DESIGN AND DEVELOPMENT OF COMMUNICATION AND TRACKING MODULE FOR A PIPELINE HEALTH MONITORING ROBOT

DESIGN AND DEVELOPMENT OF COMMUNICATION AND TRACKING SYSTEM FOR A PIPELINE HEALTH MONITORING ROBOT

A Graduate Project Report submitted to Manipal University in partial fulfilment of the requirements for the award of the degree of

BACHELOR OF TECHNOLOGY

In

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Submitted by

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INSPIRED BY LIFE

DEPARTMENT OF MECHATRONICS ENGINEERING

MANIPAL INSTITUTE OF TECHNOLOGY
(A constituent Institute of MANIPAL UNIVERSITY)

MANIPAL - 576 104, KARNATAKA, INDIA

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DEPARTMENT OF MECHATRONICS ENGINEERING

MANIPAL INSTITUTE OF TECHNOLOGY
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21/05/2015

CERTIFICATE

This is to certify that the project titled **DESIGN AND DEVELOPMENT OF COMMUNICATION AND TRACKING MODULE FOR A PIPELINE HEALTH MONITORING ROBOT** is a record of the bonafide work done by **Jal Panchal (110929010**) submitted in partial fulfilment of the requirements for the award of the degree of **BACHELOR OF TECHNOLOGY** in **MECHATRONICS ENGINEERING** of Manipal Institute of Technology, Manipal, Karnataka (A constituent college of Manipal University) during the year 2014-2015.

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CERTIFICATE

This is to certify that Mr. Jal Panchal, a student of Manipal Institute of Technology, Manipal has successfully completed his Internship in the Smart Material Structures and Systems (SMSS) Laboratory, Department of Mechanical Engineering during the period 19.01.2015 to 18.05.2015. He worked on the project titled Design and Development of Communication and Tracking Module for a Pipeline Health Monitoring Robot.

Dr. BISHAKH BHATTACHARYA
Project Guide

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ABSTRACT

Pipelines exist for the transport of crude and refined petroleum, fuels - such as oil, natural gas and biofuels - and other fluids including sewage, slurry, water, and beer. Pigging refers to the practice of using devices known as Pipe Inspection Gauges (PIGs) to perform various maintenance operations on a pipeline. This is done without stopping the flow of the product in the pipeline.

Gas Authority of India Ltd, has natural gas pipelines running across India and has given Indian Institute of Technology, Kanpur the project of developing a pipeline health monitoring system which can be transported inside pipes of variable diameters with the help of a conduit crawler robot, to inspect their pipeline for defects.

My part in the project was to *design and develop a communication and tracking module for the Pipeline Health Monitoring Robot (PHMR)*. This report narrates in detail, the research carried out and the steps followed in designing two systems; an acoustic tracking system using a Helmholtz resonator, in which a suitable resonator was designed along with the analysis of the jet flow required to excite it, the other system is a wireless location monitoring system using ZigBee communication protocol, which shows the live motion of the PHMR inside the pipeline during operation.

CONTENTS

LIST OF FIGURES

LIST OF NOTATION AND ABBREVIATIONS

PIG	Pipe Inspection gauge
PHMR	Pipeline Health monitoring Robot
GPS	Global Positioning System
GAIL	Gas Authority of India Ltd.
API	American Petroleum Institute
NB	Nominal Bore
NI	National Instruments
VI	Virtual Instrument
FFT	Fast Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
LED	Light Emitting Diode
LDR	Light Dependent Resister
PCB	Printed Circuit Board
SD	Secure Digital
GUI	Graphical User interface
USB	Universal Serial Bus
PVC	Polyvinyl Chloride
ROV	Remotely Operated Vehicle
DAQ	Data Acquisition

Chapter 1 INTRODUCTION

Pipelines exist for the transport of crude and refined petroleum, fuels - such as oil, natural gas and biofuels - and other fluids including sewage, slurry, water, and beer. Pipelines are useful for transporting water for drinking or irrigation over long distances when it needs to move over hills, or where canals or channels are poor choices due to considerations of evaporation, pollution, or environmental impact [1].

1.1.Pigging

A process which is the act of propelling a properly sized spherical or cylindrical device through the interior of a pipeline by manipulating the pressure & flow of the existing media, or by artificially introduced media or by mechanically pulling the device through the pipeline for the specific purpose of cleaning, inspecting, distributing inhibitor throughout the pipeline or as a plug to isolate a section of the pipeline [2].

Pigging in the context of pipelines refers to the practice of using devices known as Pipe Inspection Gauges (PIGs, crudely refers as *pigs*) to perform various maintenance operations on a pipeline. This is done without stopping the flow of the product in the pipeline.

These operations include but are not limited to cleaning and inspecting the pipeline. This is accomplished by inserting the *pig* into a 'pig launcher' (or 'launching station') - an oversized section in the pipeline, reducing to the normal diameter. The launcher/launching station is then closed and the pressure-driven flow of the product in the pipeline is used to push it along down the pipe until it reaches the receiving trap – the 'pig catcher' (or 'receiving station') [3].

1.2. Reasons for Pigging

Pigging of a pipeline is required at various stages of a pipeline's life for a variety of reasons. These are:

1.2.1. Pre-commissioning

When new pipelines are built, they generally need to be cleaned of construction debris and prepared for hydrostatic testing. This is generally done by utilising a pig train consisting of cleaning, gauging, and batching pigs to flood the line. Depending on the medium to be transported in the line, further pigging may be required for dewatering and drying operations.

1.2.2. Commissioning

As the product is introduced into the line, a batching pig or pigs can be used to separate the product from the medium currently in the line.

1.2.3. Operational Pigging

During the life of a line, operational pigging is a cheap effective way of maintaining flow and minimising back pressure. Pigs can be used to mechanically clean waxes and other hydrocarbon build-ups, or chemicals can be batched between pigs to provide chemically enhanced cleaning. Inline inspection is generally carried out as part of a routine maintenance plan.

1.2.4. Decommissioning

Whether pipelines reach the end of their useful life, or have their use changed (e.g. changing a production line to a produced water disposal line), they generally require some form of cleaning. Again, mechanical and chemical means can be used to allow subsea disconnection/reconnection, and in some cases pipelines can be dewatered for recovery and reuse [4].

1.3. Types of Pigs

Pigs can be broadly divided into three categories:

- **Utility Pigs**: which are used to perform functions such as cleaning, separating, or de-watering. Types of utility pigs are:
    - *Cleaning Pigs*: which are used to remove solid or semi-solid deposits or debris from the pipeline.
    - *Sealing Pigs*: which are used to provide a good seal in order to either sweep liquids from the line, or provide an interface between two dissimilar products within the pipeline.
- **In Line Inspection Tools:** which provide information on the condition of the line, as well as the extent and location of any problems.
- **Foam Pigs**: which are used in conjunction with conventional pigs to optimize pipeline dewatering, cleaning, and drying tasks.
- **Plugs**: isolate a section of the pipeline [2].

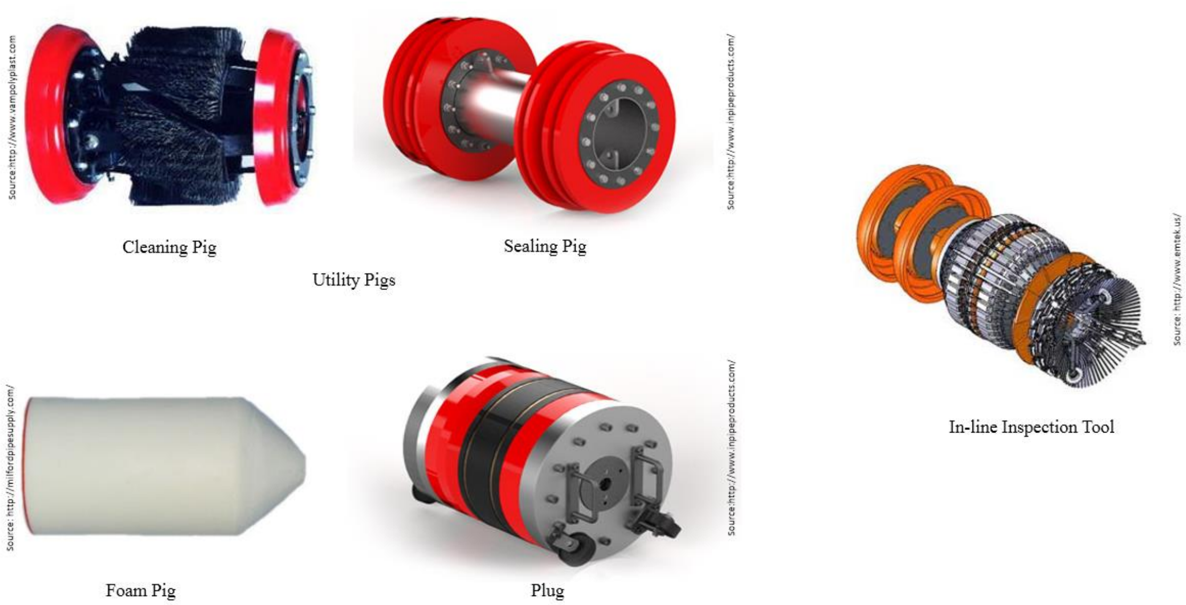


Figure 1-1: Types of Pigs.

1.4.Selection of a Pig

The type of pig to be used and its optimum configuration for a particular task in a particular pipeline is determined based upon several criteria, which include:

- **The Purpose** :
    - The type, location, and volume of the substance to be removed or displaced in conventional pigging applications.
    - Type of information to be gathered from an intelligent pig run.
    - Objectives and goals for the pig run.
- **The Line Contents:**
    - The contents of the line while pigging.
    - Available vs. required driving pressure.
    - Velocity of the pig.
- **Characteristics of the Pipeline**:
    - The minimum and maximum internal line sizes.
    - Maximum distance pig must travel.
    - Minimum bend radius, and bend angles.
    - Additional features such as valve types, branch connections, and the elevation profile [2].

1.5.Pig tracking

'Pig tracking' is used as a generic term to cover any requirement to monitor the movement or locate the position of pigs during the pigging operation. It is a method of verifying either the pig's location or movement through the line. Tracking the movement reduces the search area in the event a pig does become lost or stuck in the line. This is very beneficial in lines that are not pigged routinely and especially in lines that have never pigged before [5].

A typical pig tracking system will contain the following components:

- A sensor to detect the distance of the pig
- Transmitter to transmit the tracking information
- A microcontroller to control the sensor and transmitter
- Power supply
- A receiver at regular intervals to receive transmitted signal

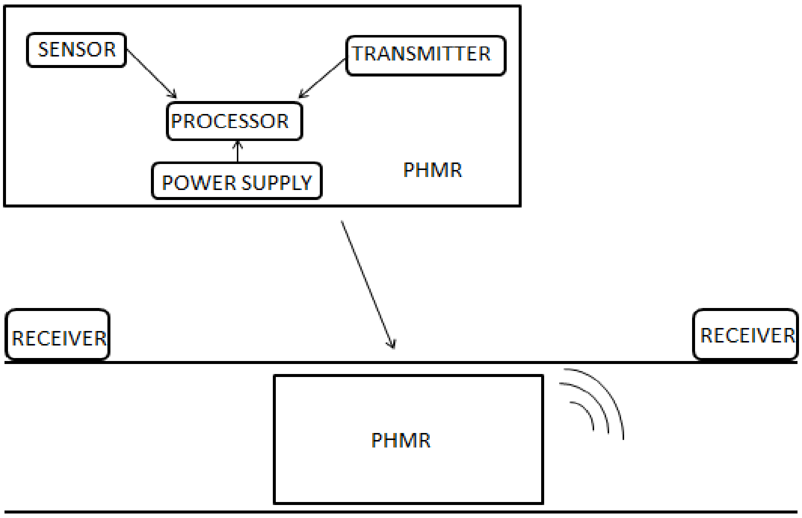


Figure 1-2 : Typical pig tracking system.

1.6.Importance of Pig tracking

Location verification is often accomplished by surface instruments that record the pig's passage by either audible, magnetic, radio-transmission or other means. The sensors record when they detect the passage of the pig (time-of-arrival); this is then compared to the internal record for verification or adjustment. The external sensors may have GPS capability to assist in their location. A few pig passage indicators transmit the pig's passage, time and location, via satellite uplink. The pig itself cannot use GPS as the metal pipe blocks satellite signals.

After the pigging run has been completed, the positional data from the external sensors is combined with the pipeline evaluation data (corrosion, cracks, etc.) from the pig to provide a location-specific defect map and characterization. In other words, the combined data reveals to the operator the location, type and size of each pipe defect. This information is used to judge the severity of the defect and help repair crews locate and repair the defect quickly without having to dig up excessive amounts of pipeline. By evaluating the rate of change of a particular defect over several years, proactive plans can be made to repair the pipeline before any leakage or environmental damage occurs [3].

Efficient live tracking of the operating pig helps in pin pointing the exact location of defects and deformations by comparing the location data with the inspection sensor data. It also helps it monitoring the correct working of the pig, Stuck pigs, technical glitches in pigs can create a lot of problems while trouble shooting if not identified in tine and if the location is unknown. Constant communication with the pig also aids in the effective and efficient pigging process.

Chapter 2 LITERATURE REVIEW

This Chapter addresses the different factors affecting and the types of pig tracking systems and contains the review of the past and existing technologies that have been tried and tested to track a pig inside a pipe.

2.1.Factors affecting a tracking system

The motion tracking of a pig in different conditions and environments will vary. The factors that affect the selection of the tracking system best suited for the situation are listed below:

2.1.1. *Type of fuel being transported in the pipe*

Depending on the type of fuel that is being transported the mechanism and technology of tracking system will vary due to the difference in properties of the different fuels.

The fuels that are commonly transported through pipes are:

- Crude Petroleum
- Refined petroleum, Oil
- Natural gas
- Biofuel
- Sewage
- Water

2.1.2. Surrounding environment of the pipeline

The surrounding environment also plays a key role in selecting the tracking mechanism. The accessibility to the pipe in the environment it is in, properties of the environment, help us select the mechanism.

The different environments based on pipe placements are:

- Air, pipeline is on suspended on supports.
- Air and ground; pipe is placed on the land
- Ground; pipe is submerged underground.
- Water; pipe is placed deep under water.

2.1.3. Interference with the other systems on the pig

The pig contains systems for detecting defects, cleaning of pipe walls, communication with the ground station, in house energy generation. One system must not interfere with the signals generated by the other system to ensure efficient working of the pig. For example, if an acoustic module is used for detecting of flaws on the pipe wall, an acoustic tracking system may not be a good option as the two systems will interfere.

2.1.4. Range of detection needed

The range till which the detection of the pig is desired is also important and to be considered while designing the tracking system. It will affect the signal strength, propagation, energy dissipation and related parameters.

Based on the range the tracking system can be classified as:

- Short range; detecting for up to 1km
- Mid-range; detection between 1 to 5km
- Long range; detection for more than 5km.

2.1.5. Characteristics of the pipe

The pipe material and bore diameter can either aid or be a hindrance while tracking the pig moving along the pipe. Lower bore pipe require micro systems to be designed. The pipe material can be crucial in blocking of communication signals and may also act as the transmission medium for the communication signals.

Pipe internal bore varies from 1/8th inch to 48 inches.

Pipe materials commonly used are:

- Polyvinyl Chloride (PVC)
- Aluminium
- Stainless Steel
- Carbon Steel

To select a suitable system of tracking, all factors that could possibly influence the tracking system are to be identified and analysed. This analysis is used to evaluate the different tracking systems. Weightage for different factors should be decided and suitable selection of system can then be made.

2.2. Types of tracking systems

2.2.1. Signalling

It is a method of indicating when the pig has reached a certain point in the pipeline. This is usually achieved by attaching a triggering device or 'signaller'. This may be activated by the pig physically moving a lever or a plunger, which protrudes, into the line (referred to as intrusive), or by remotely sensing the pig's presence from outside the pipe wall by, for example, a change in the magnetic field. This is usually referred to as a non-intrusive signaller.

Pig signallers are required at the very least at the exit and entrance to the pig traps. Traditionally these have been mechanical devices, which flip up a flag when the pig actuates a pressure or mechanical sensor during its passage. They have the disadvantage that they need to be well maintained and need reset prior to the passage of the next pig. Non-intrusive signallers – i.e. those which do not require any interference with the pipe integrity are now the preferred method and indeed are the only feasible method for subsea use.

2.2.2. Locating

To locate a pig normally when it gets stuck, it is necessary to mount a transmitter of some sort in the pig. It is a method of determining the position of a pig, normally when it is stationery, and usually due to it being either held up (due, perhaps, to low flow conditions), or stuck (due to damage or obstruction). This normally requires the pig to carry a transmitter device of some kind and a receiver to be carried along the line to locate it.

2.2.3. Continuous Tracking

It is a method of literally following the path of a pig either continuously or, more likely, by locating it at a series of predetermined points. This can be achieved by various methods including transmitter/receiver systems, mass balance via computer calculations, and by acoustics. Pig tracking can either be achieved by continuously following the pig or 'tracking' its progress passed fixed points. This methodology can considerably reduce search times on long lines and is particularly common on landlines. All the available technologies can be utilised [5].

2.3.Existing tracking technologies

The original pigs were made from straw wrapped in wire and used for cleaning. Pigging technology and tracking of these pig has since then has gradually developed, with smart pigs with multiple tracking technologies used today. In the past methods such as using a radioactive material, a hammer on the pig that hits the pipe wall which is heard my workmen following the pig movement from the outside have been used. Today the tracking systems are sophisticated and give more accurate and reliable data on the motion and position of the pigs.

The following techniques have been explained below:

- Electromagnetic
- Radio Transmitters
- Radioactive materials
- Inertial Measurement Unit
- Acoustic Trackers

2.3.1. Electromagnetic pig tracking

The pig is designed as a magnetic circuit with field strength sufficient to saturate the wall of the pipe through which it is traveling. The pig normally comprises of a steel body which houses the magnetic section, four urethane cups, urethane spacers, a nose plate designed to take shock, and a rear locking plate. The Magnetic circuit may take the form of the entire pig body, as in small size pigs or a collar in larger diameter pigs.

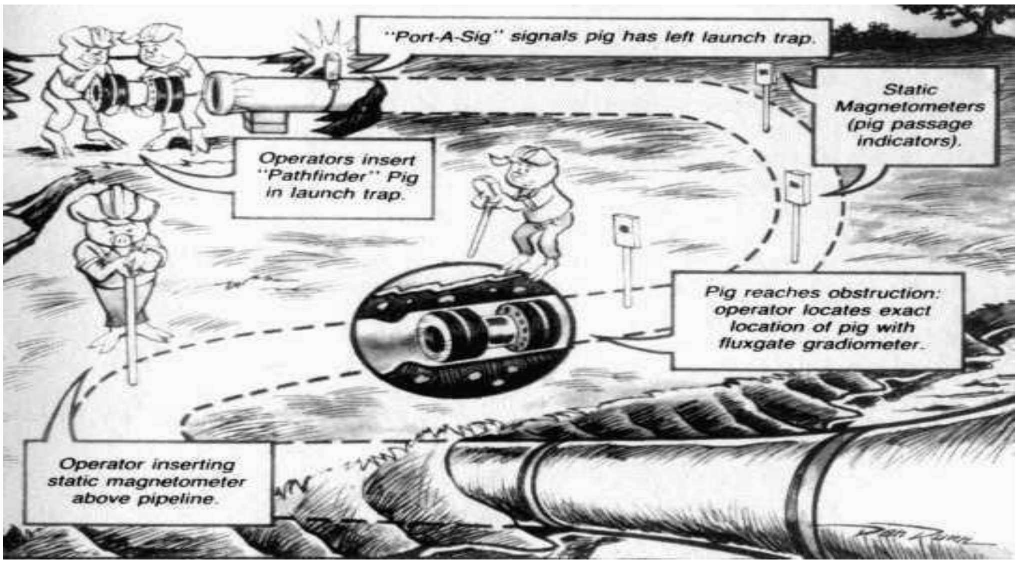


Figure 2-1 : Electromagnetic pig tracking [6].

The collar is made up of two mild steel discs with independent magnetic modules around the centre-line of the circle. The magnetic circuit may be used in conjunction with cast urethane pigs, poly pigs, or spherical pigs. The station or static magnetometers are remote field passage indicators which allow the operator to track the pig through sections of line. These units not only indicate the pig's arrival at that point, but indicate also the time of the event.

Flux Gate Gradiometer provides a very essential part of the total system, it is used to locate the whereabouts of a pig should it become lost in a line. The gradiometer may take the form of a portable hand held unit, a "fish" for offshore location of pipelines or magnetic pigs, or be used in conjunction with an R.O.V. or with an airborne vehicle. These steady magnetic fields penetrate soil and water, and so indicate the presence of magnetic objects.

2.3.2. Radio transmitters

A battery operated unit which is attached to the pig. In order to penetrate the pipe wall, which is a natural screen against radio signals, the chosen frequency has to be extremely low. The resultant signal through the pipe wall is minute, and in consequence the receiving unit has to be ultra-sensitive.

2.3.3. Radioactive trackers

Radioactive Materials are encapsulated in a small container housed within the body of the pig. And as the pig moves along the pipe, a tracker is either held in hand by a tracker or is placed on a tracking vehicle moving along the length of the pipe detecting the emissions from the radioactive material to pinpoint the position of the pig. This method is highly dangerous and is not recommended to be used due to the possible hazards and damage to Human and pipe health [6].

2.3.4. Inertial Measurement Unit

To monitor the physical profile of the pipeline, a gyroscope – accelerometer package is installed in a pig. A typical package contains 3 single axis gyroscopes and 3 single axis accelerometers placed along the 3 perpendicular axes. The gyroscopes measure direction of tilt or movements and the accelerometer measure the rate of the movement. When the data from both the sensor sets is combined the complete path travelled by the pig can be plotted with respect to an initial reference set while installing the pig into the pipeline. When the pig exits the pipeline, the data is compared to a previous profile to look for significant differences that could indicate a problem with the pipeline [7].

2.3.5. *Acoustic Tracking:*

An acoustic tracking system basically contains an acoustic emitter, which either sends a signal at regular intervals, or continuously or at a specific time as controller by the processor in the pig. The frequency, intensity and characteristics of the signal to be emitted are pre decided and a receiver strategically placed received the signal and acknowledges the position of the pig.

Based on this general scheme the following different acoustic tracking systems are being used:

2.3.5.1. *Ultrasonic tracking for underwater pipes.*

In this system the pig carries an Ultrasonic acoustic emitter, used specifically for oil pipes placed deep underwater, which emits the ultrasonic signal to be received by a bot/ship travelling at the water surface along the pipe length or floating buoys placed at regular intervals. These receivers record the sound signal and analyse the movement of the pig underneath.

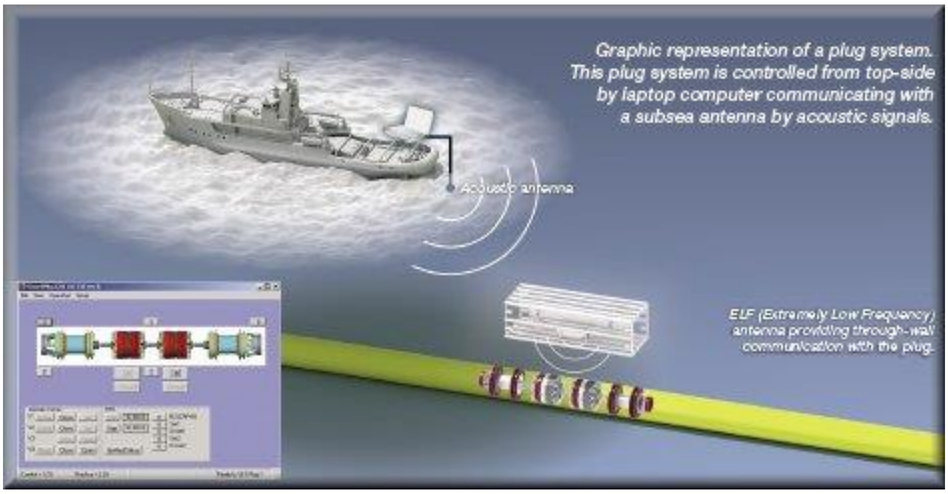


Image courtesy: Pigging Products and Services Organisation

Figure 2-2 : Ultrasonic acoustic pig tracking.

2.3.5.2. *Acoustic transmitters with mobile of stationary receivers*

In this system the pig contains a low frequency acoustic emitter and the receiver is either stationary or mobile.

In stationary receiver system, acoustic sensors tuned to listen to the set signal are placed on the ground, like geophones, at regular intervals along the pipe length and receive the signal as the pig passes underneath them. The maintenance team then collects the recorded data from all the sensors or ground markers and compile them for further processing and analysis.

Image courtesy: Hand Wedemeyer Huoston

Figure 2-3 : Acoustic tracking using geophones.

In the mobile receiver system the acoustic receiver is usually on the form of a stick attacked to a control circuitry, and a person has to walk along the pipe length with the sensor or drive along on a vehicle to continuously track the motion of the pig.

Image courtesy: Spy Pippeline Inspection Company Ltd

Figure 2-4 : Acoustic tracking using handheld sensor.

2.3.5.3. *Acoustic pig tracking with transmission along the pipe walls:*

In this system the pig had an acoustic emitter which emits a low frequency acoustic signal, below 10 kHz and the transmission is studied through the pipe walls. The receiver is placed at regular intervals flush to the pipe walls to receive the vibrations from the wall surface. In the research carried out by G. F. Kuhn and C. L. Morfe (1975) [8] they observed that low-frequency airborne sound transmission through cylindrical steel pipe walls is likely under practical conditions to be dominated by bending wave radiation.

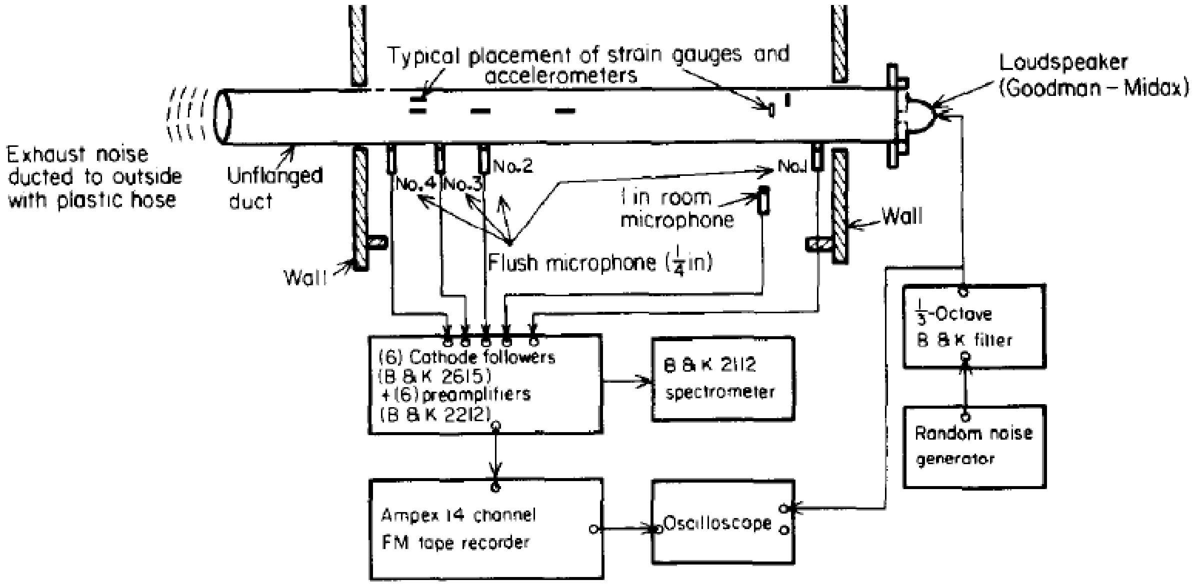


Figure 2-5 : Acoustic tracking using sensors on pipe wall [8].

Chapter 3 OBJECTIVES

The objective of the project was to develop two separate systems, to track the motion of the PHMR, with the following specifications:

1. *System One*: To design and develop an innovative and reliable system to track the motion of PHMR during operation. The system must have the following characteristics:
   - It must be scalable from a laboratory setup to the on-site active pipelines of GAIL.
   - The motion tracking need not be live tracking during operation, though live tracking is preferred.
   - It must be highly robust and stable.
   - It must be energy efficient and economical.
2. *System Two*: To design and develop a wireless system to monitor the live motion of the PHMR during operation. The system must have the following characteristics:
   - It must use wireless technology to communicate between the PHMR and the base station.
   - It must be able to show the live movement of the PHMR at the base station, while in operation.
   - It must be energy efficient and reliable.

Chapter 4 METHODOLOGY

This Chapter contain the steps followed and decisions taken during the development of the system. The experiments perfumed, the results obtained and their analyses have also been reported.

4.1.Selection of tracking system

The following characteristics and system specifications, with reference to the details provided by GAIL were considered to select a suitable tracking system:

- Fluid characteristics:
  - The pipe will be used for transportation of natural gas.
  - Velocity of gas: 0.6 m/s to 0.8 m/s.
  - Operating Pressure: 28-30 kg/cm^2.
  - Operating Temperature: 40°C
  - Gas Flow Rate: 24552 kg/hr
  - Gas Density: 27.412 kg/m^3 (at Temperature & Pressure)
  - Gas Viscosity: 0.016
- Pipe Characteristics:
  - Diameter of pipeline : 8" NB
  - Pipe Grade : API 5L Grade 56 and API 5L Grade A.
  - Material: Carbon steel.
  - Wall Thickness : 6.4 mm.
- Continuous tracking of the pig is required during the time of operation.
- The inspection system uses a high energy rare earth magnet (0.5-1Tesla).
- The energy consumption of the tracking system should be minimal.
- The range of pig tracking should be up to 10m initially and then must be scaled to 1km.

Based on the above factors and considerations, it was decided that an **acoustic tracking system** will be developed. The characteristics are:

- The system will use the flow of the gas to generate a sound signal instead of electronic sound generation, making it energy efficient.

- The signal will be generated using a “whistle” like resonator mounted on the PHMR; this will be received by acoustic receivers placed at regular intervals flush with the pipe wall.
- The first resonator that will be tried is a **Helmholtz resonator** that will generate the required sound signal at a desired frequency inside the pipe. This will be tracked by microphones/accelerometers placed along the path of the signal.

4.2.Helmholtz resonator

Image courtesy: Thomas B. Greenslade, Kenyon College, Ohio

Figure 4-1 : Resonators made by Helmholtz.

A Helmholtz resonator or Helmholtz oscillator is a container of gas (usually air) with an open hole (or neck or port). A volume of air in and near the open hole vibrates because of the 'springiness' of the air inside. A common example is an empty bottle: the air inside vibrates when you blow across the top.

The vibration is due to the 'springiness' of air: when you compress it, its pressure increases and it tends to expand back to its original volume. Consider a 'lump' of air at the neck of the bottle. The air jet can force this lump of air a little way down the neck, thereby compressing the air inside. That pressure now drives the 'lump' of air out but, when it gets to its original position; its momentum takes it on outside the body a small distance. This rarefies the air inside the body, which then sucks the 'lump' of air back in. It can thus vibrate like a mass on a spring. The jet of air from your lips is capable of deflecting alternately into the bottle and outside, and that provides the power to keep the oscillation going [9].

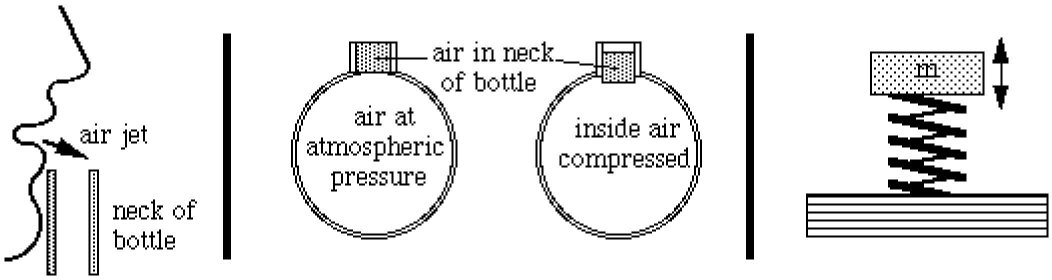


Figure 4-2 : Understand a Helmholtz resonator [9].

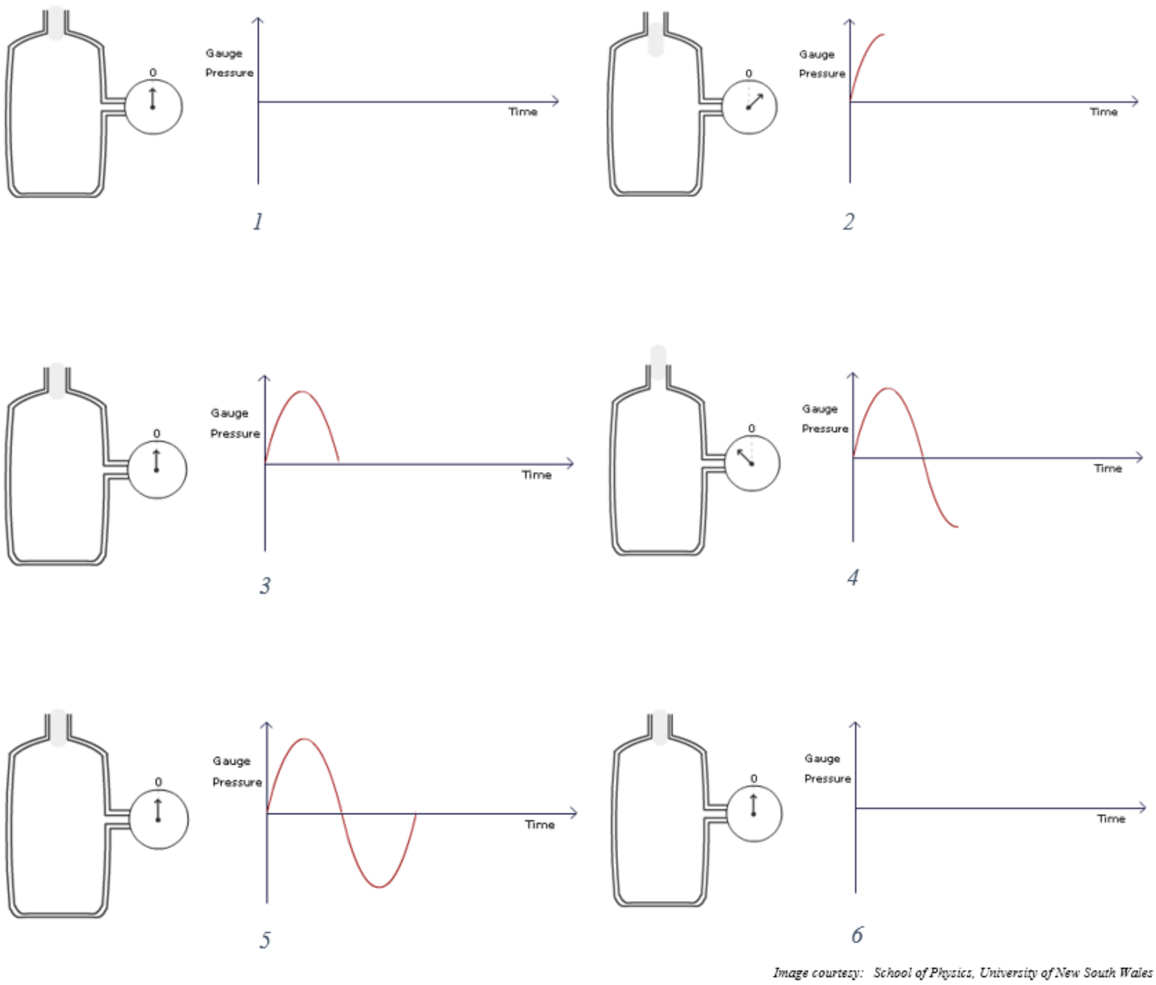


Figure 4-3 : The variation of pressure inside the resonator with vibration of mass plug can be seen [9].

4.2.1. Resonance Frequency

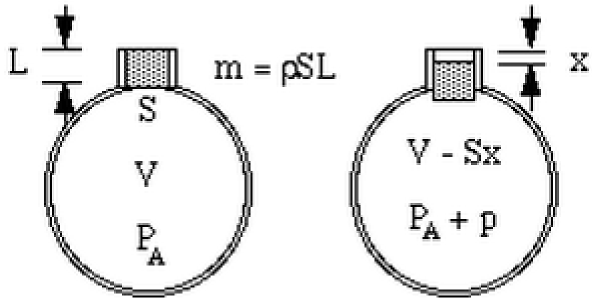


Figure 4-4 : Derivation of resonance frequency [9].

Let the air in the neck have an effective length L and cross sectional area S. Its mass is then SL times the density of air ρ. If this 'plug' of air descends a small distance x into the bottle, it compresses the air in the container so that the air that previously occupied volume V now has volume V − Sx. Consequently, the pressure of that air raises from atmospheric pressure P_A to a higher value P_A + p.

Normally the pressure increase would just be proportional to the volume decrease. That would be the case if the compression happened so slowly that the temperature did not change. In vibrations that give rise to sound, however, the changes are fast and so the temperature rises on compression, giving a larger change in pressure. Technically they are adiabatic, meaning that heat has no time to move, and the resulting equation involves a constant γ, the ratio of specific heats, which is about 1.4 for air. As a result, the pressure change p produced by a small volume change ΔV is just

$$\frac{p}{P_A} = -\gamma\frac{\Delta V}{V} = -\gamma\frac{Sx}{V}$$

Now the mass m is moved by the difference in pressure between the top and bottom of the neck, i.e. a nett force pS, so we write Newton's law for the acceleration a:

$$F = ma \text{ or } \frac{d^2x}{dt^2} = \frac{F}{m}$$

Substituting for F and m gives: $\frac{d^2x}{dt^2} = \frac{pS}{\rho SL} = -\frac{\gamma SP_A}{\rho VL}x$

So the restoring force is proportional to the displacement. This is the condition for Simple Harmonic Motion, and it has a frequency which is 1/2π times the square root of the constant of proportionality, so

$$f = \frac{1}{2\pi}\sqrt{\frac{\gamma SP_A}{\rho VL}}$$

Now the speed c of sound in air is determined by the density, the pressure and ratio of specific heats,

$$c = \sqrt{\frac{\gamma P_A}{\rho}}$$

So we can write:

$$\boxed{f = \frac{c}{2\pi}\sqrt{\frac{S}{VL'}}}$$

`Where,

f: Resonant frequency of the Helmholtz resonator, in Hz.

c: Speed of sound in the medium, in m/s.

S: Cross-sectional area of the orifice, in m^2.

V: Volume of the cavity, in m^3 [9].

L’: Effective length of the stem, in m.

4.2.2. Equivalent length of the neck

When the fluid exits the tube and enters the volume, the acoustic waves disperse and the acoustic pressure drops. However, the waves initially continue along the axis of the tube when they just leave it, and moreover they cannot move into the region occupied by the tube. Consequently, they do not completely disperse immediately as they leave the tube and the immediate region downstream of the tube is therefore still felt by the fluid in the tube where it imposes an acoustic load. In ideal models, this load results in an additional acoustic inheritance corresponding to an effective increase in the length of the tube.

To calculate the effective length of the neck, an additional amount must be added at each end. This amount is related to whether the end of the duct is flanged or unflanged and the radius, R of the orifice.

For a flanged end the end correction is found to be 0.85R. While for an unflanged end the end correction is 0.6R.

I have considered flanged at both ends, taking into consideration the flange when the resonator is mounted on the robot.

$$L' = L_{neck} + 0.85R + 0.85R = L_{neck} + 1.7R$$

Where,

L_{neck} : Actual length of the neck.

R: Hydraulic radius of the neck [10].

4.3. Experiments Performed

The following experiments were performed to study and understand the propagation of sound through the pipe wall using different sources and receivers of sound.

4.3.1. *Experiment 1*

To study and understand the transmission and propagation of sound inside the pipe using:

- Speaker as sound source
- Mice/accelerometer as sound receiver.

Experiment setup:

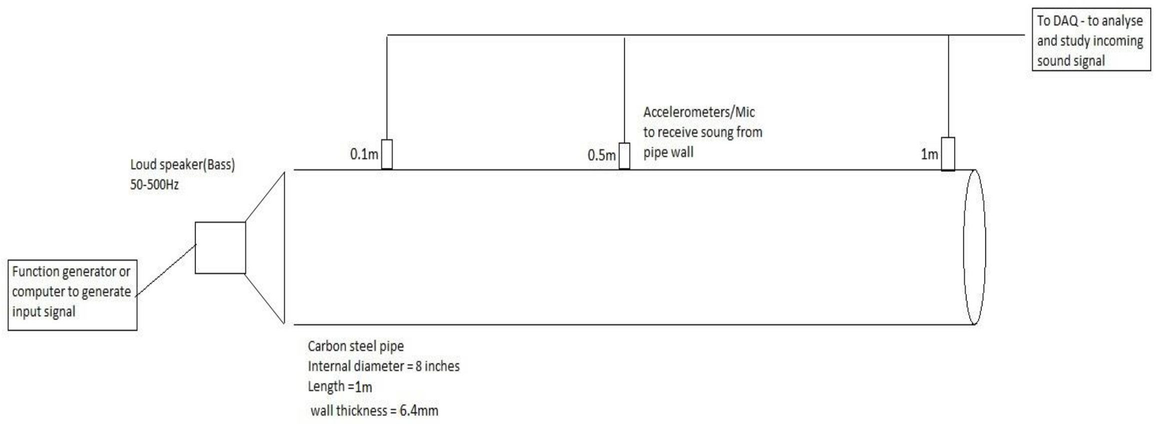


Figure 4-5 : To study and understand the transmission and propagation of sound using a speaker source.

Experiment 1a: To study the acoustic signal generated from a loudspeaker and received from a microphone placed on the pipe wall.

Brief Overview:

- The experiment setup contains a loud speaker (Sub-woofer, Creative A300) at one open end of a 8 inch carbon steel pipe, and a microphone (Logitech Desktop Mic) placed at intervals of 0.1m on the outer surface of the pipe wall.
- The speaker is connected to a function generator, and the mic is connected to a computer and audio signal is recorded.
- A sine wave of amplitude 9.38V and frequency of 50Hz was generated and played form the speaker, the received sound signal was recorded and played.
- The steps were repeated for sound signal ranging from 50-200 Hz and the mic is placed at 10 cm intervals from 0.1 m to 1m, for each sound signal.

Results:

- The sound signals received from the mic were acoustic signals transmitted by air medium and not through the pipe wall as desired.
- The signal generated from the speaker was of low amplitude which experienced high dissipation along the pipe length.

Inference:

Sound propagation is occurring through the air medium and the mic is unable to pick signal transmission form the pipe.

To study the signal propagation through the pipe wall an accelerometer was used on the pipe wall.

Experiment 1b: To study the acoustic signal generated from a loudspeaker and received from an accelerometer placed on the pipe wall.

Brief Overview:

- The experiment setup contains a loud speaker (Sub-woofer, Creative A300) at one open end of an 8 inch carbon steel pipe, and an accelerometer (Dytran instruments, 3041A2) placed at intervals of 0.1m on the outer surface of the pipe wall.
- The speaker is connected to a function generator, and the accelerometer is connected to a computer using NI DAQ and signal is studied using NI LabVIEW.
- A sine wave of amplitude 9.38V and frequency of 50Hz was generated and played form the speaker, the received sound signal viewed on a graph in LabVIEW
- The steps were repeated for sound signal ranging from 50-200 Hz and the accelerometer is placed at 10 cm intervals from 0.1 m to 1m, for each sound signal.

Result:

The accelerometer showed no input signal received from the pipe wall.

Inference:

The sound signal generated by the speaker is being transmitted only by air and no transmission through the pipe wall is being observed.

To study the propagation of acoustic signal through the pipe wall we decided to generate the sound on the pipe wall rather than in air. This was achieved by striking an impact hammer on the pipe wall.

4.3.2. Experiment 2

To study and understand the transmission and propagation of sound through the pipe wall:

- Impact hammer as sound source.
- Mice/accelerometer as sound receiver.

Experiment setup:

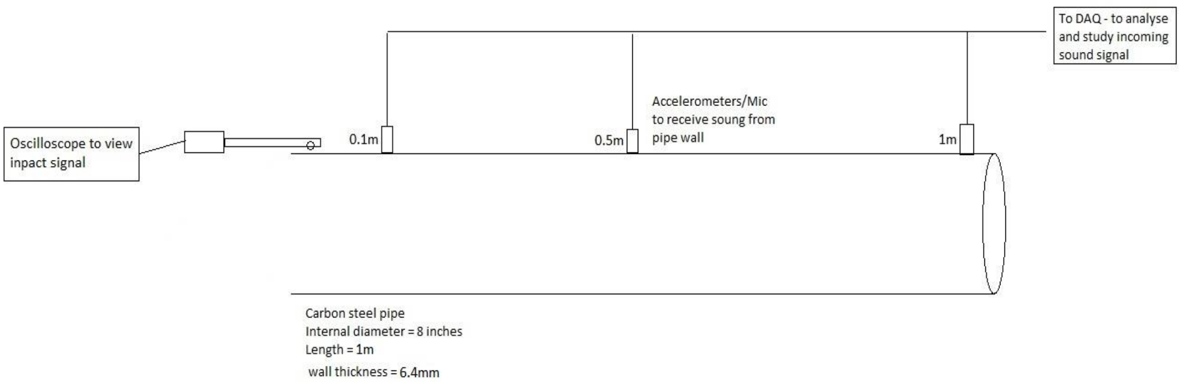


Figure 4-6 : To study and understand the transmission and propagation of sound using an impact hammer.

Experiment 2a: To study the acoustic signal generated from an impact hammer and received from a microphone placed on the pipe wall.

Brief Overview:

- The experiment setup contains an impact hammer (Spranktronics) at one open end of a 8 inch carbon steel pipe, and a microphone (Logitech Desktop Mic) placed at intervals of 0.1m on the outer surface of the pipe wall.
- The speaker is connected to an oscilloscope to study the input given, and the mic is connected to a computer and audio signal is recorded.
- Impacts of 0-100N force were given by hand and the input given was studied using a oscilloscope, the received sound signal from the mic placed at 0.1m from the impact was recorded and played.
- The steps were repeated for the range of impact forces and the mic is placed at 0.1 m intervals from 0.1 m to 1m, for each sound signal.

Result:

- The audio signal received by the mic was sound signals transmitted through air medium.
- No sound signal transmitted through the pipe wall was received by the mic.

Inference:

The mic is incapable of receiving sound signal transmitted through the pipe. It can only receive sound signals transmitted through air medium.

To study the signal propagation through the pipe wall an accelerometer was used on the pipe wall, while the input was given on the pipe wall by the impact hammer.

Experiment 2b: To study the acoustic signal generated from an impact hammer and received from an accelerometer placed on the pipe wall.

Brief Overview:

- The experiment setup contains an impact hammer (Spranktronics) at one open end of a 8 inch carbon steel pipe, and an accelerometer (Dytran instruments, 3041A2) placed at intervals of 0.1m on the outer surface of the pipe wall.
- The speaker is connected to an oscilloscope to study the input given, and the accelerometer is connected to a computer using NI DAQ and signal is studied using NI LabVIEW.
- Impacts of 0-100N force were given by hand and the input given was studied using a oscilloscope, the received sound signal viewed on a graph in LabVIEW.
- The steps were repeated for the range of impact forces and the accelerometer is placed at 0.1 m intervals from 0.1 m to 1m, for each sound signal.

Result:

The audio signal received by accelerometer were inconsistent and of very low amplitude (below 1mV).

Inference:

The sound signal is generated in the pipe wall by the impact hammer but the transmission along the pipe wall is very poor and highly attenuated. The signal is being absorbed by the coating over the pipe.

Conclusions:

From the above experiments the following conclusions were made:

- When acoustic signal of low frequency (below 500Hz) is generated, its attenuation along the air medium in which it is generated is low.
- Acoustic signal transmission from a source in air medium into the pipe made of carbon steel is poor. High attenuation was observed when the sound signal travels from air to carbon steel. Due to this sound source in an air medium cannot be used to transmit sound through the pipe wall over long distances.
- Microphones receive sound signals only from the air medium; they are not designed to receive sound signals transmitted through the carbon steel pipe wall.
- The sound signal generated by the impact hammer was transmitted better through the air medium as compared to the pipe wall in which the vibrations were generated.
- The pipe wall has a coating which absorbs sound signals to a large extent.
- The accelerometer used was not sensitive enough to receive the vibrations generated by the impact hammer.

Based on the above experiments we decided:

- To design a Helmholtz Resonator of resonant frequency 200Hz.
- This resonator will be embedded with the body of the pipe. The sound signal will be generated due to the flow of the fuel that is also propagating the pig.
- The receiver system has not been finalised but the following considerations are bring made:
    - Using a highly sensitive mic place flush with the inner pipe wall surface to receive signals from the fuel flow.
    - Using a highly sensitive mic placed on the outer surface of the pipe wall.
    - Using a piezo electric strip to generate output due to the vibrations of the pipe wall.

4.4. Design of Helmholtz Resonator

4.4.1. Deciding the frequency of the resonator

Acoustics analyses have proved that low frequency sound signals have higher transmission across several media. This means that a signal of low frequency will travel a longer distance when it has to travel through multiple media. This decision was made to increase the transmission of the sound signal from the air medium to the wall of the pipe.

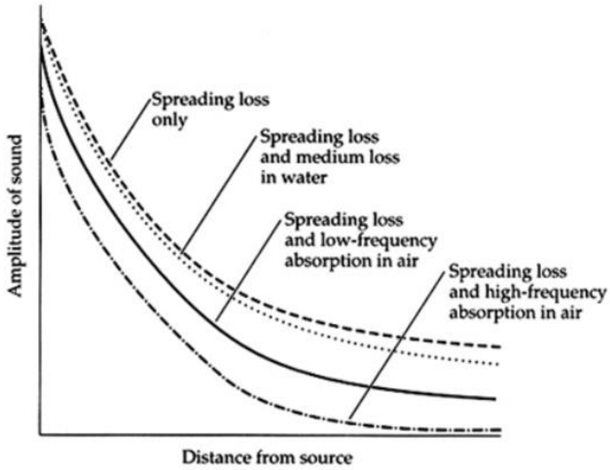


Figure 4-7 : Study amplitude of sound with distance [11].

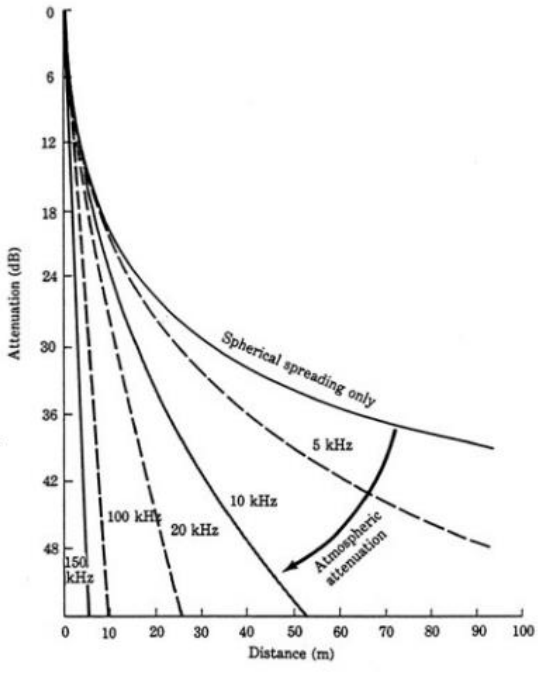


Figure 4-8 : Attenuation of sound with distance [11].

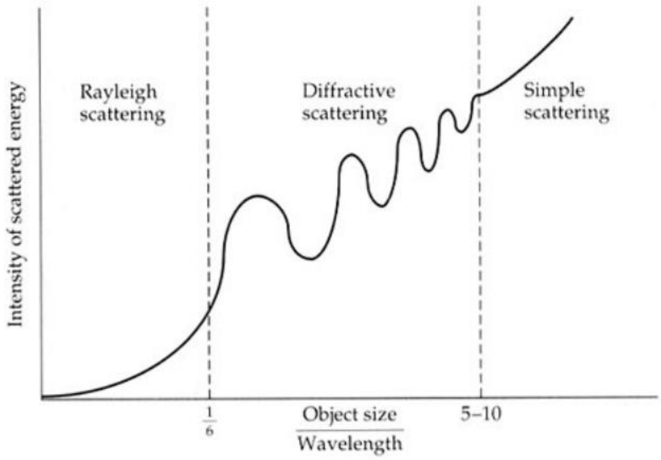


Figure 4-9 : Scattering of sound with change in wavelength [11].

From the above graphs the following conclusions were made:

- The wavelength of the sound must be more than 5 times the diameter of the pipe and larger than the dimensions of the resonator
- Lower frequency acoustic signals have low attenuation while travelling in air medium

The nature of signal to be generated was decided as an acoustic signal of **frequency 200Hz**, if the attenuation will be high from practical experimentation we will design for 150Hz and 100Hz.

4.4.2. Deciding the Geometry

Based on the following analysis by R.C. Chanaud (1994) [12], where comparisons with respect to agreement of experiment data with respect to frequency calculated by Rayleigh equation were made.

The deviation of the Rayleigh equation from the present equation depends on the ratio of certain dimensions to the characteristic lateral dimension of the cavity. The deviation is greater when the condition in the table is violated. Deviation is minimum for a thin, small orifice on a cubical cavity. Orifice position is the most restrictive condition

Rayleigh equation	1%	5%
Deep cavity	$d/a > 2{\cdot}2$	$d/a > 3$
Wide cavity	$d/a < 0{\cdot}88$	$d/a < 0{\cdot}66$
Asymmetric cavity	$b/a > 1{\cdot}5$	$b/a > 2$
Orifice size	$r_o/a > 0{\cdot}35$	$r_o/a > 0{\cdot}65$
Orifice shape	Not significant	Not significant
Orifice position	$y_o/a > 0{\cdot}08$	$y_o/a > 0{\cdot}25$

Figure 4-10 : Effect of geometry on resonant frequency [12].

The observations made based on Chanaud's analysis are:

- The geometry of the orifice whether square or round doesn't have an effect on the frequency.
- The orifice must be centrally and symmetrically located on the cavity.
- The cavity gives better results when its geometry is symmetrical in width and depth.

4.4.3. Deciding neck length

Based on research by Asami Nishikawa [15] lower neck length has more agreement between the experimental and theoretical data.

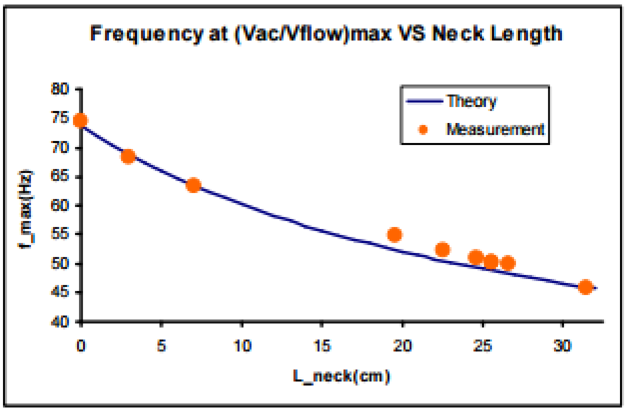


Figure 4-11 : Study effect of neck length on frequency [13].

Based on the analysis and different studies along with consideration for implementation in the developed pig, the following parameters were finalised for the desired resonator:

- Orifice will be circular in cross-section and orifice diameter will be 20mm.
- Neck length will be 50mm, neck will be of straight cylindrical form.
- Neck will be centrally and symmetrically placed on the cavity.
- The resonant frequency of the resonator will be 200Hz.
- The shape of the cavity will be spherical, if problems arise due to difficulty in manufacturing a cubical cavity, due to its symmetry, will be chosen.
- The radius of the cavity was calculated using Rayleigh's equation, and was found to be 43.5mm.
- The resonator will be made of brass or bell metal due to its favourable acoustic properties.

Based on the above parameters a suitable resonator was designed in CATIA V5 and simulated on COMSOL Multiphysics 4.4 software for cross verification before approval for manufacturing.

Figure 4-12 : 3D model of resonator design

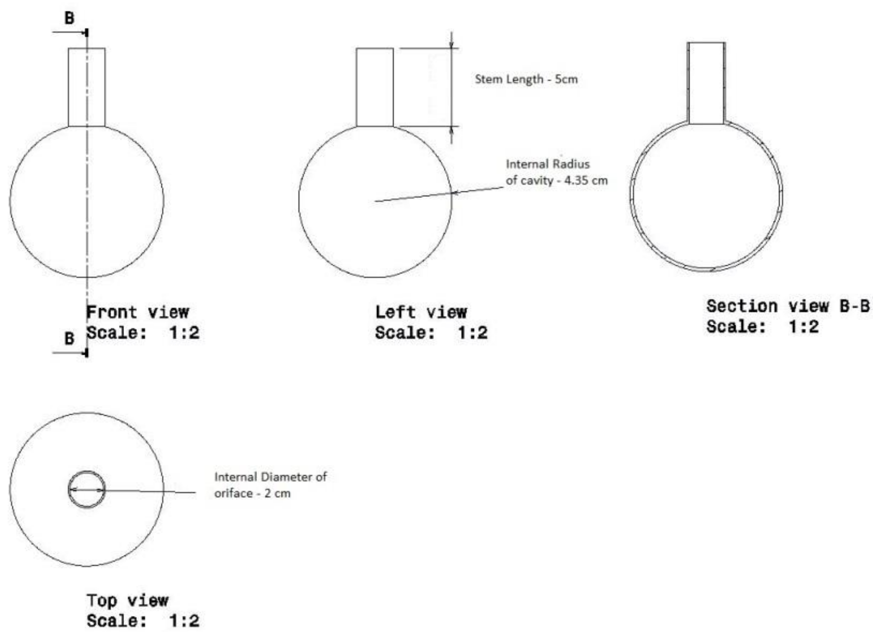


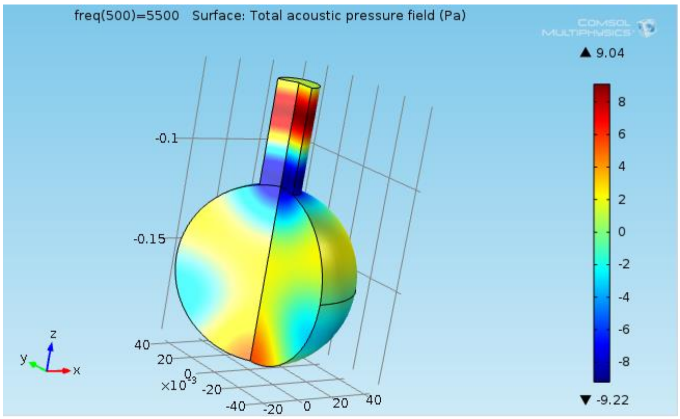
Figure 4-13 : Draft views of the resonator

4.4.4. Simulation of resonator design

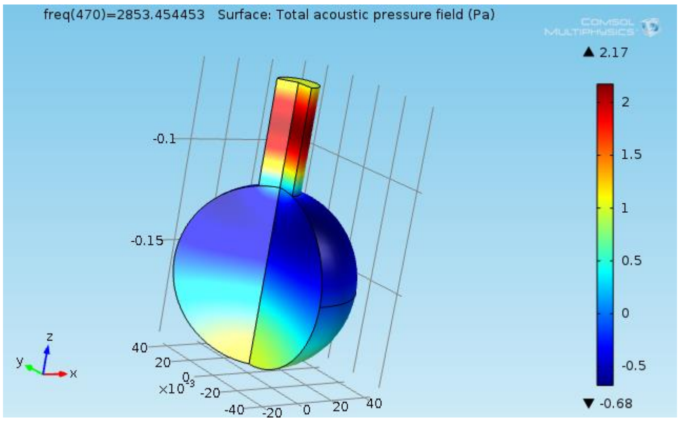
To verify the resonant frequency using simulation, the fluid inside the resonator (air) needed to be modelled, as the vibrations due to which the sound is generated is because of the fluid medium. This fluid volume was meshed with suitable meshing parameters, the various properties of the fluid and the boundary conditions were fed in COMSOL and the simulation result showed pressure distribution plots for excitations of different frequencies.

With reference to the research by Daniel O. Ludwigsen et. el. (2006) [14]analysing the pressure plots of a resonator simulation, which shows typical characteristics when excited at its resonant frequency. Due to the lumped-mass approximations of a Helmholtz resonator, the simulation shows that the pressure in the cavity will be acceptably uniform, and the air in the neck will oscillate as a single mass. As the bulk of the bottle is red, there is fairly uniform pressure. And the mass plug in the neck will exhibit low pressure.

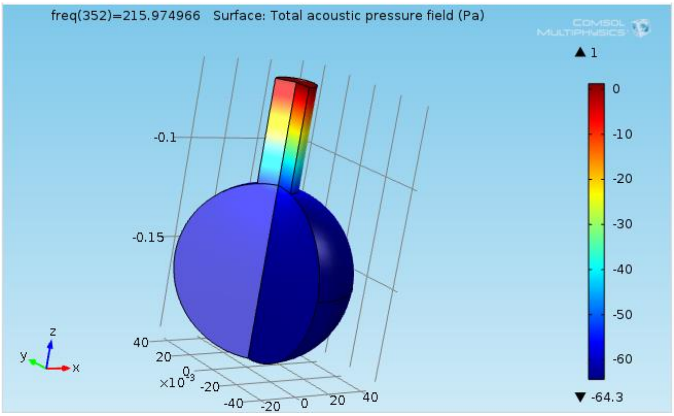
To simulate the resonator in COMSOL, the air present in the cavity was modelled and then it was excited at various frequencies to study the variations in the pressure map and hence identify the resonance frequency. Simulations were carried out and the following results were obtained:



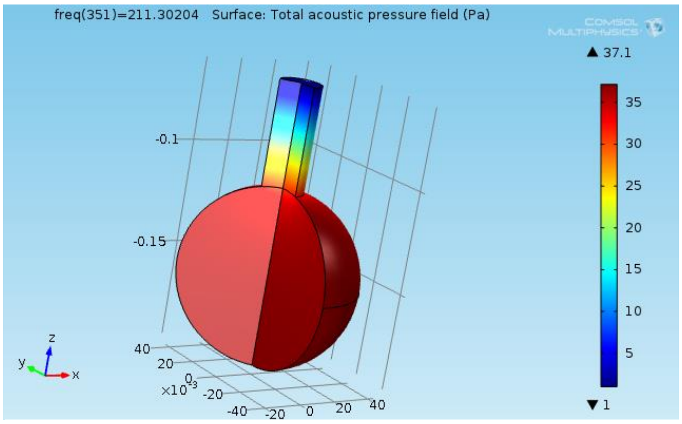
14(a)



14(b)



14(c)



14(d)

Figure 4-14 : Simulation of resonator design in COMSOL at different excitation frequencies. (a) 5500Hz, (b)2853Hz, (c)215Hz, (d)211 Hz. The resonant frequency is observed to be 211Hz

Simulation Results

The simulation results show a shift in the pressure plot at when excited at 211.3 Hz. It can be seen that the cavity, which represents the spring-damper in the lumped–mass mechanical equivalent, shows uniform and high pressure. The pressure gradually reduces in the neck till the outer opening.

This agrees will the previous study and the results are prove that the designed model with resonate at a frequency around 200Hz, will an error of 10 Hz, which is within acceptable error limits.

4.4.5. Redesigning the Resonator

It was decided that due to its acoustic properties, the resonator will be made from brass. But due to complexity in manufacturing a spherical cavity from brass, the design was modified to a cubical cavity. The dimensions of the new design:

- A cubical cavity of internal side length of 70mm.
- Orifice will be circular in cross-section and orifice diameter will be 20mm.
- Neck length will be 50mm, neck will be of straight cylindrical form.

The geometry was decided keeping in mind to main the theoretical resonance frequency at 200Hz.

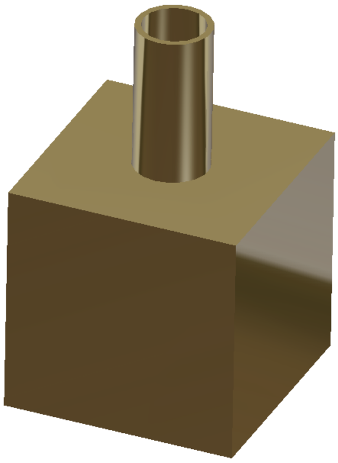


Figure 4-15 : 3D brass render of resonator with cubical cavity

Similar to the previous resonator modal with spherical cavity, the air medium inside this resonator was modelled and simulation was carried out on COMSOL to identify the resonant frequency. The resonant frequency was identified based on the simulation analysis by Daniel O. Ludwigsen et. el. (2006) [14], to be 215Hz.

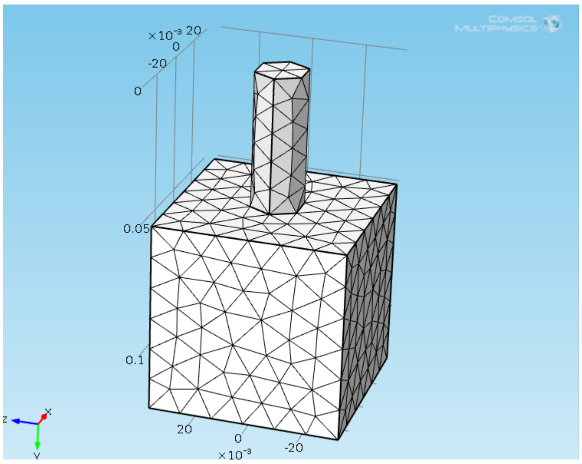


Figure 4-16 : Meshing of the fluid in the resonator

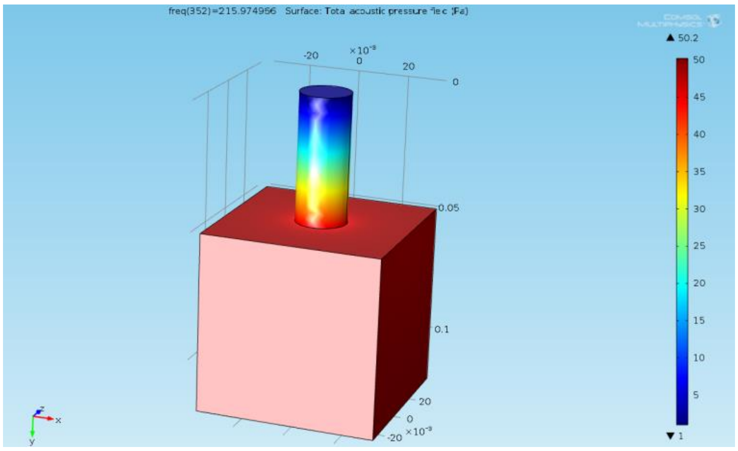


Figure 4-17 : Simulation shows resonance at 215Hz.

Figure 4-18 : Resonator made from brass

Once the manufactured resonator was received, it was tested to analyse the frequency of the sound generated. To do this, the resonator was gently blown with air at a small angle (<15 deg.) to the orifice using my mouth. The sound generated was received by a good quality sensitive microphone (Logitech) and the signal received was analysed on LabVIEW.

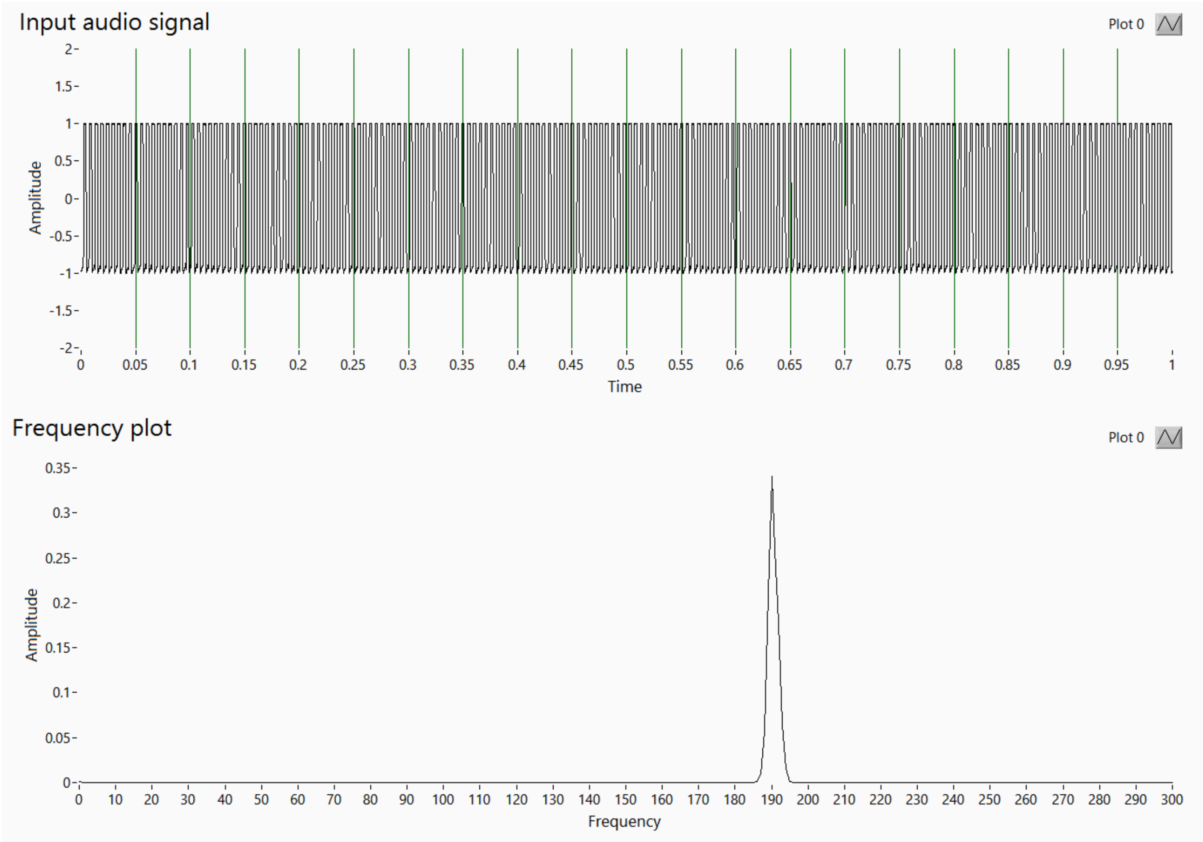


Figure 4-19 : FFT analysis of sound signal produced by the resonator

On the received sound signal, FFT was carried out to study its frequency components.

From the received audio signal and the FFT graph it can be seen clearly that the resonator produces a pure single frequency sound, with frequency between 190 and 200Hz.

Summary

The characteristics of a Helmholtz resonator including its resonance frequency and geometry were decided. A resonator of 200 Hz was designed with 20mm orifice diameter and 50mm neck length. Both spherical and cubical cavity were designed, but due to manufacturing limitations, a resonator with a cubical cavity of 70mm side length was manufactured. The designed resonators were simulated on COMSOL to identify the resonant frequency and study the pressure distribution when excited at that frequency. The model was manufactured using brass and its acoustic output when excited with a gentle blow was analysed using LabVIEW and the theoretical and practical observation were compared and found to be within 10 Hz of the desired value.

4.4.6. *Characteristics of air jet to excite the resonator*

To excite the resonator to produce a sound of highest amplitude the dependence of three characteristics of the air jet were analysed:

1. Jet velocity.
2. Nature of jet.
3. Angle of impact of jet.

To understand the influence of these parameters on resonance, several experiments were carried out by producing an air jet using three different types of jet sources and the sound produced was majorly analysed by listening to the sound.

The sources of sound were:

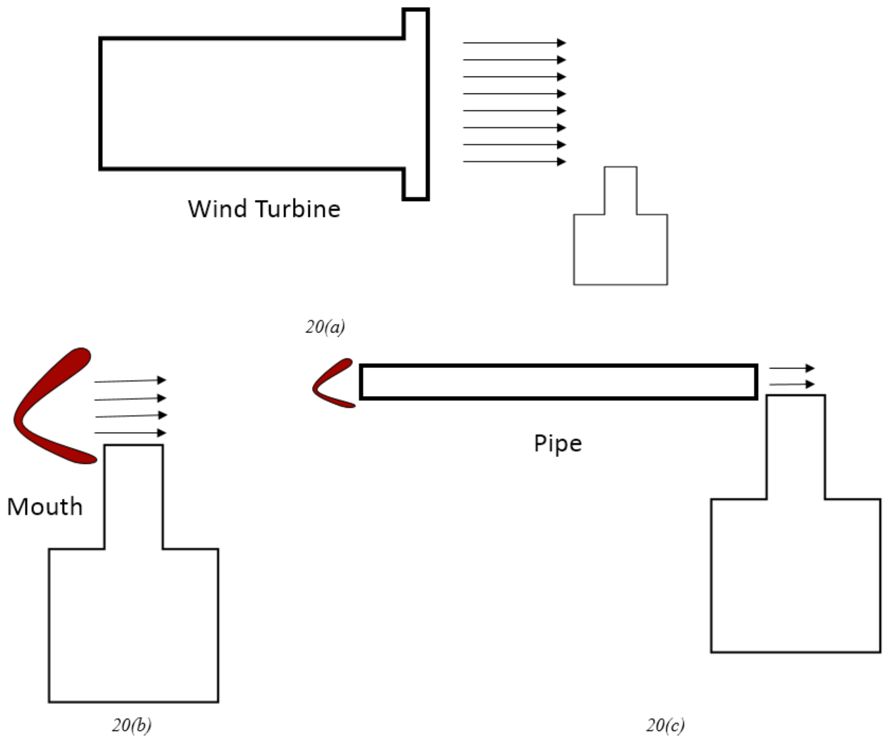


Figure 4-20 : Jet sources; (a) wind turbine, (b) mouth, (c) pipe.

Each characteristic was individually analysed and the influence of the factors was analysed and the results are explained. While testing the influence of one, the other two factors were kept constant.

Jet Velocity

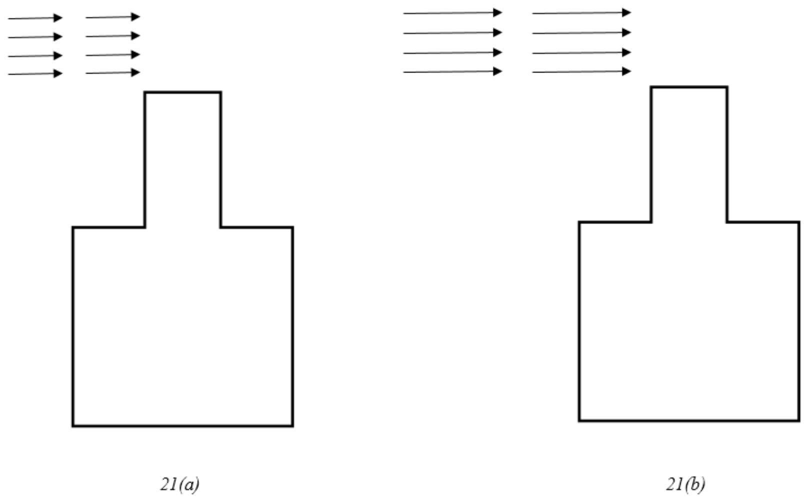


Figure 4-21 : Influence of varying jet velocity; (a) low, (b) high.

During the tests the jet velocity was gradually increased, and in each of the three sources it was observed that the amplitude of sound produced gradually increases and it's reached a peak and starts decreasing. For very high velocities (> 50 m/s) the next harmonic frequency was produced.

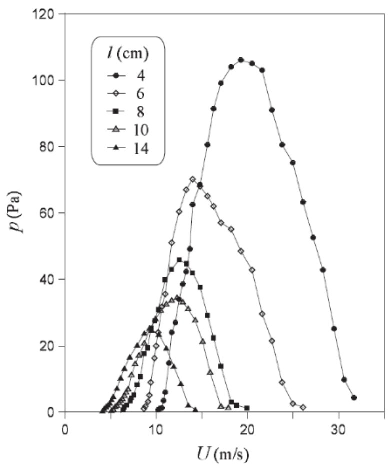


Figure 4-22 : Oscillation pressure amplitude versus jet velocity for resonator with different cavity lengths [15].

Results from research by M. Meissner (2005) [15] and, Roset Khosropouar and Peter Millet (1990) [16] carried out to study the response of a Helmholtz resonator when it is excited by an air jet also support the observations made here.

In *Figure 4-22* from M. Meissner (2005) [15]the highest oscillating pressure, which signifies the resonance condition, for different cavity lengths is observed at different jet velocities, based on the resonator geometry.

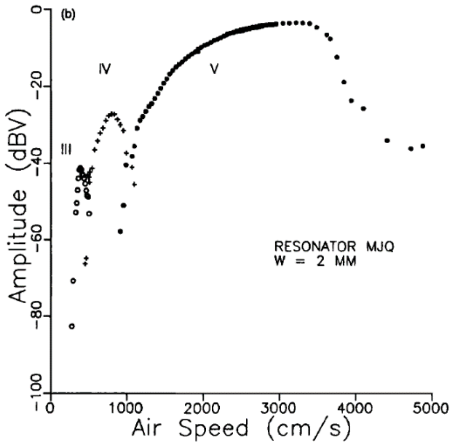


Figure 4-23 : Output amplitude versus air jet speed [16].

In *Figure 4-23* from Roset Khosropouar and Peter Millet (1990) [16], the sound amplitude variation with increase in jet velocity can be seen. The amplitude reaches a maximum at a particular jet velocity depending on the geometry of the resonator.

From the tests we concluded that to excite the resonator at the optimal frequency with the maximum amplitude, a low jet velocity will be needed. To calculate the optimal velocity range, numerical calculations will be needed, which will be performed in the next stage of the research.

Nature of jet

To understand the type of flow, the uniformity of the flow that is required to obtain optimum results was observed.

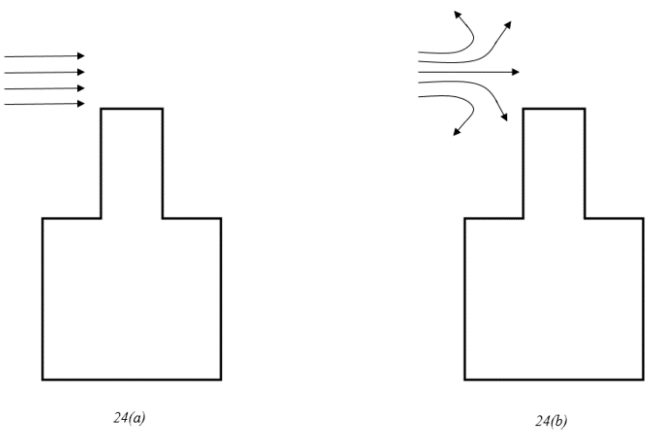


Figure 4-24 : Influence of nature of jet; (a) uniform, (b) non uniform.

A uniform air jet with laminar air flow was observed to produce the maximum sound amplitude. Non-uniform and turbulent jets either produced a very weak sound or did not produce sound at all.

Angle of impact of jet

The angle at which the air jet hits the mouth of the resonator was observed to be important and finding the optimum angle is necessary to produce sound of maximum amplitude.

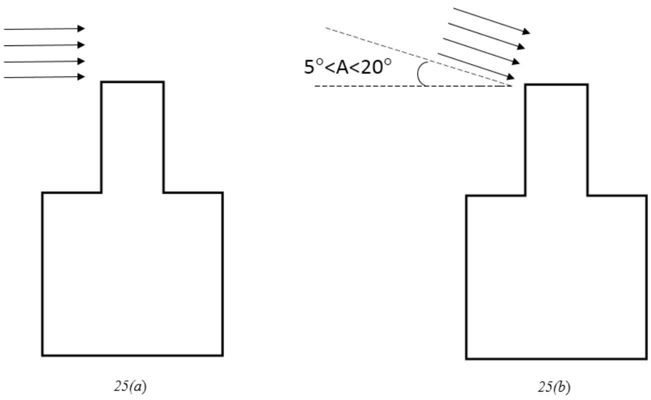


Figure 4-25 : Influence of angle of impact of jet.

By blowing at the resonator at different angles, it was observed that a small angle of impact between 5 and 20 degrees produced the maximum sound and angles of impact outside this range generated a very weak sound.

Summary

To obtain the optimum excitation, a high amplitude sound of required frequency, the ideal air jet must have the following characteristics:

- Low velocity (depending on geometry).
- Uniform laminar flow.
- Small angle of impact (5°<A<20°).

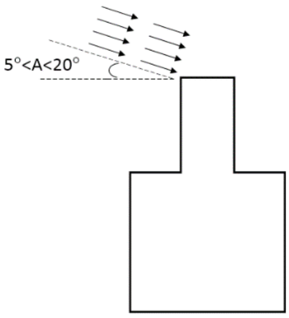


Figure 4-26 : Ideal jet flow.

4.4.7. Design changes and Simulation

Natural gas a medium

After the validity of the manufactured resonator to resonate close to the theoretical frequency, the medium was changed to natural gas to analyse the effect of change in medium on resonance.

The various specification of natural gas are:

- Density: 27.412 kg/m^3 (source: GAIL)
- Operating pressure in the pipe: 28.3 kg/cm^2 (source: GAIL).
- Operating temperature: 40°C (source: GAIL).
- Ratio of specific heat: 1.27

From the data the velocity of sound in the medium was found to be: 358.3 m/s, this data was modified and fed into the COMSOL simulator.

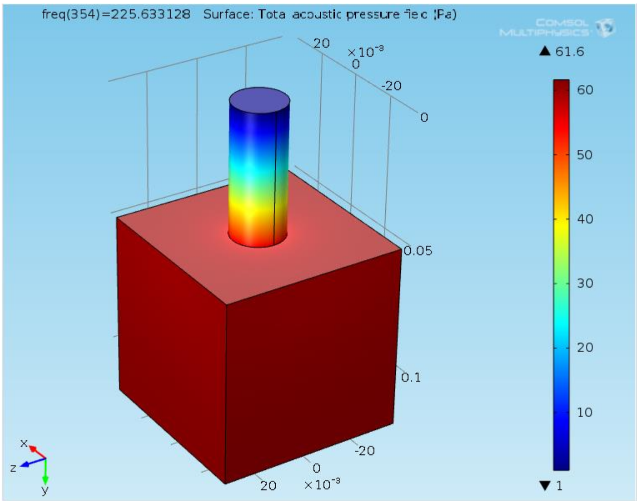


Figure 4-27 : Simulation with natural gas as fluid.

Observation

It was observed that with the change in medium the resonance frequency elevated to 225Hz. The increase in speed of sound and characteristics of the natural gas medium caused the shift in resonance. This data and observation can be used to design a resonator for use in the pipeline system with natural gas.

Using Smart Material to control resonance

To control the resonant frequency of the resonator, variations with the neck of the resonator made up of smart material were designed. COMSOL simulation were analysed to study their effect on resonance.

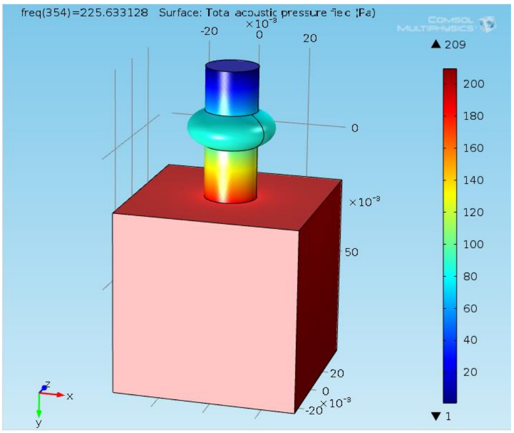
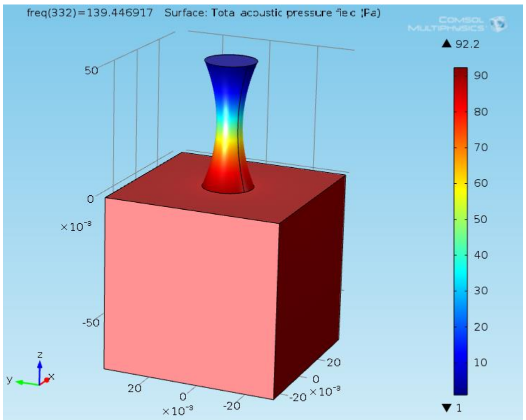
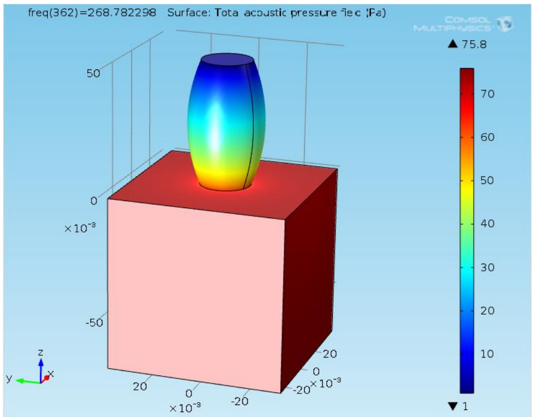


Figure 4-28 : Simulation of resonance with an ellipsoid bulb in the neck.

As seen in *Figure 4-28*, the resonator was designed with an ellipsoid build in the neck. The position and shape of the bulb is controlled sing properties of smart materials in order to control the resonant frequency. The resonance frequency was 225Hz.



29(a)



29(b)

Figure 4-29 : Simulation of resonators with concave (a) and convex (b) necks.

As we can see in *Figure 4-29*, the neck is made of smart materials which allows change of shape from a concave profile to a convex profile. This flexibility will allow change in resonance over a wide range of frequencies.

The resonance frequencies are: 139Hz for (a) and 268Hz for (b).

4.5. Wireless location monitoring using ZigBee Protocol

As a part of Phase I of the project, it was required to develop a wireless system for the motion tracking of the PHMR. For this, a setup based on ZigBee protocol was developed.

4.5.1. ZigBee

ZigBee is a specification for a suite of high-level communication protocols based on an IEEE 802.15.4 standard. It is typically a low power, low data rate communication used in applications that require long battery life.

4.5.2. Setup

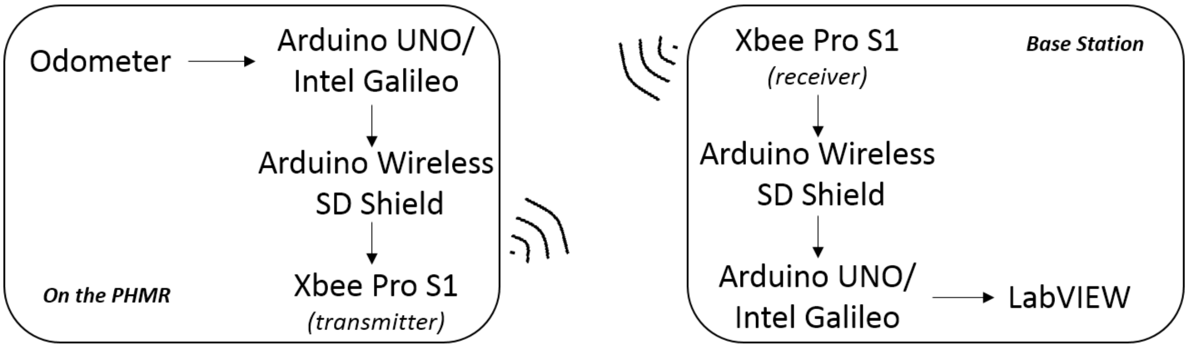


Figure 4-30 : Setup – Wireless location monitoring.

The system consisted of the following components:

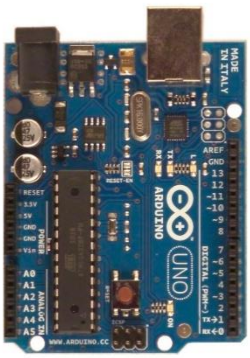
1. Odometer made using a wheel, LED, and LDR.
2. Microcontrollers (Arduino UNO and Intel Galileo).
3. Arduino Wireless Shield to connect Xbee module to the Microcontroller.
4. Xbee Pro S1 PCB antenna– ZigBee communication module.
5. LabVIEW interface.
6. Power source on PHMR to power odometer and microcontroller.

4.5.3. Selection of components

1. Xbee Pro S1 PCB antennaZigBee module was chosen due to:
    - Ease of configuration and use with Arduino Uno and Intel Galileo boards.
    - Suitable range of transmission of about 1.6km.
    - Low power consumption.
    - Contains a PCB antenna, making it easier to install and use

Figure 4-31 : Xbee Pro S1 PCB antenna module.

2. For the microcontroller, 2 boards were selected: Arduino Uno R3 and Intel Galileo Gen 2. The Arduino Uno R3 was selected due to its ease of use and compatibility with NI LabVIEW. Intel Galileo boards was chosen as an alternative to the Uno due to:
    - Higher processing power.
    - Ease of use and compatibility with Arduino software and hardware, and also with LabVIEW.
    - Presence of multiple serial ports which will be useful for efficient data transmission without loss or lag.



32(a)

32(b)

Figure 4-32 : Microcontrollers; (a): Arduino UNO R3, (b): Intel Galileo Gen 2.

The setup was made and tested with both, Uno and Galileo, at the receiver and the transmitter end. At the transmission end both the boards performed equally well. At the receiver end the output on LabVIEW interface from the Galileo boards was better than the Uno. It was observed that the output from the Uno board viewed on LabVIEW inherited a lag which was absent in the output from the Galileo board. This was due to the fact that the Uno board had a single serial port which was being used for communication with the Xbee module and the LabVIEW VI, while the Galileo boards has multiple serial ports, which are independently used to communicate with the Xbee module and the LabVIEW VI.

3. The Wireless shield was Arduino Wireless SD shield, due to its easy compatibility with the Xbee module, Uno and Galileo board. It also has an on-board SD card slot which was used to store data from the other sensors on the robot.

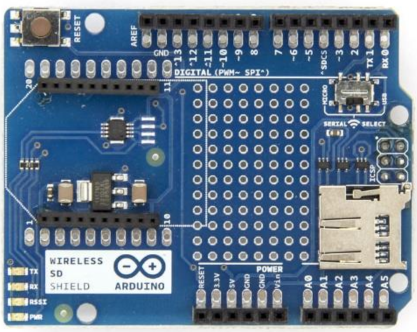


Figure 4-33 : Arduino Wireless SD Shield.

4. LabVIEW was selected as the software for data acquisition from the receiver microcontroller board and to display the data suitably in a graphical format due to its compatibility with Uno and Galileo and the ease of developing a GUI to display the movement of the robot in the pipe.
5. For the odometer, a wheel with holes with an LED on one side and a LDR on the other side was used.

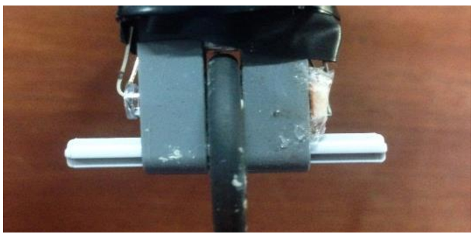


Figure 4-34 : Odometer assembly. Wheel contains LED on one side and a LDR on the other.

4.5.4. Initial System Configuration

To use the setup for location monitoring, the Xbee modules and the microcontrollers need to be configuration.

1. The Xbee Pro S1 module may be used without configuration. To ensure reliable operation, they can be configured to act as receiver and transmitter using the XCTU software. For this, the Xbee modules are mounted on the Uno board using the wireless shield and the steps as given in the XCTU software are to be followed to setup one Xbee module as the transmitter and the other as the receiver.

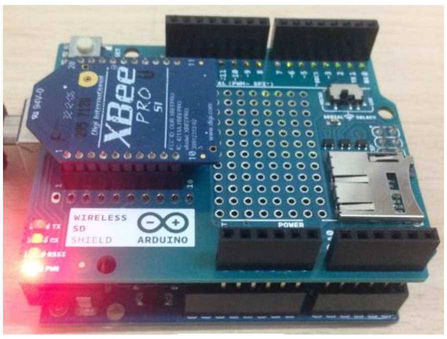
The wireless SD shield has an on-board switch labelled Serial Select. It determines how the Xbee's serial communication connects to the serial communication between the microcontroller and USB-to-serial chip on the Uno/Galileo board.

When in the Micro position, the wireless module will communicate with the microcontroller. Data sent from the microcontroller will be transmitted to the computer via USB as well as being sent wirelessly by the wireless module. With the switch in the USB position, the module can communicate directly with the computer. The microcontroller on the board will be bypassed.

The Uno/Galileo code is uploaded with the switch in the USB position and then it is toggled to the micro position to transmit the data from the odometer to LabVIEW.

2. The Xbee modules are mounted onto the slots provided on the wireless SD shield, which is further mounted on the Uno/Galileo board.
3. Once the Xbee modules are ready, the Uno board is uploaded with the code to receive the data from the odometer and to transmit it from the Xbee transmitter mounted on it. And the Galileo board is uploaded with the code to receive the data form the Xbee module and transmit it to the LabVIEW VI.

35(a)



35(b)

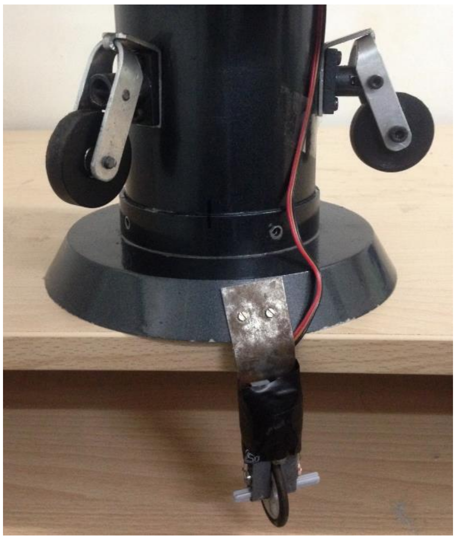
Figure 4-35 : Complete controller systems. (a)Receiver Galileo board with Xbee module, (b) Transmitter Uno with Xbee module.

4.5.5. Working of the system

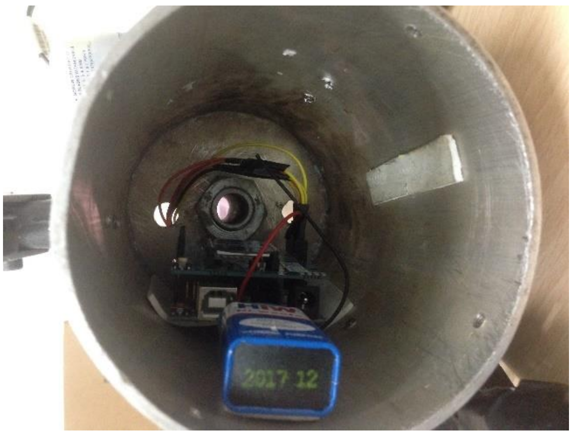
1. The odometer wheel is attached to the frame of the robot. As the robot moves inside the pipe the data from the odometer (LDR) is sent to the microcontroller (Uno/Galileo).
2. The data received by the microcontroller is sent to the Xbee transmitter through the wireless shield. The communication between the Xbee module and the Uno takes place from the serial port on the microcontrollers. The data written by the microcontroller on its serial port is read by the Xbee transmitter module for transmission.

   The Uno board, Xbee transmitter and the odometer are powered using an onboard battery on the robot.

3. The data received by the Xbee transmitter is transmitted via RF waves using ZigBee protocol, this data is received by the receiver Xbee.
4. The receiver Xbee is mounted on the Galileo board using the wireless SD shield. The data received by the Xbee receiver is sent to the serial1 port of the Galileo board. The Galileo board reads the data at the serial1 post and writes appropriate data to the serial0 port to be later read by the LabVIEW VI.
5. LabVIEW reads the serial0 port of the Galileo boards and displays the data which is the distance travelled be the robot on its front panel.



36(a)



36(b)

Figure 4-36 : Odometer system; (a) odometer assembled on the back plate, (b) transmission module inside the PHMR.

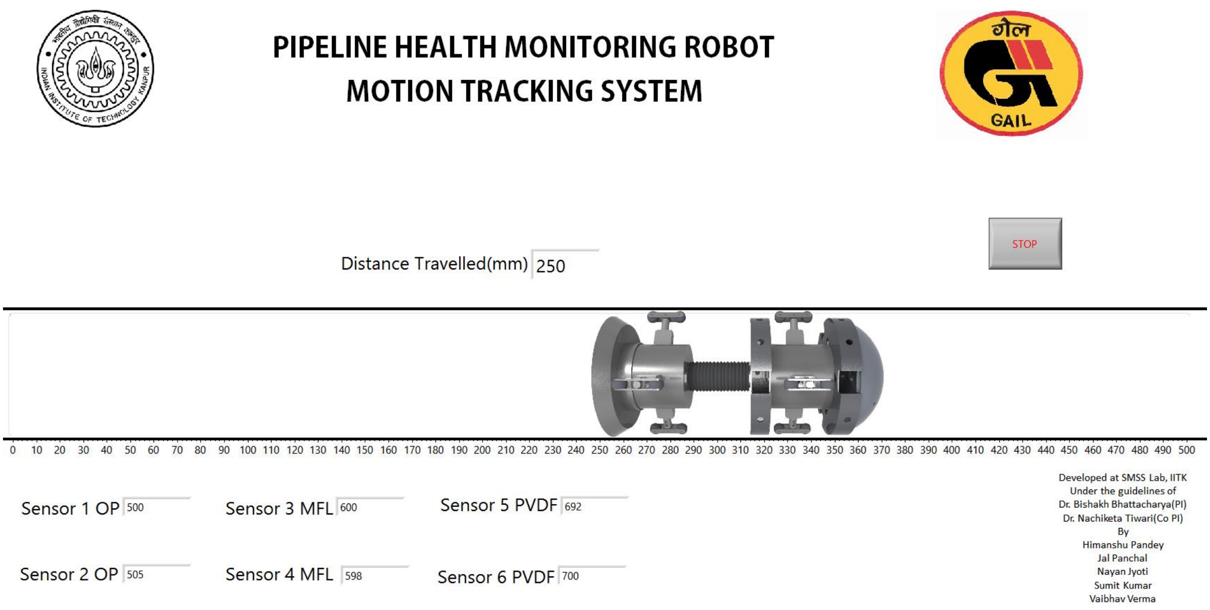


Figure 4-37 : Front Panel - PHMR motion tracking system.

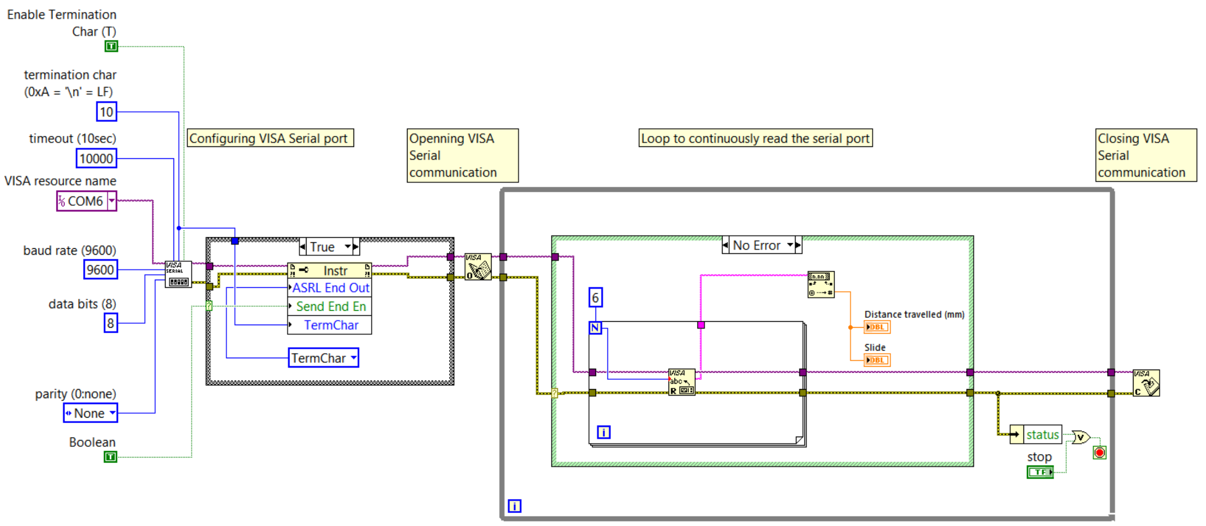


Figure 4-38 : Block Diagram - PHMR motion tracking system.

Summary

To monitor the location of the PHMR a system was developed to wirelessly transmit distance travelled by the robot from one end of the pipe. In the system, an odometer was mounter on the body of the robot which was in contact with the inner wall of the pipe and moved along with the robot. The motion data was then transmitted to the base station using ZigBee communication protocol, with the help of a Xbee module and Arduino Uno board. At the base station, the data is received by a Xbee receiver module and then sent to LabVIEW via an Intel Galileo board. The LabVIEW VI displays the movement of the robot. Repeated tests were carried out with successful location monitoring of the PHMR.

Chapter 5 RESULT ANALYSIS

Based on the experiments performed, simulations and tests carried out, the following analysis of the results obtained have been made:

1. When a sound signal is generated inside a pipe in the air medium, the signal propagates along the length of the pipe in the air medium, and no signal/very weak signal was detected to travel through the pipe walls. Sound generated from the pipe walls was found to travel through the air medium and the signal propagation through pipe walls was negligible or absent.
   From these results, in order to develop an acoustic tracking system, the sound signal must be generated in the air medium (or and gas) and the signal must be sensed also from the air (or gas) medium.
2. A Helmholtz resonator of desired resonance frequency can be reliably designed using the Ryleigh formula for resonance. The surface are of the orifice, neck length, volume of the cavity, and the speed of sound in the medium influence the resonance of the resonator. The influence of these factors can be analysed using COMSOL simulations.
3. To generate a single frequency sound of high amplitude the resonator must be excited with an air jet of low velocity, uniform, laminar flow, and at a small angle to the mouth of the resonator. This frequency changes with the change in medium from air to natural gas. The geometry of the neck of the resonator can be modified to change its resonance frequency.
   From these results, a Helmholtz resonator suitably mounted on the PHMR can be used to generate a pure, single frequency sound, which further be received by sensors kept inside the pipe wall at regular intervals. This system can successfully be used to track the movement of the PHMR inside the pipe.
4. The setup using wireless communication using ZigBee protocol can be used to track the live motion of the PHMR for short distances (below 1km). It is important to use a Galileo board at the receiver end to display real time tracking on the LabVIEW VI.

Chapter 6 CONCLUSION AND SCOPE OF FUTURE WORK

The project was aimed to design a complete system to track the motion of the pig, during operation, inside a pipe. The various mechanisms for motion tracking of a pig were studied and an acoustics based system was identified suitable for given scenario. It was found that sound generated inside the pipe can be sensed by sensors placed inside the pipe wall. Keeping this in mind, a Helmholtz resonator of 200Hz was designed, simulated and manufactured to generate the sound signal, using the flow of air (or gas), from the PHMR during operation. The characteristics of the air jet required to produce such a sound signal of high amplitude was also studied.

To track the motion of the PHMR over short travel distances (10m), a wireless tracking system was developed using ZigBee protocol. The motion of the robot was successfully displayed on LabVIEW.

The work done on the project can be expanded and developed further in future, in the following ways;

1. Testing the dependence of material of resonator in its performance and selecting a light material for manufacturing.
2. To design a mounting to control the nature of jet hitting the mouth of the resonator.
3. To develop a sensor system to receive the sound signals inside the pipe to record motion of the robot.
4. To further develop the wireless tracking system to enable remote control of system from base station.

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