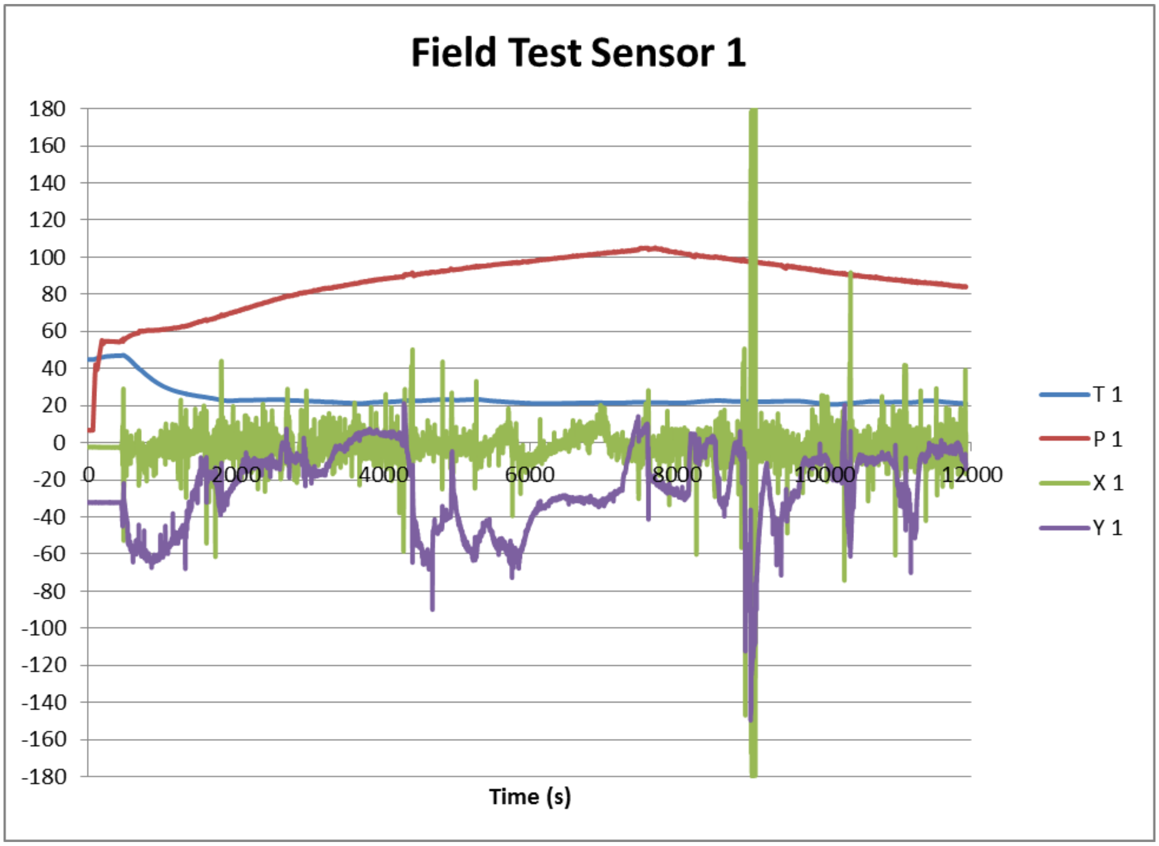

Figure 6.2 Sensor 1 Mounted in the 12 oclock position

In Figure 6.2 and Figure 6.3 we see that the difference in the sensor location results in very different data. In Figure 6.3 the x tilt data is shown to be bouncing between +180 and -180. In contrast, this is not happening with the other tilt sensor, Figure 6.2, that was mounted 30 degrees offset from the other sensor. As seen in Figure 6.1 the y tilt, pressure, temperature, and accelerometers were very similar. The y tilt did show a phase difference but a similar pattern.

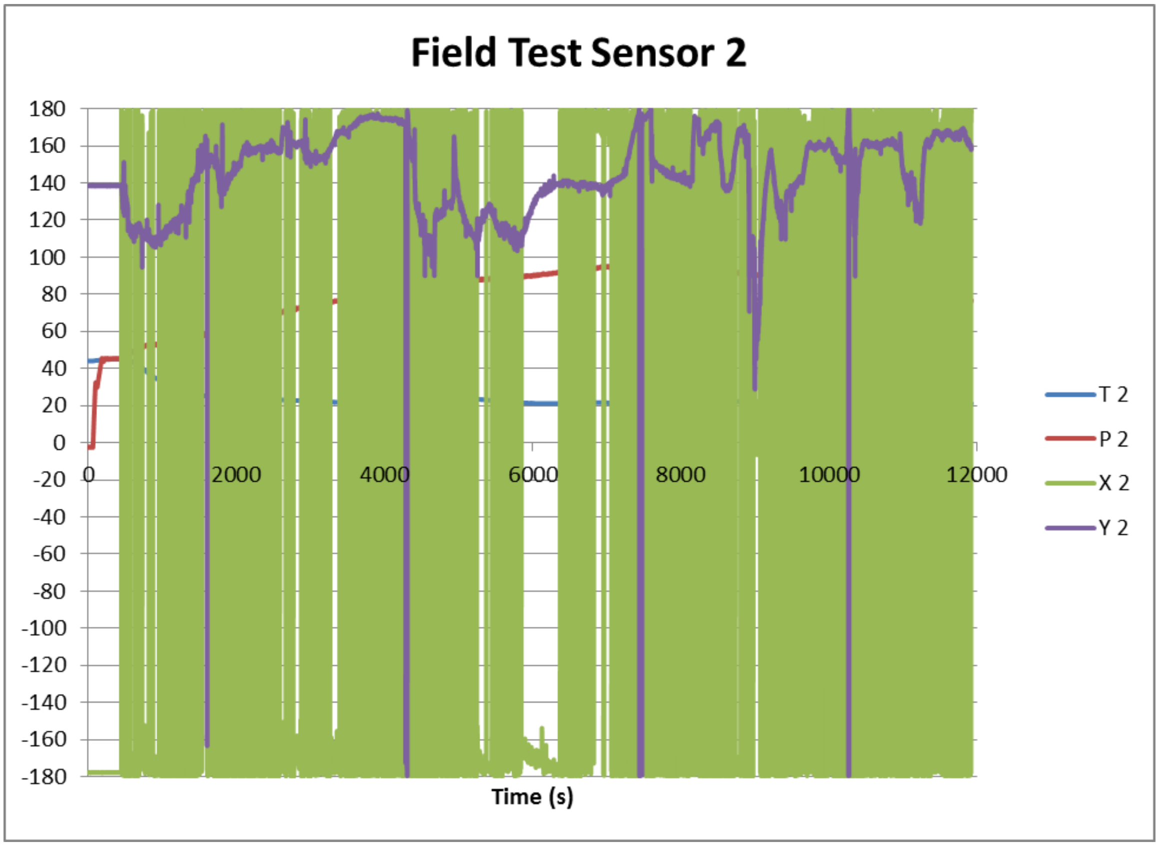

Figure 6.3 Sensor 2 mounted between the 2 and 3 o’clock position.

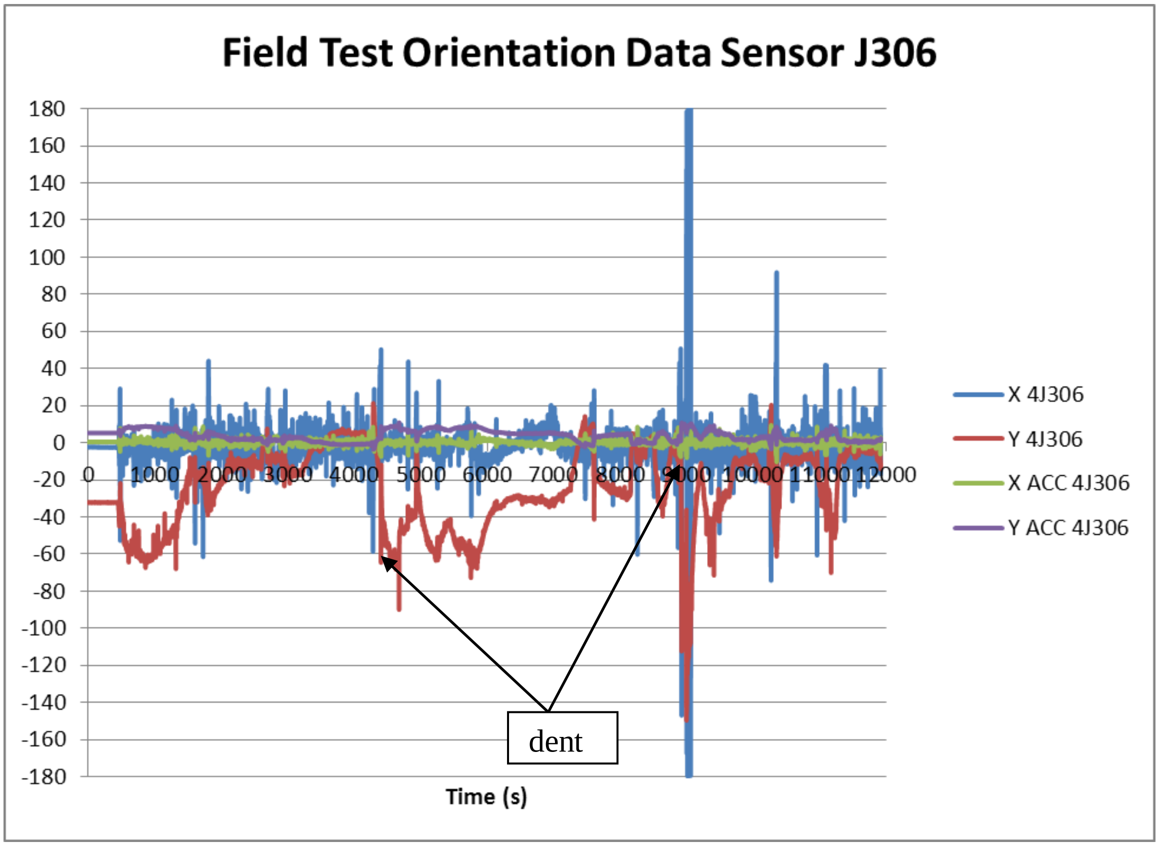

Figure 6.4 Sensor 1 Tilt and Acceleration data, showing location of two dents in the pipewall.

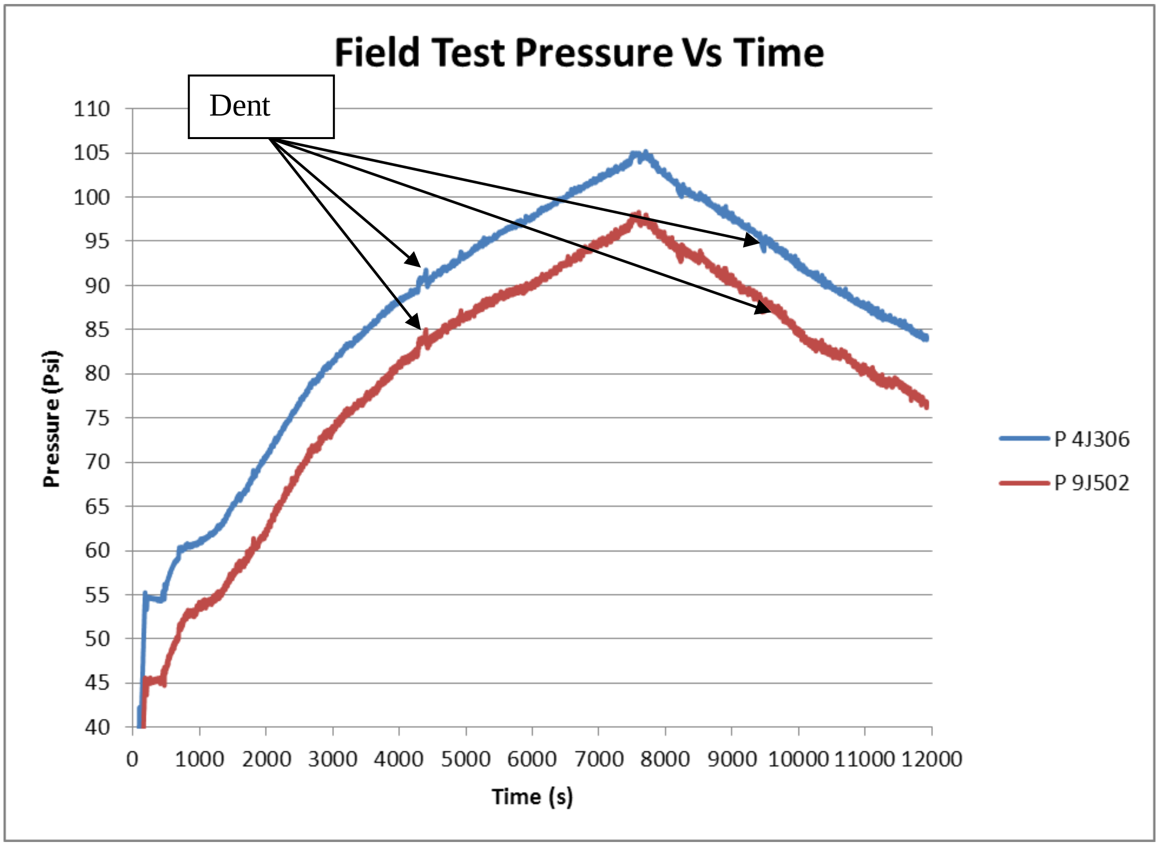

Figure 6.5 Field test comparison of pressure data

Deformation Listing

Order by Distance

ID #	Time	Distance (ft)	Depth (in)	Depth %	Orient.	Type	Min X Sec Dia	Description	On Weld	U/S Reference Name	Distance U/S Reference (ft)	D/S Reference Name	Distance D/S Reference (ft)
14000009	5907.4	7311.8	0.57	2.8%	172	DENT	18.68			Valve (Launcher)	7311.75	Valve (Receiver)	15333.64
14000010	7085.8	8814.4	0.88	4.4%	83	OVALITY	18.40			Valve (Launcher)	8814.36	Valve (Receiver)	13831.04
14000008	14445.8	22341.4	1.10	5.5%	193	DENT	18.31			Valve (Launcher)	22341.44	Valve (Receiver)	303.96

Deformation Summary

DENT	2
OVALITY	1

Figure 6.6 TDW Pig Data

In Figure 6.4 and 6.5 the pressure data is focused on. Two bumps in the pressure signatures are shown at 4500 seconds and 9200 seconds. These bumps coincide with the dents shown in figure 6.5. This is also shown in the acceleration and orientation data from Figure 6.4 at the corresponding times. This confirms that when mounted on a caliper pigs the sensor can detect dents as well as turns.

Chapter 7 – Summary, Conclusions, and Future Work

7.1 – Summary

A novel technique for inspecting pipelines using a capsule-sized sensor has been successfully demonstrated. To date we have demonstrated that we can launch and recover the sensors in a variety of means. Depending on how it is packaged, the sensor is capable of reliably locating pipeline bends, changes in wall thickness, as well as temperature and pressure profiles.

Further research is necessary to develop a robust package that will be able to survive severe conditions of pressure, temperature, and environment. The sensor itself requires increases in data storage and battery autonomy in order to be acceptable for long field test trials. Increases in sampling rate are also necessary in order to more precisely understand conditions inside the pipe. A sensor that can measure temperature, pressure, velocity, and salinity with an increased data rate and storage capacity is required.

7.2 – Conclusions

1. A novel technique for inspecting pipelines using a small, capsule-sized sensor has been demonstrated.
2. We are able to see temperature and pressure changes. Changes in velocity and orientation will need more packaging development.
3. This technique is capable of reliably and repeatably detecting pipeline bends and changes in pipe wall thickness.

4. Our results show the sensor is capable of being deployed in various packages, including off the shelf maintenance pigs and custom-designed free-floating packages.
5. Results from the sensor are dependent on which package is selected. A variety of pigs offering the best choice, and free floating packages offering a pig-less configuration.
6. With further research and sensor development, a free-floating sensor will be able to be deployed in unpiggable pipelines, allowing them to be mapped.

7.3 – Recommendations

The novel inspection technique described herein shows great promise for improving the state of the art in pipeline inspection. However, much important work remains before this technique is ready for application in industry.

1. Sensor limitations. A new sensor is required with the following attributes:

    (a) Greater battery autonomy. The ability to have it record data for several days will suffice for this type of testing but weeks of data would be more preferable.

    (b) Higher sampling rate. The current sensor only has a 1 Hz sampling rate. Something along the lines of 30 to 60 Hz is desired for more accurate orientation data.

(c) Improved precision. Currently the temperature has a tolerance of °C ±2, the pressure has a tolerance of ± 3 PSI, and the orientation has a tolerance of ± 2°.

(d) More robustness. The current sensor has a max temp of 76°C and a max pressure of 1500 PSI. To deal with the deep water pipelines, the maximum pressure and temperature of the sensor will have significantly exceed the operating pressure and temperature.

2. New 3-D pipeline mapping software that is derived from the acceleration data. Similar software has been demonstrated on iPhones.

3. Ability to get velocity through 3-D software and GPS data being coupled together. This will combine information from the sensor that will allow velocity calculations to be derived from the 3-D software and the start and end times will be provided by GPS markers.

4. Work on neutrally buoyant device. This will allow the sensor to travel down the pipeline at the maximum velocity point on the velocity profile.

5. A bypass pig was just developed for use in natural gas pipelines where you can dial in the speed that you want by allowing fluid flow through the pig. This combined with the sensor would possibly yield some really good data for a field trial.

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