Master's Thesis

Master in Telecommunications Engineering

Study and Monitoring of Steam Traps

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CERTIFICA:

Que el projecte presentat en aquesta memòria de Treball Final de Master ha estat realitzat sota la seva direcció per l'alumne *Mahin Anwar*.

I, perquè consti a tots els efectes, signa el present certificat.

Bellaterra, *02 de Setembre de 2019*

Signatura: *Joan Oliver Malagelada*

Resum:

Els sistemes de vapor estan dissenyats amb trampes de vapor per eliminar la condensació de les canonades per protegir els equips de la planta i permeten un funcionament eficient dels equips i processos de la planta. Quan fracassen, hi ha un impacte significatiu. Causen danys físics a l'equip i afecten molt el cost de les operacions. El mètode tradicional de comprovació d'aquestes trampes és contactar amb un tercer per venir i fer auditories manuals. Aquestes auditories consisteixen a utilitzar el nivell i la temperatura d'ultrasons de la trampa de vapor per determinar una condició de les trampes. Aquest mètode té inconvenients en tant que només mira una captura de pantalla de l'operació i, per tant, no pot ser un bon pronòstic de l'estat del parany. El problema que hi ha en aquest moment és que no hi ha sistemes disponibles que puguin supervisar de forma autònoma la trampa de vapor eliminant la necessitat d'un tercer. Això estalviarà molts diners a la planta i serà rendible. Amb l'arribada d'un sistema programable de baixa potència en xips, ara és possible supervisar la salut de les trampes de vapor d'una manera efectiva i rendible. L'objectiu d'aquest projecte és desenvolupar un algorisme o un sistema que pugui supervisar aquestes trampes de vapor i detectar falles en elles eliminant així el requisit d'un tercer i reduint el cost operatiu de les plantes.

Resumen:

Los sistemas de vapor están diseñados con trampas de vapor para eliminar la condensación de las tuberías para proteger los equipos de la planta y permitir la operación eficiente de los equipos y procesos de la planta. Cuando fallan, hay un impacto significativo. Causan daños físicos al equipo y afectan en gran medida el costo de las operaciones. El método tradicional de verificar esas trampas es contactar a un tercero para que ingrese y realice auditorías manuales. Esas auditorías consisten en utilizar el nivel ultrasónico y la temperatura de la trampa de vapor para determinar la condición de las trampas. Este método tiene inconvenientes ya que solo mira una instantánea de la operación y, por lo tanto, no puede ser un buen predictor de la condición de la trampa. El problema que existe en este momento es que no hay sistemas disponibles que puedan monitorear de manera autónoma la trampa de vapor eliminando la necesidad de un tercero. Esto ahorrará mucho dinero a la planta y será rentable. Con el advenimiento del sistema programable de baja potencia en chips, ahora es posible monitorear la salud de las trampas de vapor de una manera rentable y eficiente. El objetivo de este proyecto es desarrollar un algoritmo o un sistema que pueda monitorear estas trampas de vapor y detectar fallas en ellas, eliminando así el requisito de un tercero y reduciendo el costo operativo de las plantas.

Summary:

Steam systems are designed with steam traps to remove condensation from the piping to protect plant equipment and allow the efficient operation of plant equipment and processes. When they fail, there is a significant impact. They cause physical damage to the equipment and greatly affect the cost of operations. The traditional method of checking those traps is to contact a third party to come in and do manual audits. Those audits consist of using ultrasonic level and temperature of the steam trap to make a determination on the condition of the traps. This method has drawbacks in that it only looks at a snapshot of the operation and therefore cannot be a good predictor of trap condition. The problem that exists at this moment is that there are no systems available that can autonomously monitor the steam trap eliminating the need of a third party. This will save the plant lots of money and will be cost effective. With the advent of low power programmable system on chips, it is now possible to monitor the health of steam traps in a cost effective and efficient manner. The objective of this project is to develop an algorithm or a system that can monitor these steam traps and detect faults in them thus eliminating the requirement of a third party and reducing a plants operational cost.

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1. Introduction

Steam-based heating processes use latent heat and transfer it to a given product. When the work is done (i.e. steam has given up its latent heat), steam condenses and becomes condensate. In other words, condensate does not have the ability to do the work that steam does. Heating efficiency will therefore suffer if condensate is not removed as rapidly as possible, whether in steam transport piping or in a heat exchanger.

A steam trap is a device used to discharge condensate and non-condensable gases with negligible loss of live steam. Steam loss through non-failed steam traps is referred to as functional steam loss (FSL) [1]. Steam traps are vital elements in steam lines, as performance degradation of these strongly impairs energy efficiency in most of the process industries. Steam traps represent a large portion of a manufacturing plant's total operating costs. In fact, one of the main concerns of today's automated world is energy waste and its consequences on overall productivity.

There are no concrete solutions to autonomous steam monitoring present now. With steam traps present in large quantities (thousands) it is time consuming and not cost efficient to hire a third party to inspect all the steam traps. If a proper autonomous monitoring and detection system existed, then the plant could hire just one person who could monitor all this and not only decrease the total operational costs but also increase efficiency and make an overall safe environment. Hence, to develop this system, a step by step plan is formulated that will allow the steam traps to be studied at a detailed manner and devise a solution. Furthermore, all the components required for the system will be researched and a methodology will be developed on the concept. This will then be tested in real world conditions and their results analysed finally resulting in an autonomously operated steam trap monitoring system.

1.1 Steam Traps

A steam trap is the separation point between the steam system and the condensate system. The purpose of a steam trap is to pass condensate, air and non-condensable gases from the steam system into the condensate system while not allowing live steam to pass into the condensate system. A steam trap is really nothing more than an automatic valve that discharges condensate and some non-condensable gasses. In a perfect world, they perform this task without consuming much live steam in the system. The most important functions a steam trap performs are the following:

- They get rid of condensate as soon as they are formed.

- They get rid of non-condensable gases.

In industry, steam is used regularly for heating or as a driving force for mechanical power. Steam traps are used in such applications to ensure that steam is not wasted. If condensate is not drained immediately or trapped, it reduces operating efficiency by slowing the heat transfer process and can also cause physical damage.

Figure 1. Steam Trap

The purpose of a steam trap is not as the name may indicate to trap steam, but rather to trap condensate in the steam line. The trap should be closed when the steam is present in the line. It is usually important that the traps perform closing and opening quickly to reduce steam and condensate losses.

1.1.1 Types of Steam Traps

Steam traps can be fit into four major types depending on their functionality:

- Mechanical Traps (Inverted Bucket, Float and Thermostatic)

- Thermostatic Traps
- Thermodynamic Traps
- Venturi or Orifice Traps

Mechanical Traps:

Mechanical traps operate in direct relationship to condensate levels present in the body of the steam trap. A float rises when condensate levels increase, and a mechanical linkage opens the steam trap valve so that it can drain. This is a rather straightforward process. Inverted bucket, Float and Thermostatic and float traps are examples of mechanical traps.

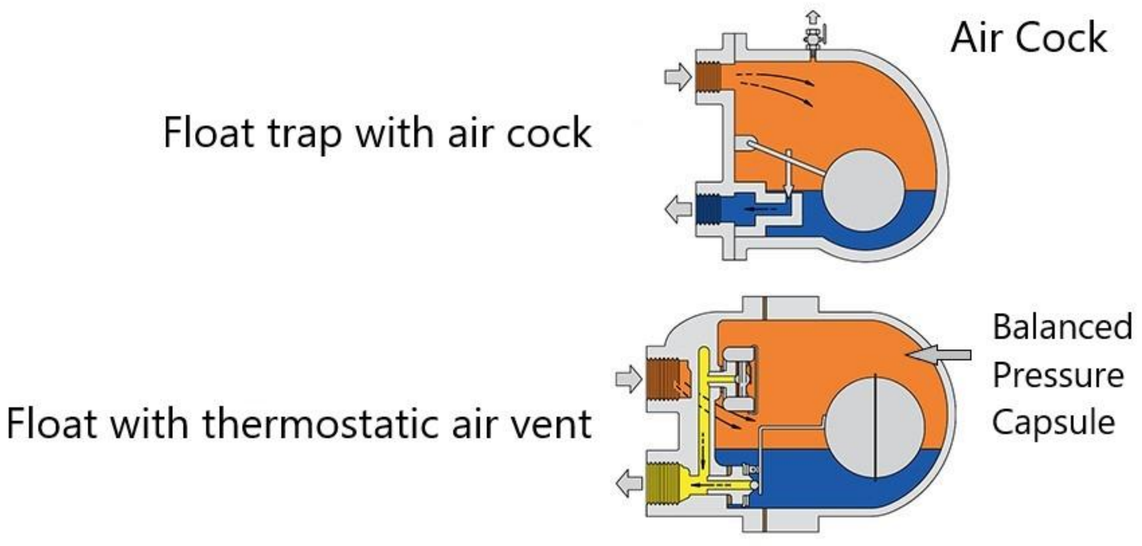


Figure 2. Mechanical Trap

Thermostatic Traps:

Thermostatic traps respond to changes in temperature and therefore discriminate very well between steam and other types of gases. They can rapidly purge air from a system, especially on a cold start-up, and can be installed in various positions. Most frequently, actuation is by means of a bimetallic element or a bellows like capsule filled with a vaporizing liquid.

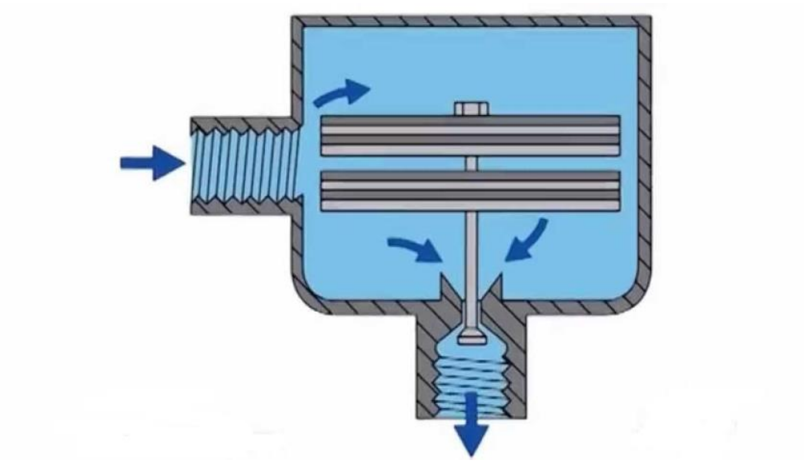


Figure 3. Thermostatic Trap

Thermodynamic Traps:

Thermodynamic traps are phase detectors in that they can discriminate between liquids and gases. But they do not discriminate between steam and air or other non-condensable gases. Therefore, they have a reduced ability to bleed-off those gases. Minute amounts of steam may also be passed. The thermodynamic working principle is simple, and with only one moving part, these small devices are rugged.

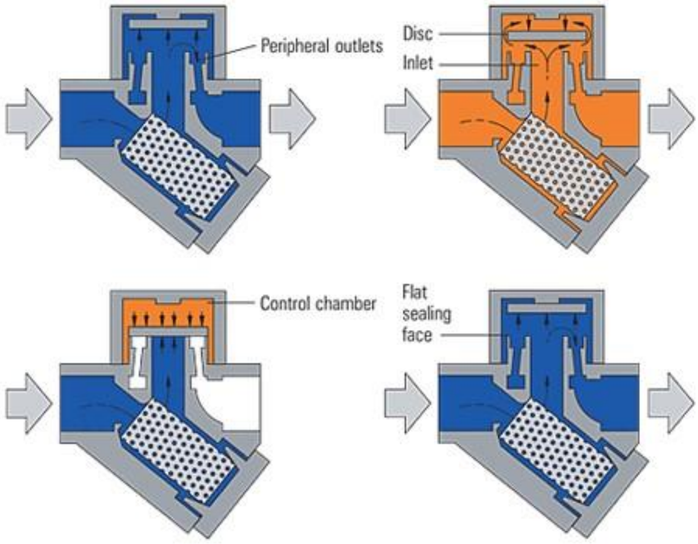


Figure 4. Thermodynamic Trap

Venturi or Orifice Traps:

These steam traps work by utilizing the basic physics of two-phase flow for the effective removal of condensate from steam systems. Steam and condensate pass through the Venturi nozzle steam traps by a series of staged steps. The denser liquid (condensate) throttles the Venturi nozzle, which keeps the steam from escaping. Erosive eddy currents are eliminated, and any contamination is carried away with the condensate. Because condensate is created continuously in a working steam system, the condensate continuously chokes the nozzle from losing steam as condensate is removed continuously

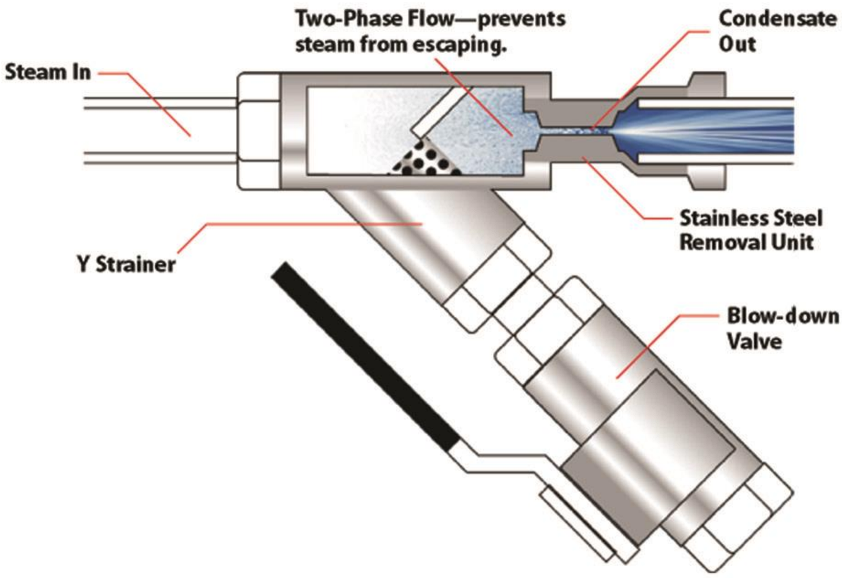


Figure 5. Venturi Trap

1.2 Microphones

The microphone pervades our daily lives through the sound we hear on radio, television and recordings, paging in public spaces, and of course in two-way communications via telephone.

A microphone, colloquially nicknamed mic or mike is a transducer that converts sound into an electrical signal. It translates sound vibrations in the air into electronic signals or scribes them to a recording medium [2]. Microphones are used in many applications such as telephones, hearing aids, public address systems for concert halls and public events, motion picture production, live and recorded audio engineering, sound recording, two-way radios, megaphones, radio and television broadcasting, and in computers for recording voice, speech recognition, VoIP, and for non-acoustic purposes such as ultrasonic sensors or knock sensors.

Figure 6. Shure Brothers Microphone

1.2.1 Working Principle

When someone speaks, sound waves created by voice carries energy towards the microphone. Remember that the sound one hears is energy carried by the vibrations in the air. Inside the microphone, the diaphragm (much smaller than you'd find in a loudspeaker and usually made of very thin plastic) moves back and forth when the sound waves hit it. The coil, attached to the diaphragm, moves back and forth as well. The permanent magnet produces a magnetic field that cuts through the coil. As the coil moves back and forth through the magnetic field, an electric current flow through it. The electric current flows out from the microphone to an amplifier or sound recording device.

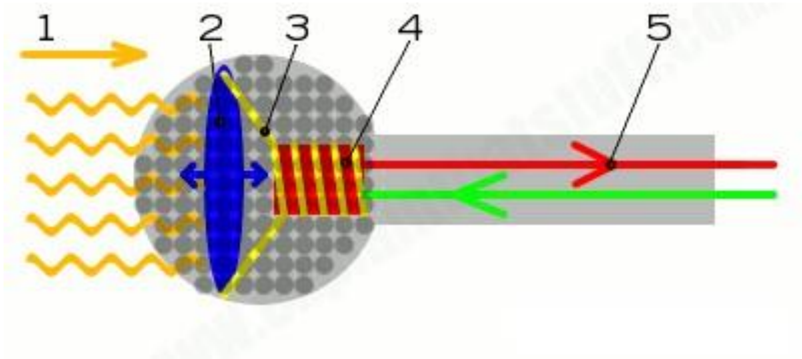


Figure 7. Working Principle

1.2.2 Types of Microphone

Using the right mic for the job is vital. Several different types of microphone are in use, which employ different methods to convert the air pressure variations of a sound wave to an electrical signal. However, almost all the microphones available can be grouped into three umbrella categories, which are:

- Dynamic Microphones
- Condenser Microphones
- Ribbon Microphones

Dynamic Microphones:

The dynamic microphone (also known as the moving-coil microphone) works via electromagnetic induction. They are robust, relatively inexpensive and resistant to moisture. Because they're insensitive, they're very versatile. Dynamic microphones have a unidirectional pattern (otherwise known as a cardioid pattern because it looks like a heart). This means that the microphone picks up sound in the direction it is being pointed at and cancels out any sound coming from behind it. Dynamics are great mics to use on almost everything. Be aware though that the sound will not be as accurate or 'pretty' if compared to the other types of microphones available.

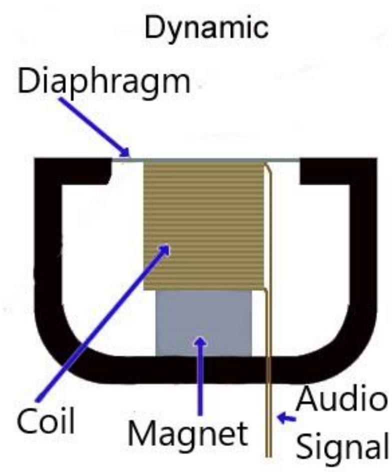


Figure 8. Dynamic Microphone

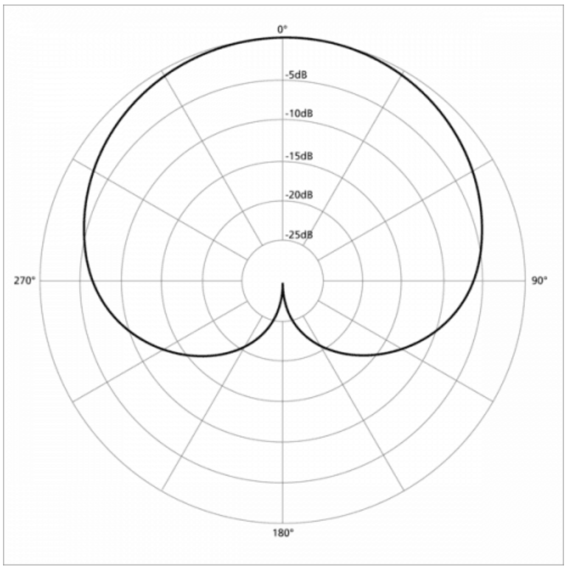


Figure 9. Cardioid Pattern

Condenser Microphone:

The condenser microphone was invented at Western Electric in 1916 by E. C. Wente. It is also called a capacitor microphone or electrostatic microphone (capacitors were historically called condensers). Here, the diaphragm acts as one plate of a capacitor, and the vibrations produce changes in the distance between the plates. The plate is biased by which, it also amplifies the signal. Capacitance varies with movement of the diaphragm in relation to the other plates providing the means to record the sound in electrical signal. Electret microphones used in cell phones and computers are a type of condenser microphone that use a polarized Ferro-electric clearer in comparison to dynamics.

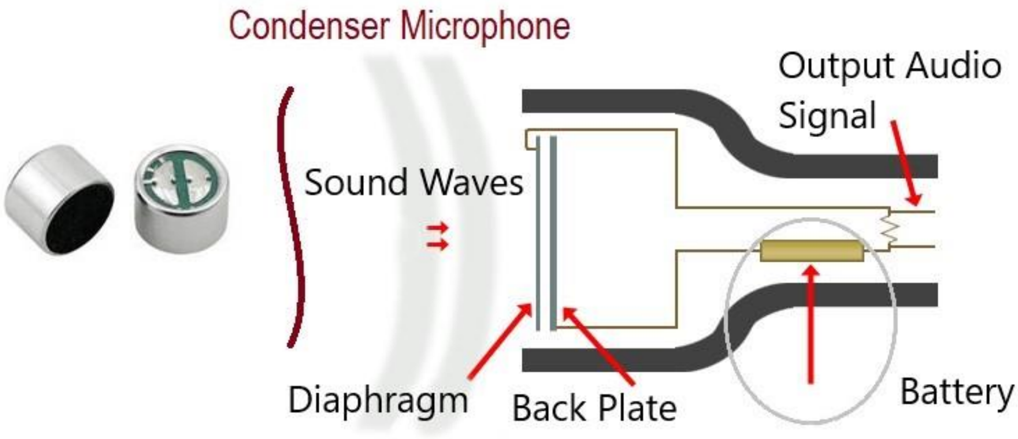


Figure 10. Condenser Microphone

Ribbon Microphone:

Ribbon microphones use a thin, usually corrugated metal ribbon suspended in a magnetic field. The ribbon is electrically connected to the microphone's output, and its vibration within the magnetic field generates the electrical signal. Ribbon microphones are similar to moving coil microphones in the sense that both produce sound by means of magnetic induction. Basic ribbon microphones detect sound in a bi-directional (also called figure-eight) pattern because the ribbon is open on both sides.

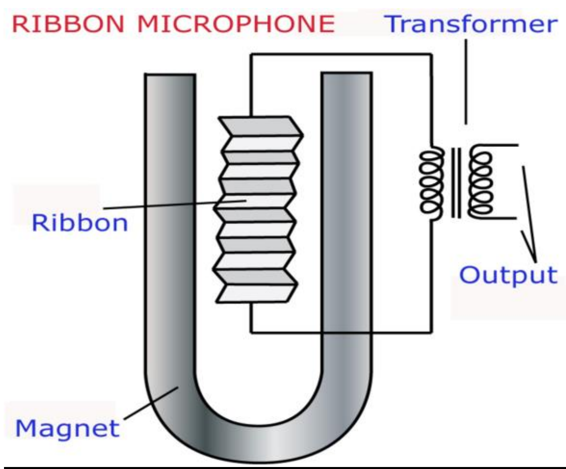


Figure 11. Ribbon Microphone

Other types of Microphones:

- Piezo Electric Microphones:

  A crystal microphone or piezo microphone uses the phenomenon of piezoelectricity (the ability of some materials to produce a voltage when subjected to pressure) to convert vibrations into an electrical signal. An example of this is potassium sodium tartrate, which is a piezoelectric crystal that works as a transducer, both as a microphone and as a slim-line loudspeaker component. Piezoelectric transducers are often used as contact microphones to amplify sound from acoustic musical instruments, to sense drum hits, for triggering electronic samples, and to record sound in challenging environments, such as underwater under high pressure.

Figure 12. Piezo Electric Microphone

Fiber Optic Microphone:

A fiber optic microphone converts acoustic waves into electrical signals by sensing changes in light intensity, instead of sensing changes in capacitance or magnetic fields as with conventional microphones. Fiber optic microphones do not react to or influence any electrical, magnetic, electrostatic or radioactive fields. The fiber optic microphone design is therefore ideal for use in areas where conventional microphones are ineffective or dangerous, such as inside industrial turbines or in magnetic resonance imaging (MRI) equipment environments.

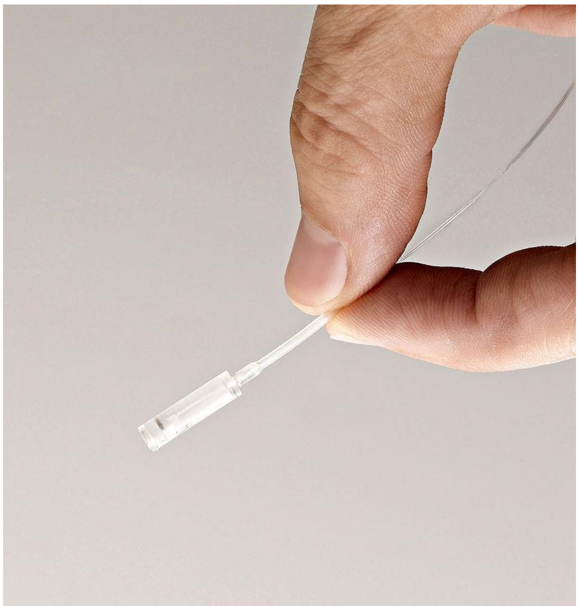


Figure 13. Fiber Optic Microphone

1.3 Monitoring of Steam Traps

The question which is often asked is, 'Why is steam trap monitoring essential?' The simple answer is, to reduce the fuel bills and limit the carbon footprint. Over the period, the performance of steam traps might deviate from the ideal. If the number of steam traps is very large, this deviation might result in reduced system efficiency and as a result, the fuel consumption will go up. If steam traps are opening too frequently because of temperature volatility, it's likely that the extra wear and tear will necessitate frequent replacement. Conversely, if steam traps are not opening frequently enough and condensation can accumulate, this causes a whole other problem.

According to a white paper published by Emerson [3] , 20% of the steam leaving a central boiler plant is lost via leaking traps in typical space heating systems that do not have a steam trap monitoring system. If the steam traps have not been maintained for a duration of 3 to 5 years, then between 15% and 30% of the installed steam traps may have failed. Failing steam traps also increase the total cost of operations.

John Napier discovered the equation for calculating steam flow through an orifice (opening). Since every steam trap has an internal orifice to reduce steam loss in the case of a failed open steam trap, the equation is widely used to estimate the losses through a failed trap.

$$W = 24.24 * P_{abs} * D^2$$

Where,

W = Steam loss in lbm/hr *(1 lbm/hr = 0.125998 g/s)*

24.24 = Constant

P_{abs} = Steam pressure in psia *(average atmospheric surface pressure at sea level is roughly 14.7 PSIA)*

D = Diameter of the internal orifice *(in inches)*

An example is taken of a steam trap operating on a 250-psi steam system with an internal orifice of 3/16 inches, steam loss through a blow-through trap can be calculated in the following manner.

$$W = 24.24 * P_{abs} * D^2$$

$$W = 24.24 * (250psi + 14.7psi) * \left(\frac{3}{16} in\right)^2$$

$$W = 225.6\ lbm/hr$$

The cost of steam for a process unit to find the financial impact of a blow-through trap can then be applied. A typical cost of steam is $10/1,000lbm [3] so this is what will be used in the following example.

$$Cost\ \left(\frac{\$}{yr}\right) = Steam\ loss\ \left(\frac{lbm}{hr}\right) * Cost\ of\ Steam\ \left(\frac{\$}{1000lbm}\right) * \ 8760\left(\frac{hrs}{yr}\right)$$

$$Cost\ \left(\frac{\$}{yr}\right) = \left(\frac{225.6\ lbm}{hr}\right) * \left(\frac{\$10}{1000lbm}\right) * \ 8760\left(\frac{hrs}{yr}\right)$$

$$Cost\ \left(\frac{\$}{yr}\right) = \$19{,}762/yr$$

As displayed above, the cost for this particular trap is nearly 20,000 $/yr.

1.3.1 Different Methods of Monitoring Steam Traps

A major problem has always been the accurate identification of faulty traps. Wrong diagnosis can allow faulty traps to remain troublesome, and perfectly sound traps to be replaced unnecessarily. Accurate diagnosis is therefore important to any maintenance program. Several methods are used to test the operating conditions of a steam trap to determine if it is working properly. These methods include:

- Visual Observation
- Measuring Temperature
- Measuring Sound/Vibrations
- Combination of these methods

<u>Visual Observation:</u>

Although limited in its scope, visual observation is an important first step in determining whether a trap is operating properly or not. For example, certain visual signs such as the lack of any condensate discharge or extremely large quantities of steam leaking out of a trap may indicate the need for trap repair. Of course, a visual assessment is limited to reviewing open systems. When recovering condensate in a closed piping system, for instance, the piping will prevent performing visual diagnosis. Installing a sight glass at the trap's outlet may help provide a visual indication in some instances. Sight glasses offer a partial solution, especially the combined sight/check valve that gives a visual indication of flow plus a non-return facility, however, glasses will require changing occasionally.

Traps can also be externally inspected for pinhole, connection joint, and gasket leaks. In most cases, unless a condition problem can be clearly determined visually, testing traps by sound and temperature, and in some cases by thermography, will then be required to provide a correct diagnosis.

Figure 14. Sight Glass

Measuring Temperature:

Measuring the trap inlet condensate temperature is a first step in the process of testing for steam trap failure. Temperature can be extremely useful when trying to determine if a trap is blocked or if its capacity in insufficient. This is because such problems cause condensate to backlog, lowering the trap's temperature. If the temperature is significantly lower and the application is 'in service', the low reading generally indicates an undersized trap, incorrect pressure orifice for the trap or a blocked trap/strainer discharge failure among others.

Using temperature measurement to determine whether a steam trap is leaking or not can lead to erroneous analysis. This is because higher temperature condensate flashes into steam when introduced into a lower pressure system [4]. Because the flash steam temperature is the same as that of leaking live steam, it is not possible to differentiate between a steam leak and regular condensate discharge by the measured temperature. An erroneous condition report based on temperature can lead to the unnecessary replacement of a good condition steam trap. Furthermore, it is perfectly feasible (and normal) for condensate and steam to coexist at the same temperature in the same system, making accurate diagnosis difficult on temperature alone.

Figure 15. When the trap discharge capacity is insufficient.

When the trap discharge capacity is insufficient, condensate will backlog and the surface temperature of the trap will drop. (When backlog occurs, the trap inlet temperature will not appear as hot as shown above.)

Figure 16. Impossible to determine

In this case it is impossible to determine whether the trap is leaking steam or whether it's operating properly.

Measuring Sound/Vibrations or Ultrasound

Condensate flowing through a trap produces sound and vibration, and so does the opening and closing valve mechanism of most traps. When a trap is no longer operating as intended (from wear, blockage or some other reason) these sounds will often change. Recognizing this difference can be one method of assessing a steam trap's condition.

Live steam leaking from a trap may also produce a distinct sound which can be explained as the difference between a 'whistle and a wave.' A whistle is a vapour-based, high pitch sound, even if softly made. It is impossible to duplicate the same sound with a liquid, even one as large as a wave or as small as a drip from a faucet. Condensate should usually be flowing through a trap, and the sound should have a lower pitch. So, if this sound changes and appears much closer to a higher pitched sound like that of steam flow, then the trap may have a large amount of flash steam or may be leaking live steam and should be inspected further. The following images published in an article on steam traps by TLV Inc [4]. are also very helpful.

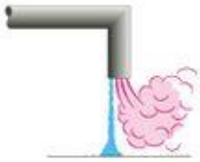
Properly Operating Trap			
Illustration			
Appearance	Small volume of condensate discharged	Flash steam and condensate continuously discharged	Large volume of condensate and flash steam continuously discharged
Sound	Almost no sound	Swoosh-like sound	Louder swoosh

Figure 17. Properly Trap Operation

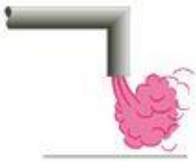
Leaking Trap			
Illustration			
Appearance	High velocity live steam (clear) discharged with condensate	High velocity live steam (clear) discharged	Continuous discharge of high velocity live steam (clear)
Sound	Similar to compressed air leak	Similar to compressed air leak with a slight whistle	Even louder whistle

Figure 18. Leaking Trap

	Cold Trap (Blocked)	Insufficient capacity
Illustration		
Appearance	No condensate or steam discharged Steam trap temperature drops (Easy to mix up with out-of-service traps)	Smooth discharge (Discharge capacity is insufficient.)
Sound	None	Very little sound

Figure 19. Blocked Trap or Insufficient Capacity

1.4 Wireless Steam Trap Monitoring

A wireless steam trap monitoring system is a simple, cost effective way to monitor the operation of the steam trap. Wireless steam trap monitoring is an invaluable tool from the standpoint that as soon as there is a trap failure a text message and/or email is sent to whomever the facility manager wants to be notified. The savings associated with catching a steam trap in a failed open condition are tremendous. Rather than allow a steam trap to waste thousands of pounds of steam, the steam trap can be fixed immediately. Employees are now freed up by the wireless steam trap monitoring system to work on other projects

By utilising a mixture of different sensors, steam traps can be monitored autonomously. The monitoring system will collect and process data from the sensors after specific intervals of time. If a fault is detected, then this fault is relayed to the main server wirelessly. The sensors to be considered for this are mainly sound sensors and vibration sensors (accelerometers).

2. Material and Testing

After a brief study and analysis of all the various components involved in the process and their functionality, the next step is to begin with the construction of the system. Proper apparatus has is selected based on the required parameters.

In this section an in-depth analysis will be made of the required parameters for sensing sound, vibrations and the different sensors available in the market accordingly. Furthermore, the shortlisted sensors will then be tested, and their behaviour observed under laboratory conditions to select one which is best suitable for the given situation. Once that has been done, a prototype will also be constructed which will serve as a reference for future improvements.

2.1 Sound Characterization

As mentioned earlier, a microphone colloquially nicknamed mic or mike is a transducer that converts sound into an electrical signal. It translates sound vibrations in the air into electronic signals or scribes them into a recording medium. Microphones are used in many applications such as telephones, hearing aids, public address systems for concert halls and public events, motion picture production, live and recorded audio engineering, sound recording, two-way radios, megaphones, radio and television broadcasting, and in computers for recording voice, speech recognition, VoIP, and for non-acoustic purposes such as ultrasonic sensors or knock sensors. In order to select a microphone, various characteristics must be measured, analysed and recorded so as to select one which is optimum for the given project or task.

2.1.1 Parameters to Be Considered

Polar Patterns:

The polar pattern is the shape of a mic's field of sensitivity, or the directions from which it accepts or ignores incoming sounds. An omnidirectional mic responds to sounds coming from all directions. A bi-directional mic, also known as a "Figure 8 microphone", picks up sounds from east and west while excluding sounds from north and south. A unidirectional mic primarily hears sounds from one direction and excludes sounds from other directions.

Unidirectional mics are the most common type, and they come in three polar patterns: cardioid, supercardioid and hypercardioid. All three of these patterns reject rear-axis and off-axis sounds coming from behind the mic or from the sides.

The cardioid pattern is roughly a heart shape (hence its name), which makes the mic most sensitive to sounds from straight on and from the sides but rejects sounds from 180 degrees opposite the direction the mic is aimed. The supercardioid mic accepts a little more sound from a 180-degree field but rejects more from each side. The hypercardioid allows yet more sounds from 180 degrees but rejects more of the sound coming from 90 or 270 degrees.

Polar patterns are important when working with noisy settings. Cardioid, supercardioid, and hypercardioid mics will tend to exclude all the sounds except the source, thus preventing the signal from becoming muddied or producing feedback.

Frequency Response:

Frequency response defines the range of sound that a microphone can reproduce and how its output varies within that range. This range is referred to by its lowest and highest frequencies, measured in hertz. The frequency response is the most significant factor in determining the sound signature of a microphone. The frequency response of a mic is represented graphically by a response curve. The two most common types are flat response and shaped, or tailored, response.

A flat response microphone is equally sensitive to all frequency ranges, so its response curve is in fact nearly a flat line. A flat response microphone reproduces the sound source accurately with little or no variation from the original sound. A shaped response microphone is more sensitive to some frequency ranges than others. Its response curve has peaks and valleys. Many microphones that have a shaped response are less sensitive to low frequencies. A shaped response microphone also typically has a boost in the upper mid-range, usually between 3,000 and 6,000 Hz. This is called a presence rise, and it enhances the clarity, or "punch" of voices.

Response Curves:

It is important to note that frequency response only depicts the overall range a mic can reproduce. How it performs at different frequencies is another matter, and this performance is what gives a mic its character.

The shape of a microphone's frequency responsiveness is called its response curve. Because it starts out at zero on the low end and drops off to zero at the high end, it takes the form of a curve when graphed. Within this overall curve, there will be peaks and dips in certain places that give the mic a certain character and make it more suited to certain applications

Sensitivity and SPL Handling Capability:

Sensitivity refers to how quiet a sound the mic can detect, and it is expressed using different systems. Regardless of the system, it is perhaps enough to know that the lower the number, the more sensitive the microphone is.

SPL stands for "sound pressure level" and is expressed in decibels (dBs). It describes the maximum volume that a mic can handle, so, in a way, it is the opposite of sensitivity.

Proximity Effect:

Proximity effect is not given as a specification but is an important mic characteristic that is sometimes mentioned in descriptions. Proximity effect causes bass frequencies to become more pronounced as the sound source moves closer to the mic. Condenser mics generally produce more proximity effect than dynamic mics.

2.1.2 Microphones under Consideration

Keeping all the above-mentioned facts in consideration, an extensive search was carried out to highlight the microphones most suited for the required situation. All the parameters in the previously mentioned section were taken into consideration. In conclusion two microphones were shortlisted which were then analysed in detail

CUI Inc. Electret Condenser Microphone:

The CMA-4544PF-W Electret Condenser Microphone by CUI Inc. is a 9.7mm Omnidirectional Microphone with a sensitivity of about '-44±2 dB'. It can detect sound from 20 Hertz up to 20,000 Hertz and has a current consumption of about 500 µAmp [5].

Figure 20. CUI Inc. Electret Condenser

What's interesting about this microphone is that it has an adequate sensitivity and the current consumption is very low. Furthermore. it has an operating voltage of 3 Volts which is quite appropriate in the current project. A representation of the 'Frequency Response' is mentioned below.

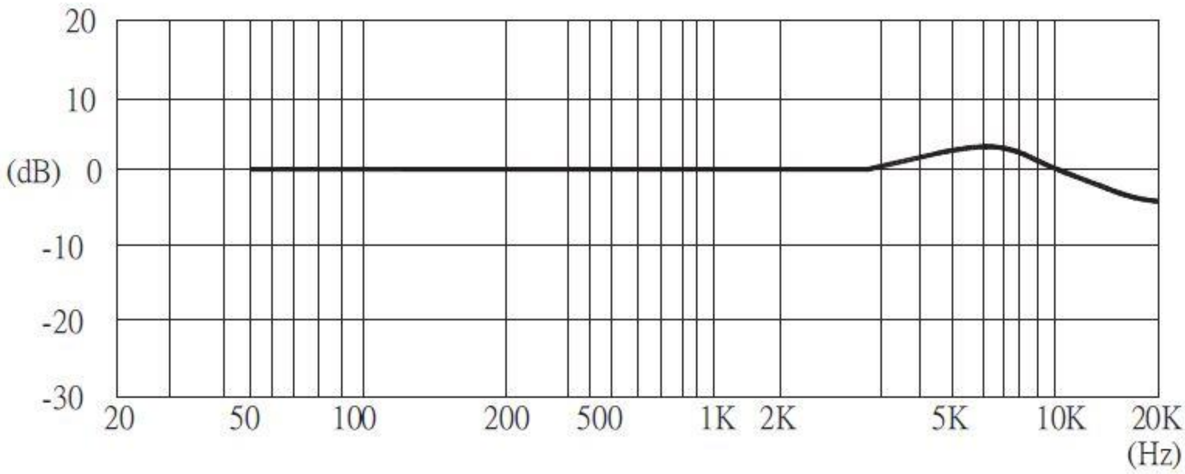


Figure 21. Frequency Response

A few of the basic design and performance specifications for the device are also mentioned on the following page for consideration.

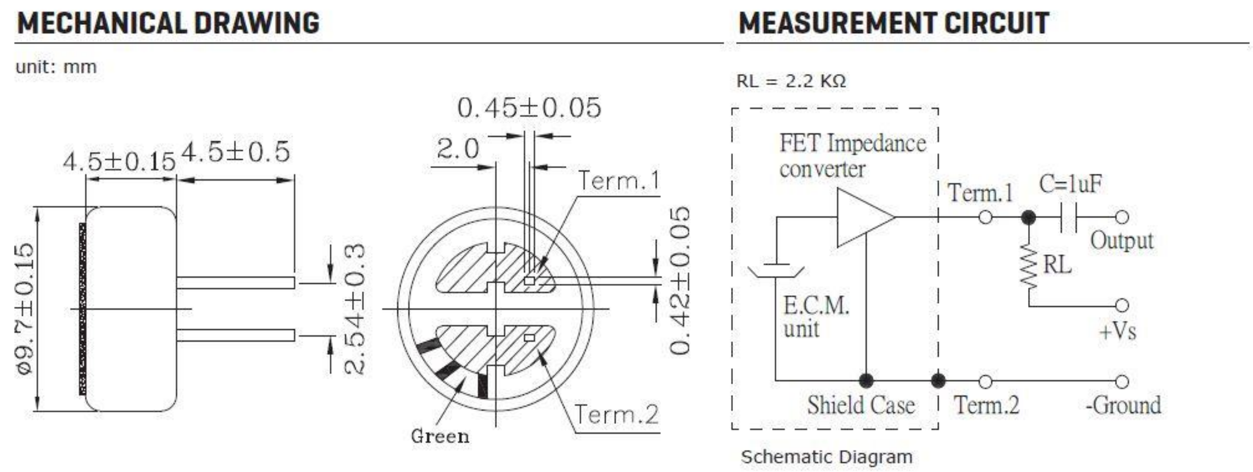


Figure 22. Mechanical Drawing and Measurement Circuit

SPECIFICATIONS

parameter	conditions/description	min	typ	max	units
directivity	omnidirectional				
sensitivity (S)	f = 1 kHz, 1 Pa, 0 dB = 1 V/1 Pa	-46	-44	-42	dB
operating voltage			3	10	Vdc
output impedance (Zout)	f = 1 kHz, 1 Pa		2.2		KΩ
sensitivity reduction (ΔS-Vs)	f = 1 kHz, 1 Pa, Vs = 3.0 to 2.0 Vdc		-3		dB
frequency (f)		20		20,000	Hz
current consumption (IDSS)	Vs = 3.0 Vdc, RL = 2.2 KΩ			0.5	mA
signal to noise ratio (S/N)	f = 1 kHz, 1 Pa, A-weighted		60		dBA
operating temperature		-20		70	°C
storage temperature		-20		70	°C
dimension	ø9.7 x 4.5 mm				
weight				0.8	g
material	Al				
terminal	pin type (hand soldering only)				
RoHS	yes				

Note: We use the "Pascal (Pa)" indication of sensitivity as per the recomendation of I.E.C. (International Electrotechnical Commission). The sensitivity of "Pa" will increase 20dB compared to the "ubar" indication. Example: -60dB (0dB = 1V/ubar) = -40dB (1V/Pa)

Figure 23. Microphone Specifications

Knowles Electronics Piezoelectric Microphone:

The BL-21785-000 Piezoelectric Microphone by Knowles is a rugged, stable and versatile 0.5", omnidirectional cylindrical shell microphone. It has a sensitivity of -69 ± 3 dB. It has a current consumption of about 140 μAmp [6].

Figure 24. Knowles Piezoelectric Microphone

The primary factor behind the selection of this microphone was the fact that it was a 'Piezoelectric' Microphone. This in return provided the Microphone with increased levels of sensitivity that were not only applicable to sound but to vibration also resulting in it being used as an accelerometer also. The frequency response curve is represented below:

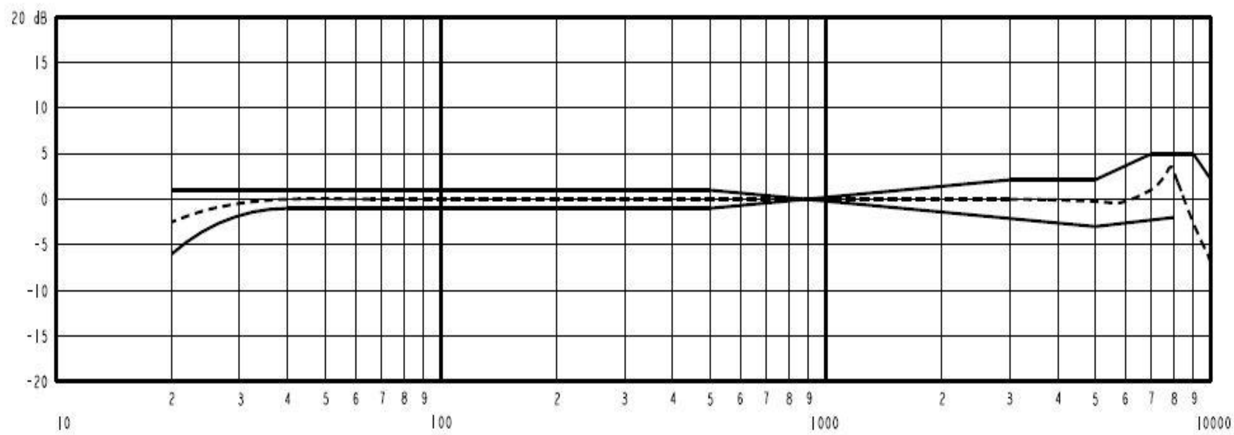


Figure 25. Frequency Response

The basic operating features and test circuits are the following:

PORT LOCATION	DC SUPPLY	BATTERY CURRENT DRAIN	"A" WEIGHTED NOISE (1 kHz EQUIV. SPL) IN 3 WIRE MODE	OUTPUT IMPEDANCE OHMS			V_L AT OUTPUT IN SOURCE FOLLOWER MODE	
				MIN.	NOM.	MAX.	MIN.	MAX.
12S	1.3 V	160 µA MAX.	34 dB MAX.	---	4000	---	0.9 VDC	1.9 VDC

Figure 26. Basic Parameters

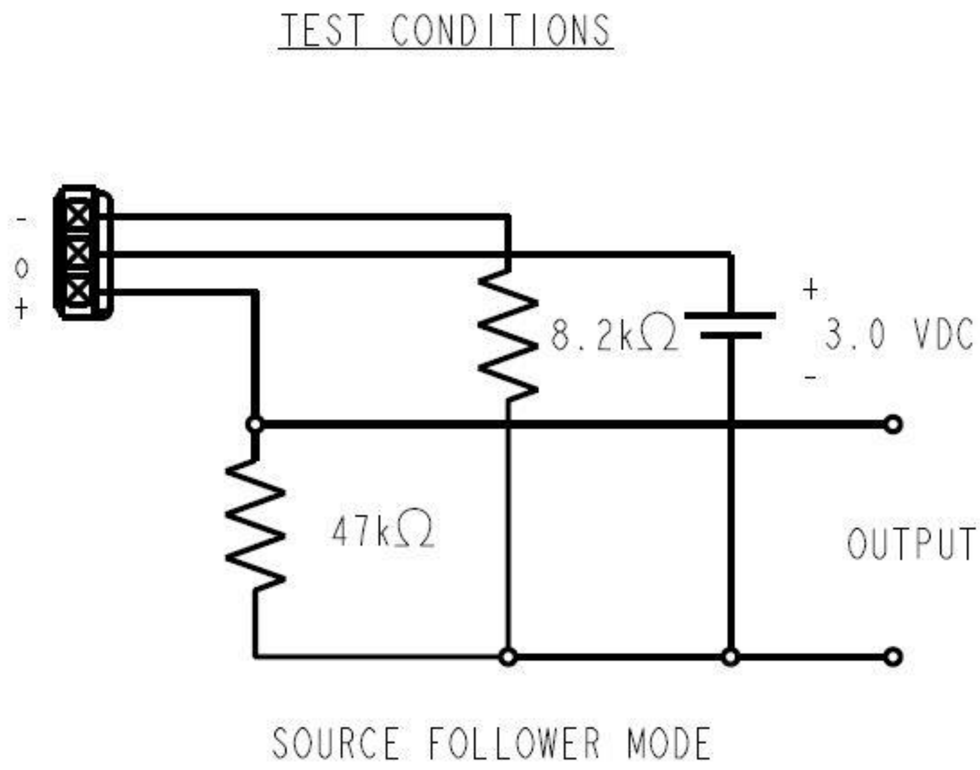


Figure 27. Test Condition

2.1.2 Design and Analysis

This section covers the design and experimental phase of both the microphones. An experimental system was set up with a set of conditions which were then applied to both the Microphones. Their performance and response were measured, recorded and further analysed. These factors were then compared with a standard off the market microphone to observe the similarity in behaviour to determine the best suited Microphone for the given condition. All the equipment required for this is mentioned below:

<u>Function Generator:</u>

A function generator is usually a piece of electronic test equipment or software used to generate different types of electrical waveforms over a wide range of frequencies. Some of the most common waveforms produced by the function generator are the sine wave, square wave, triangular wave and saw-tooth shapes. These waveforms can be either repetitive or single shot (which requires an internal or external trigger source).

Function generators are used in the development, test and repair of electronic equipment. For example, they may be used as a signal source to test amplifiers or to introduce an error signal into a control loop. Function generators are primarily used for working with analogue circuits, related pulse generators are primarily used for working with digital circuits.

Figure 28. Function Generator

Oscilloscope:

An 'Oscilloscope' is a type of electronic test instrument that graphically displays varying signal voltages, usually as a two-dimensional plot of one or more signals as a function of time. Other signals (such as sound or vibration) can be converted to voltages and displayed.

Oscilloscopes display the change of an electrical signal over time, with voltage and time as the Y- and X-axes, respectively, on a calibrated scale. The waveform can then be analysed for properties such as amplitude, frequency, rise time, time interval, distortion, and others. Modern digital instruments may calculate and display these properties directly. Originally, calculation of these values required manually measuring the waveform against the scales built into the screen of the instrument.

Figure 29. Oscilloscope

Power Supply:

A power supply is an electrical device that supplies electric power to an electrical load. The primary function of a power supply is to convert electric current from a source to the correct voltage, current, and frequency to power the load. As a result, power supplies are sometimes referred to as electric power converters. Some power supplies are separate standalone pieces of equipment, while others are built into the load appliances that they power.

Figure 30. Power Supply

IPhone 7:

The microphone of the iPhone in this case will be utilised as a reference sensor. Not much information is disclosed about the hardware specifications of the IPhone microphone, but it is safe to assume that it follows an Omni-directional pattern. It is however to be noted that the internal microphone operates independently from all other audio input ports and is always available. Furthermore, it supports recording at bit depths of 16, 20 or 24 bits per sample and at sample rates of 44.1 kHz, 48 kHz, and 96 kHz. Audio recorded from the microphone is presented as a stereo data stream appearing on both the left and right channels. The microphone gain can be adjusted from -16 dB to +30 dB [7]

Figure 31. IPhone 7

Speaker:

A loudspeaker (or loud-speaker or speaker) is an electro-acoustic transducer i.e. a device which converts an electrical audio signal into a corresponding sound. The most widely used type of speaker in the 2010s is the dynamic speaker.

The dynamic speaker operates on the same basic principle as a dynamic microphone, but in reverse, to produce sound from an electrical signal. When an alternating current electrical audio signal is applied to its voice coil, a coil of wire suspended in a circular gap between the poles of a permanent magnet, the coil is forced to move rapidly back and forth due to Faraday's law of induction, which causes a diaphragm (usually conically shaped) attached to the coil to move back and forth, pushing on the air to create sound waves.

Figure 32. Speaker

Conditioner Circuit:

Most analogue signals require some form of preparation before they can be digitized. Signal conditioning is the manipulation of a signal in a way that prepares it for the next stage of processing. Many applications involve environmental or structural measurement, such as temperature and vibration, from sensors. These sensors, in turn, require signal conditioning before a data acquisition device can effectively and accurately measure the signal.

For example, thermocouple signals have very small voltage levels that must be amplified before they can be digitized. Other sensors, such as resistance temperature detectors (RTDs), thermistors, strain gauges, and accelerometers, require excitation to operate. All these preparation technologies are forms of signal conditioning.

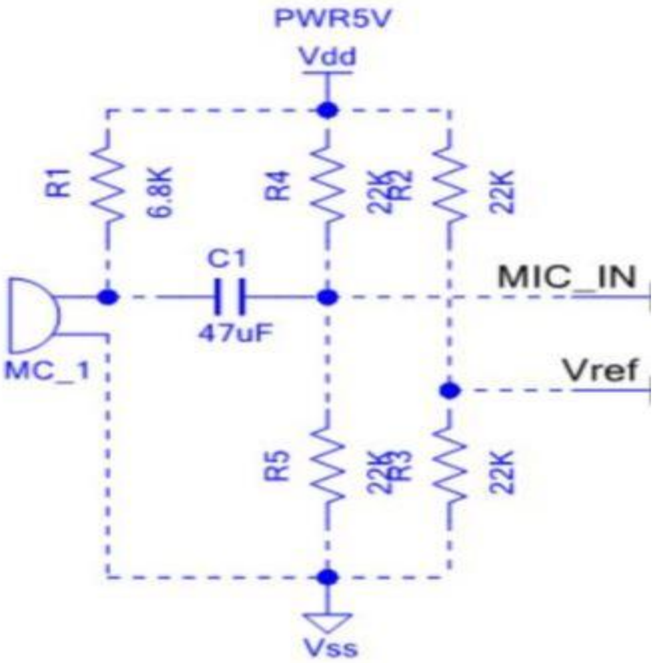


Figure 33. Conditioner Circuit

Figure 34. Board Connections

Cypress PSoC 5 LP:

PSoC 5LP is the industry's most integrated programmable SoC, combining high-precision and programmable analogue and digital peripherals with an ARM Cortex-M3 CPU in a single chip. The kit provides access to all the PSoC 5LP device I/Os in a breadboard-compatible format. PSoC 5LP also helps you simplify your system power architecture design by supporting the widest operating voltage range and multiple power domains in a single SoC. Furthermore, PSoC offers a sophisticated CPU subsystem with SRAM, EE PROM, and flash memory, multiple core options and a variety of essential system resources [8].

Figure 35. Cypress PSoC 5 LP

Besides these components, other equipment such as wires, cutters, bolts, wood etc were also used.

2.1.3 Test Conditions

To properly test the microphones and their functionality a proper laboratory setup is required. All the conditions need to be similar to not introduce discrepancies between the results. The conditions need to be the same for both the microphones so that results could be comparable.

The proposed system consists of a cube shaped wooden structure with the speaker located at the bottom of the cube and the microphone situated at the top of the structure in an inverted position. The distance between the microphone and the speaker was set to exactly 2 centimetres apart. The four corners were fixed with adjustable nuts to increase or decrease the distance between the speaker and the microphone accordingly.

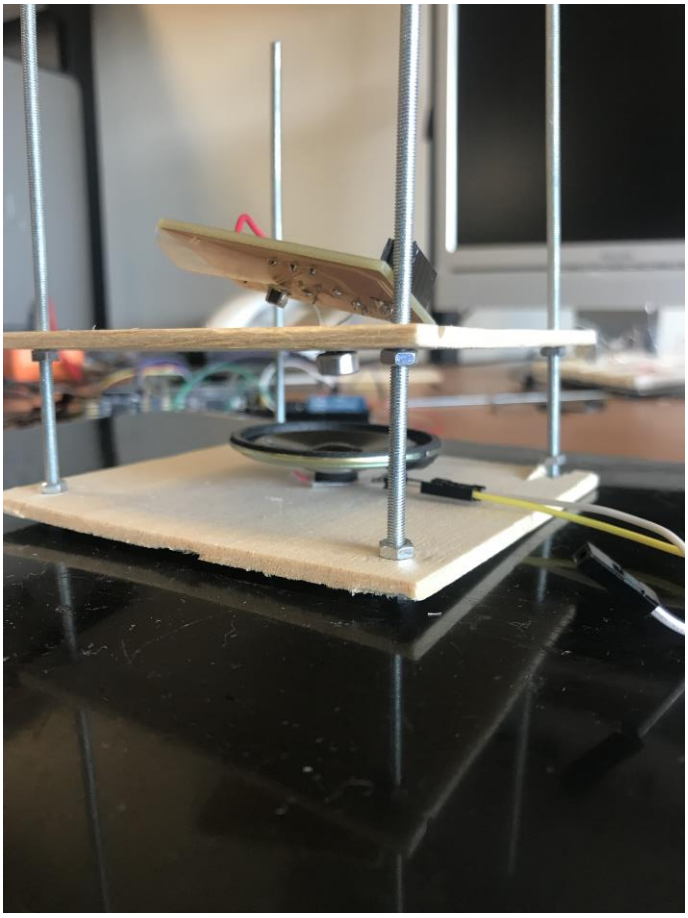


Figure 36. Test Apparatus

This apparatus was then placed in a metal box to avoid any external interference such as noise, humidity etc. and then tested. These external factors can cause undesired deviations in the response of the system leading to undesired errors in calculations and measurements.

2.1.4 Testing

Both the microphones were then tested on the previously mentioned test apparatus and their performances recorded. These performances were then compared with themselves and with the performance of the microphone in the IPhone which is being utilised as a reference microphone. It is safe to assume that the built in IPhone microphone will also contain some sort of signal conditioning and amplification, hence it is only utilised as a reference microphone to verify the similar functionality of both the microphones.

The CUI Inc. Electret Condenser Microphone was first tested followed by the Knowles Piezoelectric Microphone. The test conditions for both the sensors will be the same i.e. a distance of 2 centimetres from the speaker and 4 Volts peak to peak sine wave with varying frequencies flowing through the speaker. A high peak to peak voltage is given to obtain clearer results so as to measure the raw performance of the sensors. Their performances were then measured and fed to a table which recorded the Peak-Peak Voltage (in Volts) against the corresponding frequency (in Hertz) as shown below.

Frequency (Hertz)	Voltage P-P (volts)
20	
40	
60	
80	
100	
200	
300	
400	
500	
1000	
2000	
4000	
5000	
6000	
8000	
10000	
15000	
20000	

Figure 37. Information Table

The results were then compared to determine the best possible sensor.

CUI Inc. Electret Condenser Microphone:

It is to be kept under observation that in the case of the electric condenser microphone, the conditioner circuit was also used in conjunction. This conditioner circuit enabled the microphone to display results at a voltage exactly half the value of the supply voltage (5 Volts). The following readings were observed using the digital oscilloscope.

Frequency (Hertz)	Voltage P-P (volts)
20	0.08
40	0.08
60	0.08
80	0.08
100	0.08
200	0.08
300	0.08
400	0.2
500	0.56
1000	0.2
2000	0.2
4000	0.6
5000	0.96
6000	0.28
8000	0.2
10000	0.08
15000	0.08
20000	0.08

Figure 38. CUI Response Table

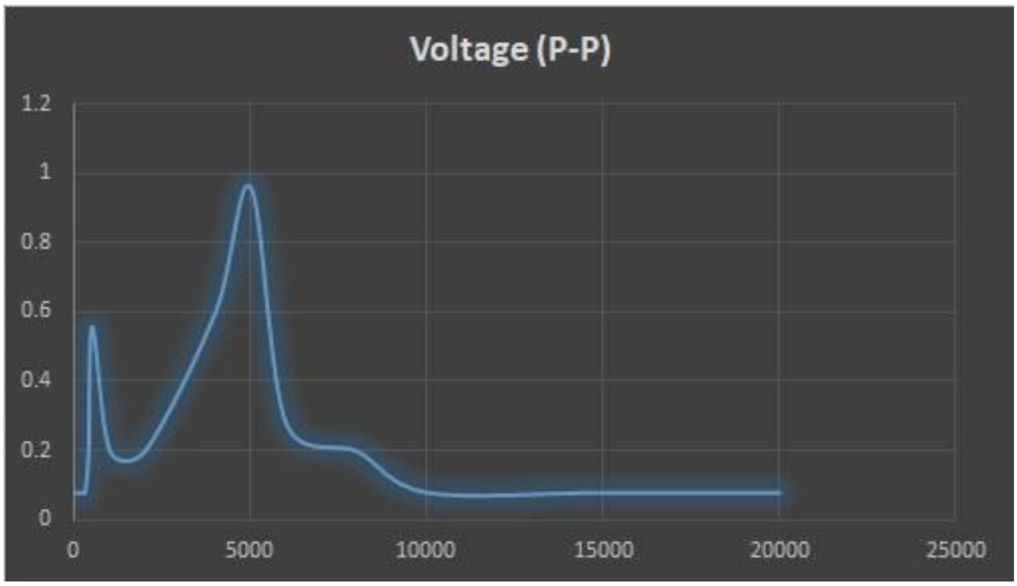


Figure 39. CUI Response Curve

Knowles Piezoelectric Microphone:

The interesting fact about this Piezoelectric Microphone is the fact that during testing, there is no absolute requirement of a conditioner circuit and the response is fairly well without it. The readings observed during the testing are mentioned below.

Frequency (Hertz)	Voltage P-P (volts)
20	0.016
40	0.008
60	0.008
80	0.008
100	0.008
200	0.016
300	0.024
400	0.072
500	0.16
1000	0.032
2000	0.032
4000	0.104
5000	0.136
6000	0.056
8000	0.056
10000	0.016
15000	0.016
20000	0.016

Figure 40. Knowles Response Table

Furthermore, the response can be plotted on a curve using the following methodology.

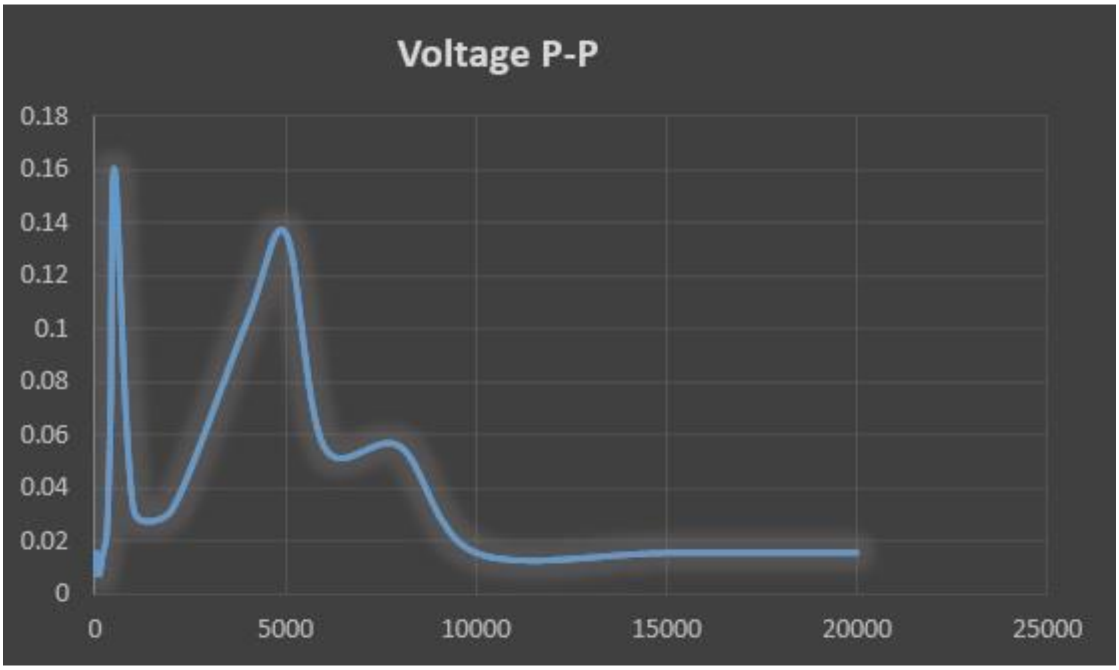


Figure 41. Knowles Response Curve

IPhone:

The inbuilt microphone of the IPhone was utilised as a reference microphone. The primary purpose behind using it was the fact that a reference microphone behaviour was required to gain semblance of the sensors being used to real world devices

One important fact that needs to be taken into consideration is that the voltage produced by the microphone cannot be directly measured from the IPhone. As a result, some software is required which will extract the microphone performance perimeters and display accordingly. These parameters most probably will not be in terms of voltage but can be in the form of Electric Gain (dB) or SNR values depending on the type and capabilities of the software being implemented.

For this purpose, an IPhone App titled "Sonic Tools" by "Rikki Systems Inc." was used. It is a free to use app which analyses sound, vibration and magnetic field using the sensors available in the IPhone. For sound analysis the app offers FFT, RTA, Spectrogram services. It furthermore has a built-in scope and can also offer signal generation features.

It was further noticed that the app does not display the perimeters in voltage values but displays the Voltage Gain (dB) for the IPhone Microphone when exposed to different situations. Hence, for comparison we will consider the voltage gain of the IPhone Microphone and then use these values for reference and try to observe a similar behaviour in both the sensor Microphones.

The values obtained on the built in IPhone Microphone are mentioned below along with the response curve.

Frequency (Hertz)	Voltage Gain (dB's)
20	30
40	36
60	44
80	50
100	53
200	64
300	78
400	88
500	94
1000	83
2000	83
4000	90
5000	95
6000	85
8000	88
10000	86
15000	66
20000	44

Figure 42. IPhone response table

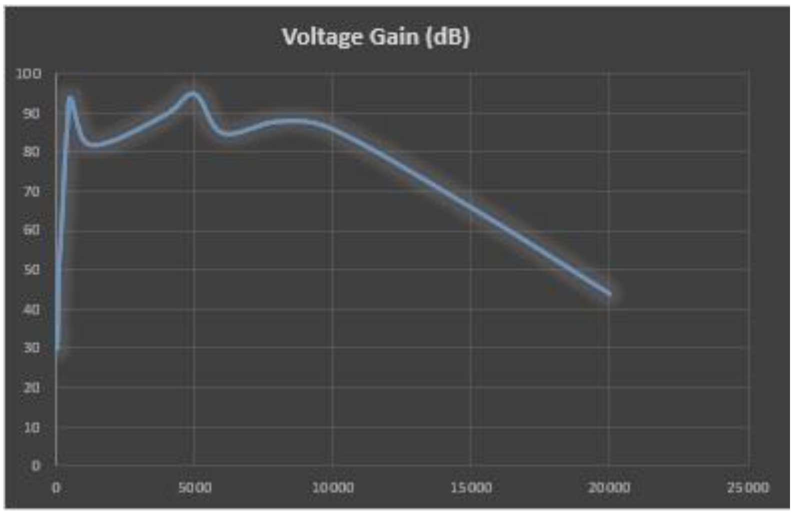


Figure 43. IPhone Response Curve

2.1.5 Comparison

Various factors were taken into consideration for the comparison of both the microphones before selecting the required microphone. These are mentioned below.

Polar Pattern:

Both the microphones offer directivity in an omnidirectional pattern. This implies that both the microphones will be able to sense sound in a 360-degree pattern. Both the microphones being omnidirectional is a bonus although for this kind of particular project i.e. monitoring of steam traps a unidirectional microphone sensor can also suffice.

Current Consumption:

The CUI Inc. Microphone offers a current consumption of 0.5 milliamperes whereas the Knowles Piezoelectric Microphone records a current consumption of 160microAmperes. The Knowles Piezoelectric Microphone clearly possesses an advantage in this aspect.

Sensitivity:

The CUI Inc. Microphones possesses a sensitivity ranging from -46 to -42 dB’s whereas the Knowles Piezo-electric Microphones offers a sensitivity of about -69 dB’s.

Frequency Response:

A careful inspection of both the microphones with the before mentioned test apparatus was carried out. Great emphasis was taken on the fact that the situations and conditions e.g. distance between sensor and speaker, external noise etc. for both the microphones were the same so as to not observe any discrepancies.

Firstly, both the microphones Frequency Response Curves were compared. During the recording of the measurements, it was observed that the Knowles Piezo-electric Microphone showed better response and sensitivity towards frequencies ranging between 5 and 10 Kilo-Hertz than the CUI Inc. Electret Condenser Microphone. This is of great importance as theoretically the main area of operation will be between these frequency ranges. This fact was also observed when comparing the response curves of both the Microphones, hereby replicated.

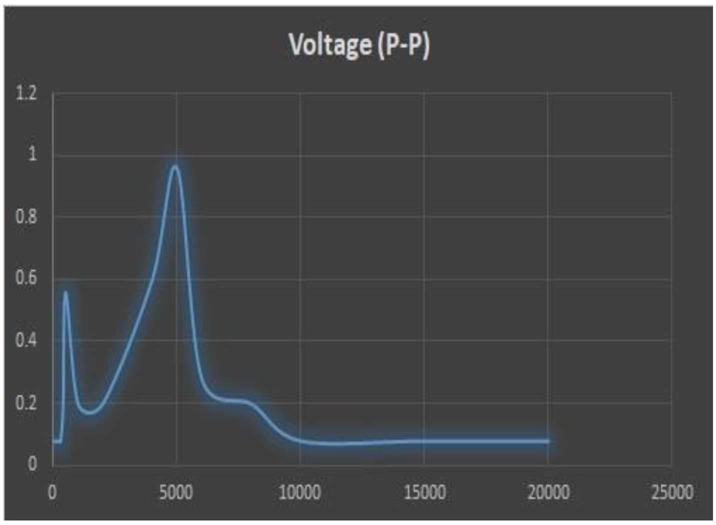


Figure 44. CUI Response Curve

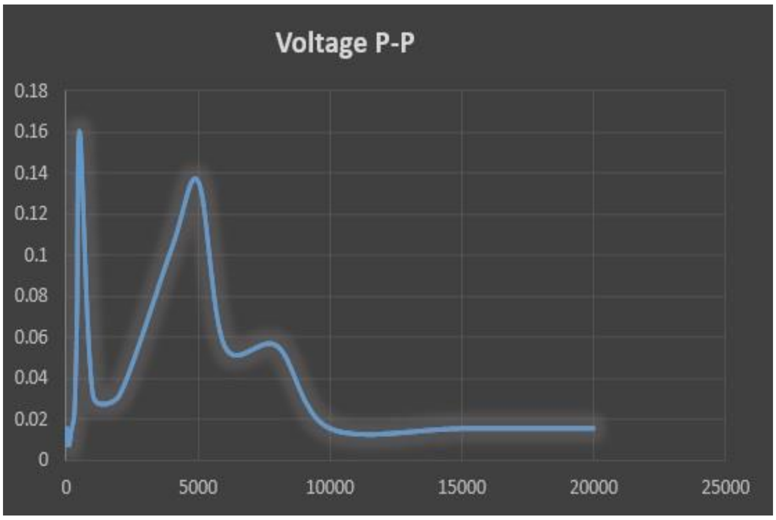


Figure 45. Knowles Response Curve

At this moment the response of the microphones was referenced with the IPhone microphone and it was observed that the behaviour of the microphones was like the reference microphone, i.e. A spike in measurements during the starting frequencies followed by another spike at 5000 Hertz, after which there is a decline in the measurements which is followed by another spike approximately in the range of 8000 Hertz. This spike is finally followed by a decline.

Proximity Effect:

As mentioned earlier, Proximity Effect causes bass frequencies to become more pronounced as the sound moves closer to the mic. Electret Condensers in general display a higher proximity effect than other kinds of microphones. Although not very significant but in this case also the CUI Inc. Microphones has a higher proximity effect than the Knowles Piezo-electric Microphone which can be an undesirable trait.

2.1.6 Decision

After carefully observing all the required parameters and the performance of both the Microphones, it was concluded that for this project, the Knowles Piezo-electric Microphone is the most suitable option. It offers greater response in the required frequency ranges, has lesser current consumption compared to CUI Inc. Microphone and overall has a desirable sensitivity.

2.2 Accelerometer

After carefully observing the performance parameters of the Microphones a decision was made on the choice of Microphone to be implemented and the Knowles Piezo-electric Microphone was selected. The next step is to integrate an accelerometer into the system. The accelerometer will act as a redundancy check for the system and will better aid the microphones in monitoring the steam traps.

This section contains information on the basic principles of the accelerometer, their functionality, different types etc. A brief analysis of the accelerometer which is under consideration will also be described in this section followed by the steps taken to ensure integration of the accelerometer within the constraints of the existing system.

2.2.1 Introduction

When a compass app is running on a smartphone, it knows which direction the phone is pointing. With stargazing apps, it knows where in the sky a person is looking at, to properly display constellations. All of this is possible with the help of accelerometers. Accelerometers have multiple applications in industry and science.

By definition, an accelerometer is a device which detects and measures proper acceleration. Proper acceleration can be defined as the rate of change of velocity a body experiences relative to free-fall and is the acceleration felt by people and objects [9].

Accelerometers have many widespread applications. For example, they can be used to detect and monitor vibrations in rotating turbines or can be used in drones for flight stabilisation. The motion sensors in accelerometers can even be used to detect earthquakes, and may be used in medical devices such as bionic limbs and other artificial body parts [9].

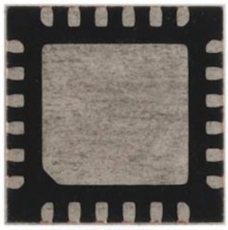


Figure 46. Typical 3 axis gyro accelerometer

Figure 47. Typical Accelerometer with excitation circuit

2.2.2 Physical Working Principle

As mentioned before, an accelerometer measures proper acceleration. Put another way, at any point in space-time the equivalence principle guarantees the existence of local inertial frame and an accelerometer measures the acceleration relevant to that frame. Such accelerations are popularly denoted as "G-Force".

An accelerometer at rest relative to the Earth’s surface will indicate approximately 1 g upwards, because the Earth’s surface exerts a normal force upwards relative to the local inertial frame (the frame of a freely falling object near the surface). To obtain the acceleration due to motion with respect to the Earth, this "gravity offset" must be subtracted and corrections made for effects caused by the Earth’s rotation relative to the inertial frame.

An accelerator looks like a simple circuit for a larger electronic device. Conceptually, an accelerometer behaves as a damped mass on a spring. When the accelerometer experiences an acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement is then measured to give the acceleration.

The accelerometer consists of many different parts and works in many ways, two of which are the piezoelectric effect and the capacitance sensor. The piezoelectric effect is the most common form of accelerometer and uses microscopic crystal structures that become stressed due to accelerative forces. These crystals create a voltage from the stress, and the accelerometer interprets the voltage to determine velocity and orientation.

The capacitance accelerometer senses changes in capacitance between microstructures located next to the device. If an accelerative force moves one of these structures, the capacitance will change and the accelerometer will translate that capacitance to voltage for interpretation. Typical accelerometers are made up of multiple axes, two to determine most two-dimensional movement with the option of a third for 3D positioning. Most smartphones typically make use of three-axis models, whereas cars use only a two-axis to determine the moment of impact. The sensitivity of these devices is quite high as they're intended to measure even very minute shifts in acceleration. The more sensitive the accelerometer, the more easily it can measure acceleration. Below is a figure of the internal structure of a piezoelectric accelerometer in compression mode [10].

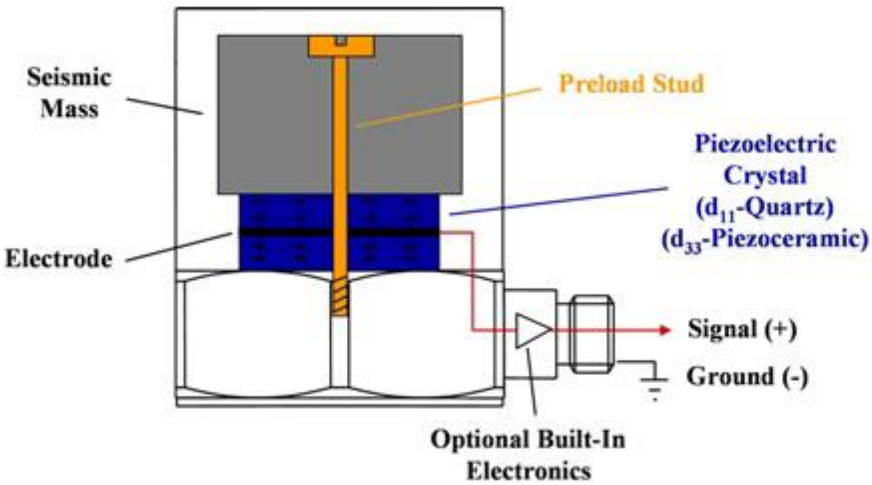


Figure 48. Piezo Accelerometer in Compression Mode

2.2.3 Types of Accelerometer

There are two classes of accelerometers in general [11]:

- AC Response
- DC Response

In an AC-response accelerometer, as the name implies, the output is ac coupled. An AC coupled device cannot be used to measure static acceleration such as gravity and constant centrifugal acceleration, for example. It is only suitable for measuring dynamic events.

A DC-response accelerometer, is DC coupled, and can respond down to zero Hertz. It therefore can be used to measure static, as well as dynamic acceleration. Measuring static acceleration is not the only reason a DC-response accelerometer should be selected, however.

<u>AC Response:</u>

The most common AC-response accelerometers use piezoelectric elements for their sensing mechanism. Under acceleration, the seismic mass of the accelerometer causes the piezoelectric element to "displace" a charge, producing an electrical output proportional; to acceleration. Electrically, the piezoelectric elements look like a source capacitor with a finite internal resistance, typically in the order of 109 ohms [12]. This forms the RC time constant which defines the high-pass characteristics of the device. For this reason, piezoelectric accelerometer cannot be used to measure static events. Piezoelectric elements can be natural or man-made. They come with varying degrees of transduction efficiency and linearity characteristics. Two types of piezoelectric accelerometer are available on the market:

- *<u>Charged Output Type:</u>*

  The majority of the piezoelectric sensors are based on lead zirconate titanate ceramics (PZT) which offer very wide temperature range, broad dynamic range, and wide bandwidth (usable to >10kHz). When housed in a hermetic, welded metal case, a charge mode accelerometer can be considered one of the most durable sensors because of its ability to tolerate hostile environmental conditions.

- *Voltage Output Type:*

The other type of piezoelectric accelerometer provides voltage output instead of charge. This is accomplished by incorporating the charge amplifier inside the housing of the accelerometer. Voltage mode devices feature three wire (Signal, Ground and Power) mode or two wire (Power/Signal, Ground) mode. The two wire mode is also known as Integral Electronics Piezoelectric (IEPE). IEPE is most popular due to its convenient coaxial (two wire) configuration in which the ac signal is superimposed on the dc power line. Unlike a charge mode device that only contains ceramic sensing elements, voltage mode device includes a microelectronic circuit which limits the operating temperature of the device to the maximum operating temperature of the electronics, usually at +125°C. Some designs push the limit to +175°C, but they come with compromises elsewhere in the performance envelope.

Figure 49. Voltage Output Type Accelerometer

DC Response:

A DC-response accelerometer is dc coupled, and can respond down to zero Hertz. It therefore can be used to measure static, as well as dynamic acceleration. Measuring static acceleration is not the only reason a DC-response accelerometer should be selected. However, two popular sensing technologies are used in making DC-accelerometers:

- *Capacitive:*

Capacitive type (based on the capacitance changes in the seismic mass under acceleration) is the most common technology used for accelerometer today. They are made popular by large commercial applications such as air-bag and mobile devices. They employ Micro-Electro-Mechanical Systems (MEMS) fabrication technology which brings economy of scale to high volume applications, hence lower manufacturing cost. But this class of low price capacitive accelerometers typically suffers from poor signal to noise ratio and limited dynamic range. One inherent characteristic with all capacitive devices is its internal clock. The clock frequency (500 kHz) is an integral part of the current detection circuit, which is invariably present in the output signal due to internal leakage. The high frequency noise may well be outside of the acceleration measurement range of interest, but it is always there with the signal. Due to its built-in amplifier/IC, its three wire (or four wire for differential output) electrical interface is straight forward, requiring only a stable DC voltage source for power.

Bandwidth of capacitive accelerometer is mostly limited to a few hundred Hertz's (some designs offer up to 1500 Hz) partly due to its physical geometry and its heavy gas damping. Capacitive sensor structure also favours the lower range of acceleration measurement. Maximum range is typically limited to less than 200 g's. Other than these restrictions, modern capacitive accelerometers, especially the instrument grade devices, offer good linearity and high output stability.

Capacitive type accelerometers are most suitable for on-board monitoring applications where cost may be the driving factor. They are suited for measuring low frequency motion where the g level is also low, such as vibration measurements in civil engineering.

Figure 50. Capacitive DC Accelerometer

- *Piezoresistive:*

Piezoresistive is the other commonly used sensing technology for DC response accelerometers. Instead of sensing the capacitance changes in the seismic mass (As in a capacitive device), a piezoresistive accelerometer produces resistance changes in the strain gages that are part of the accelerometer's seismic system.The output of most piezoresistive designs is generally sensitive to temperature variation. It is therefore necessary to apply temperature compensation to its output internally or externally. Modern piezoresistive accelerometers incorporate ASIC for all forms of on board signal conditioning, as well as in-situ temperature compensation.

Bandwidth of piezoresistive accelerometers can reach upwards of 7,000 Hz. Many of the piezoresistive designs are either gas damped (MEMS types) or fluid damped (bonded strain gage type). Damping characteristics can be an important factor in choosing an accelerometer. In applications where the mechanical input may contain very high frequency input (or excite high frequency response), a damped accelerometer can prevent sensor ringing (resonance) and preserve or improve dynamic range. Because the piezoresistive sensor output is differential and purely resistive. Signal to noise performance is generally outstanding and its dynamic range is limited only by the quality of the DC bridge amplifier. For very high g shock measurements, some piezoresistive designs can handle acceleration levels well above 10,000 g's. Due to its broader bandwidth capability, piezoresistive type accelerometers are most suitable for impulse/ impact measurements where frequency range and g level are typically high. Being a DC-response device, one can accurately derive from its acceleration output the desired velocity and displacement information without integration error. Piezoresistive accelerometers are commonly used in automotive safety testing, weapons testing, and higher shock range measurements beyond the usable range of VC accelerometers.

- *Other Types:*

Although vast in quantity there, are many different types of accelerometers present. These include:

- Laser Accelerometer

- Quantum (Rubidium atom cloud, laser cooled) Accelerometer

- Strain Gauge Accelerometer

- LVDT type Accelerometer

- Electromechanical Servo

- Seat Pad Accelerometer

- Optical Accelerometer

- Null Balance Accelerometer

2.2.4 Kionix KX022

The accelerometer considered for the current project is the KX022 by Kionix. To be accurate, an evaluation board of the KX022 accelerometer board is implemented. This section covers the basic details of the accelerometer, its specifications, functions and hardware amongst many other topics.

The KX022 is a robust, low-power, I^2C/SPI, 3-axis accelerometer with integrated FIFO/FILO buffer that features a wide range of embedded functionality, including tap detection, orientation, activity, and wake-up algorithms.

Kionix’s XAC sensor provides outstanding stability with a market-leading combination of improved shock, reflow, and thermal performance. The KX022 also offers accelerometer outputs with 16-bit resolution for greater precision. User selectable parameters include ± 2g, 4g or 8g ranges and Output Data Rates (ODR) with programmable high-pass and low-pass filters. It is packaged in an ultra-small, 12-pin, 2x2x0.9mmLGA plastic package.

Figure 51. KX022 Accelerometer

The accelerometer under consideration is embedded in an evaluation board. This evaluation board consists of all the required excitation circuits and tools for interfacing the accelerometer with the required device. Furthermore, it also contains a pressure sensitive pad which is directly connected to the accelerometer and can be used to detect taps, vibrations etc. among many other applications.

Figure 52. KX022 Evaluation Board

The internal circuitry of the evaluation board is mentioned below along with the pin configurations as per the datasheet provided by the manufacturer. It is to be taken into consideration that all of the resistors shown in the internal circuitry are 1%, 1/10W unless otherwise specified and all the capacitors are 0.1μF, 10% unless otherwise specified.

PIN	KX022	KX112	KX122
1	SDO/ADDR	SDO/ADDR	SDO/ADDR
2	SDI/SDA	SDI/SDA	SDI/SDA
3	IO_VDD	IO_VDD	IO_VDD
4	TRIG	TRIG	TRIG
5	INT1	INT1	INT1
6	INT2	INT2	INT2
7	VDD	VDD	VDD
8	GND	GND	GND
9	GND	GND	GND
10	nCS	nCS	nCS
11	NC	NC	NC
12	SCLK/SCL	SCLK/SCL	SCLK/SCL

Figure 53. Pin Configuration

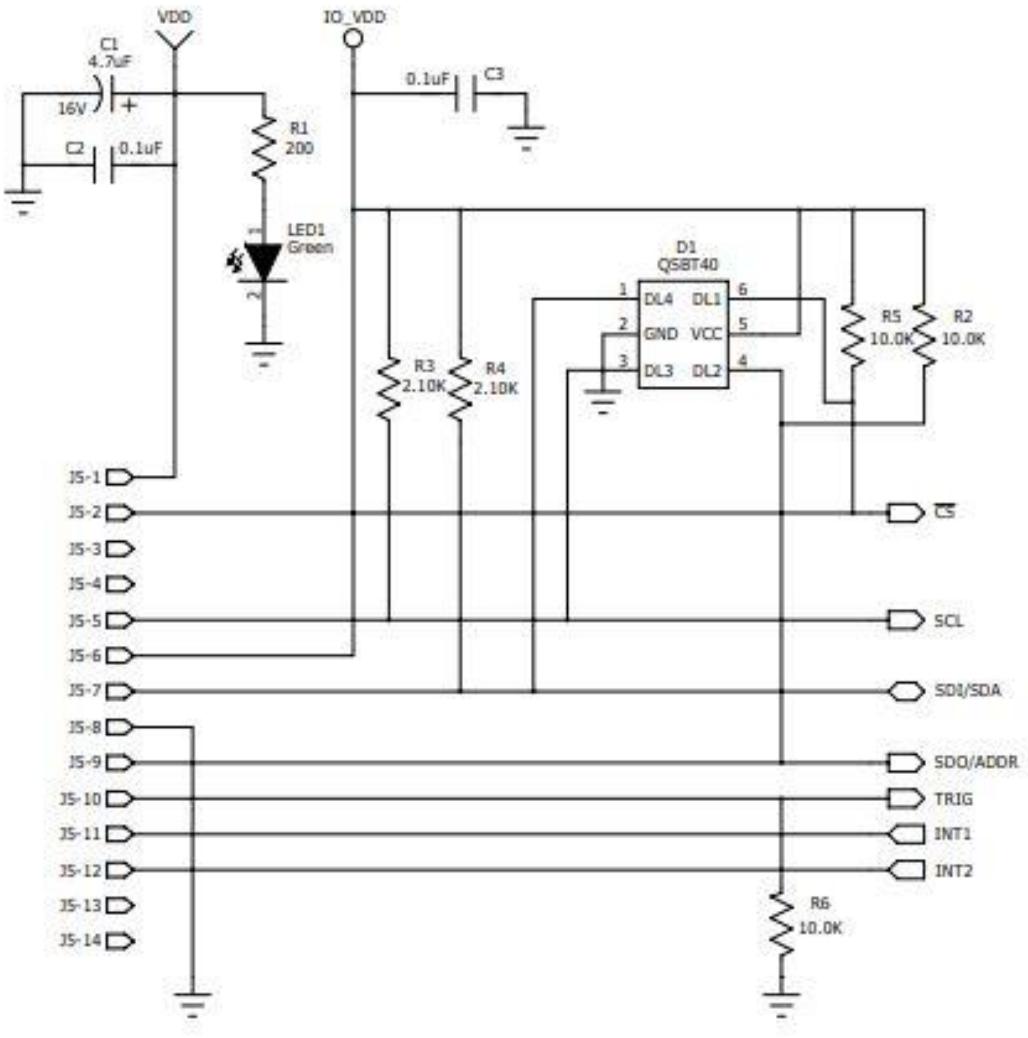


Figure 54. Internal Circuitry

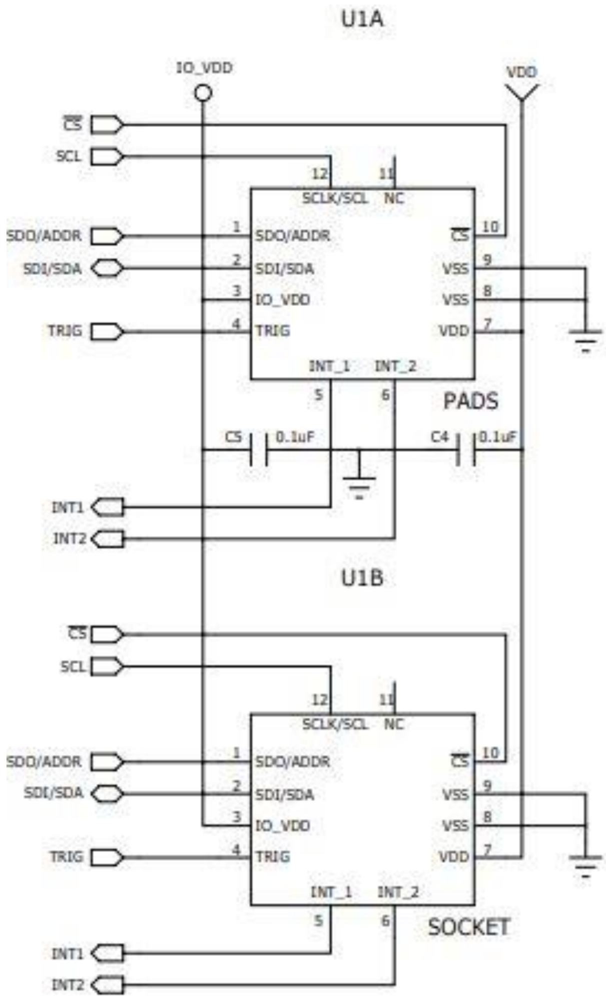


Figure 55. Internal Circuitry 2

As previously mentioned, the evaluation board consists of a KX022 accelerometer along with all the components required to excite and proper facilitate the functioning of the sensor. Some of its basic performance specifications are mentioned below.

- Sensor Type: Accelerometer, 3 Axis
- Sensing Range: ± 2g, 4g, 8g
- Interface: I^2C, SPI
- Voltage Supply: 1.71 V – 3.6 V
- Environmental Status: Lead Free/ RoHS Compliant
- Moisture Sensitivity Level: 3 (168 Hours)

2.2.5 Testing

The accelerometer is supposed to act as a redundancy check for the system. However there are certain constraints which have to be kept into consideration. Steam Traps are usually implemented in large refineries, power plants etc. and access to these facilities are restricted and limited.

The Kionix KX022 accelerometer is the proposed accelerometer which is to be taken into consideration and worked upon for the final product. However due to certain constraints such as time and lack of real testing environment, this accelerometer is not utilised and is reserved for future purposes. Instead the accelerometer of the IPhone is utilised for testing, to gain an understanding of the vibrations. Since vibrational values for both the accelerometers will be identical, it is beneficial in this case to test using the IPhone accelerometer. The previously mentioned app "Sonic Tool" in this case also contains added capabilities of vibrational analysis by utilising the accelerometer available in the IPhone. It displays the values in ’G’s at Y-axis against ’Time’ in axis.

As such, the proposed simulation technique includes a pressure cooker containing boiling water. The accelerometer is placed on the lid of the pressure cooker and the vibrational readings were then recorded. Upon observation it was revealed that the values of this simulation in ’G’s was based between the range of 0.7 to 1.3 G’s, which indicated that these range of values are to be expected when the trap is in ’Closed’ state and there is a combination of Steam and Water present in the trap. Furthermore, it also proves that when the trap is in ’Open’ position and only Steam is flowing through it, there will be less vibrations and the overall values of G’s will decrease and be lower than this particular range. A graph of the accelerometer displaying the results of the proposed simulation is mentioned on the following page.

Figure 56. Accelerometer Reading

In conclusion, this section provides the necessary information required to have a general idea about the functionality and working principals of the accelerometer. A general idea about the proposed accelerometer and its characteristics are also provided. Furthermore it mentions the test conditions which were set up to test and obtain results from the reference accelerometer. These values can be taken as a reference for adding future enhancements and functionalities if required.

2.3 Physical Architecture (Prototype)

After carefully observing the performance, functionality and characteristics of all the sensors involved, the next step is to develop a basis for a prototype which could later be worked upon to create a complete market ready product. It is necessary to have a concept or direction as to how the product is supposed to take shape and this is what will be explained in the current section. This section will also cover in detail, the steps taken for the construction of the prototype along with all the equipment used.

Various tools were utilised for the construction of the prototype. Some of these tools were previously available while some were not. For the tools which were not available, local 'Ferreteria' shops were contacted and their tools utilised. These tools include:

- Metal Sheets
- Bolts
- Screw Driver
- Thermally Adhesive Tape
- Pliers
- Metal Shear

2.3.1 Construction

This section provides a brief view of all the required steps undertaken during the construction of the prototype. The initial aim was to construct the prototype in a way that provides the sensors to be as close to the steam traps as possible without necessarily coming in contact. The structure of the laboratory test apparatus was considered.

An initial concept was first sketched and it was formulated that the apparatus will be cube shaped and of metal. [13] [14] Metal structure was selected because it would withstand high temperatures and reflect the sound also. Furthermore, it was formulated that there will be a support inside the structure where the wires, PSoC and other circuits will be placed. Regarding sensors, it was decided that there will be an opening at the bottom of the structure where the sensors will be placed for sensing. The initial design scheme is mentioned below.

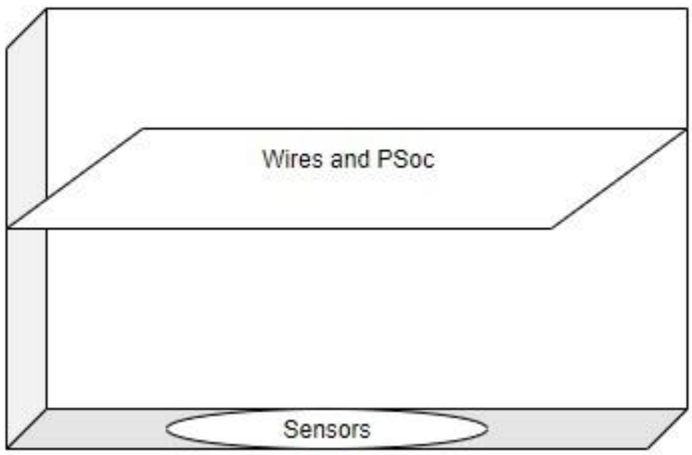


Figure 57. Initial Design Scheme

The first step in the construction process was to cut the metal sheet into desirable pieces. Metal sheets were selected because it will allow less external noise to come inside the system all the while allowing less noise to leak out of the system. The aim is to construct a housing that can encompass all the sensors, the PSoC, Power supply and all the wires associated with them. As such the concept was to build a cube shaped housing. Hence, the metal sheet were cut into squares by metallic shears. It is to be kept under observation that these squares share the same dimensions as the laboratory test apparatus on which the microphones were tested.

Figure 58. Metal Sheet

The next step was to join all these metal sheets in the form of a cube.

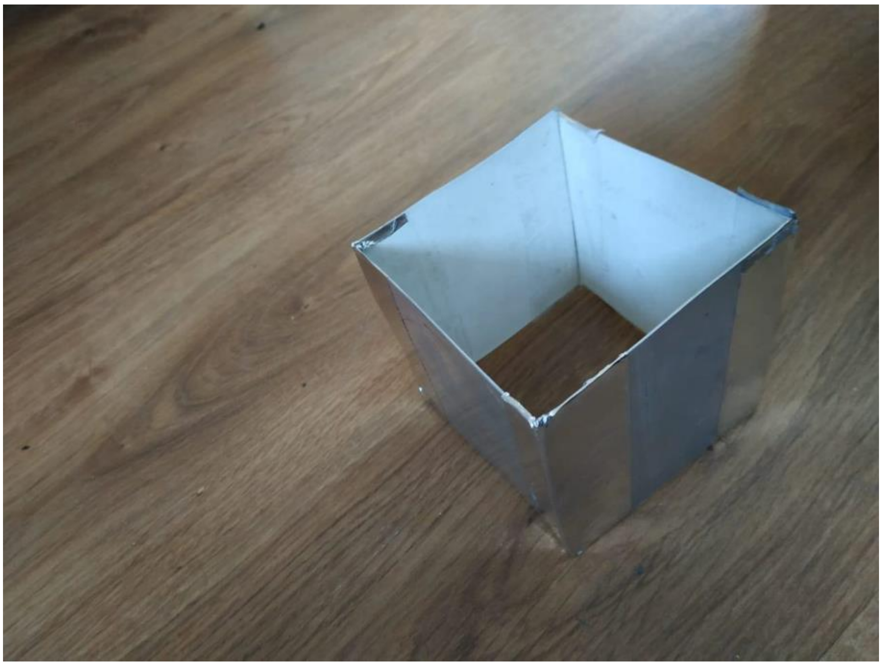


Figure 59. Cube Construction

The base of the cube in left open as it is where the sensors will be in close proximity to the steam traps while the top is removable so as to provide ease of access to place all the components inside the housing and also to close the housing so that external noise is reduced. The next objective was to provide a base to place the PSoC and all the circuitry inside the housing. Three small metal strips were aligned in an ’H’ shaped order. It is to be kept under observation that all the components in the housing are joined together using thermally adhesive tapes and glue.

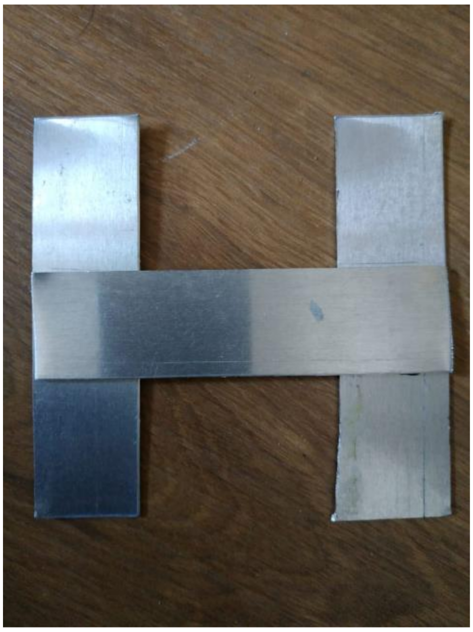


Figure 60. H Shaped Base

This base was then lowered into the housing and properly attached.

Figure 61. Base for Components

The next objective is to develop a base to attach all the sensors. This process is of great importance for the fact that this base needs to be exactly according to the requirements of the sensors. The accelerometer will measure vibrations and as such the material connected to it must compliment vibrations. For this reason a very thin metal strip was selected and a hole drilled into it. The concept is that if the strip is very thin, then it will provide more vibration as compared to a strip of a thicker material. The hole will be the location of the sound sensor.

Figure 62. Metal Strip

This metallic strip was then bent from one side and attached to the base of the housing. Now, the microphone and the proposed accelerometer are attached to the metallic strip. The accelerometer is attached in an inverted position with its vibration sensitive surface in direct contact with the base of the strip. This orientation i.e. inverted position is considered primarily for two reasons. The first being the fact that since the metallic strip is very thin, it will undergo vibrations which the accelerometer can directly sense from the strip. The second is the fact that even if there is little or no sense-able vibrations in the strip, it is still close to the steam trap. In this way it will also be able to pick up vibrations from the steam trap directly also.

Figure 63. Housing with strip attached

Finally, the last perimeter required to complete the physical architecture of the prototype is ‘Height Management’. It would be very beneficial if the distance between the steam traps and the housing is adjustable since there are multiple types of steam traps available and not all of them are of the same size and orientation. Hence, with the help of bolts, four adjustable legs were provided to the housing. These legs will be attached to clamps. The clamps will connect the housing to the steam trap and the legs will be used to adjust the distance between the sensors and the steam trap.

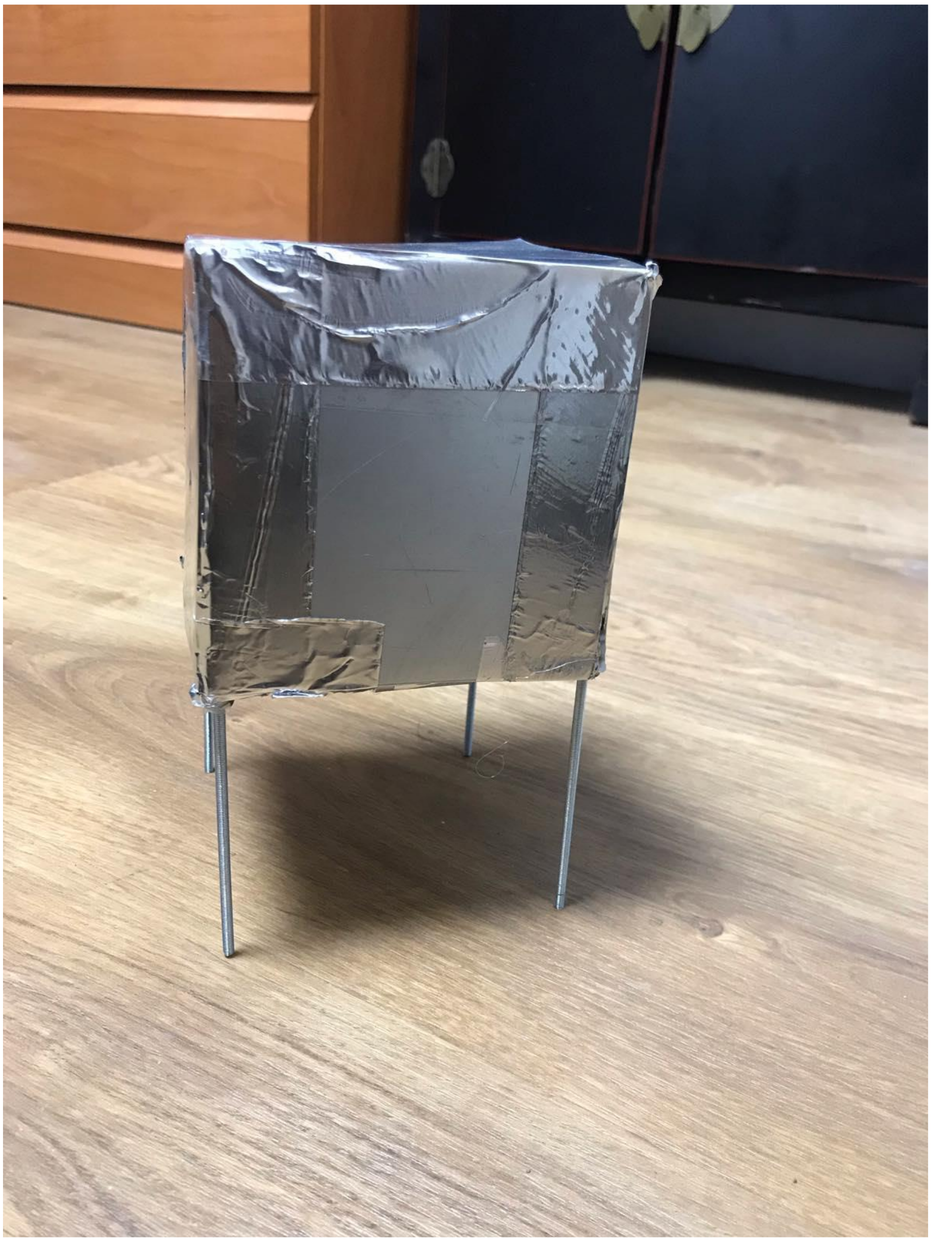


Figure 64. Final Prototype with Height Adjustment

The previously mentioned prototype will serve as a basis and reference for further advancements when required. The inclusion of thin metallic strip and height management will provide increased functionality and is a key aspect of the proposed system.

3. Method and Results

This section covers the software related dimension of the project. An in-depth analysis from a programming point of view will be undertaken in this section. The reasoning and the approach towards solving the given project will also be displayed. Furthermore, a brief description of the programming environment will also be provided.

The first step is to formulate an algorithm to what are the conditions for the system. If the conditions are available then, planning forward is simpler. The initial condition of the steam trap is very significant. It was formulated that comparisons of the initial and present state of the steam traps will serve as the basis of the methodology. A flowchart was designed as reference for both the conditions.

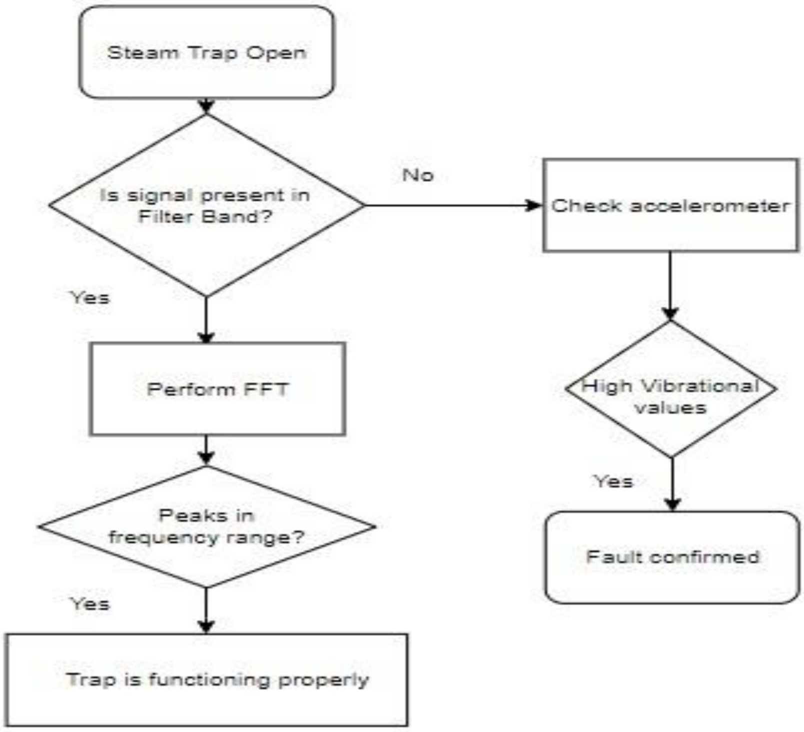


Figure 65. Trap Open

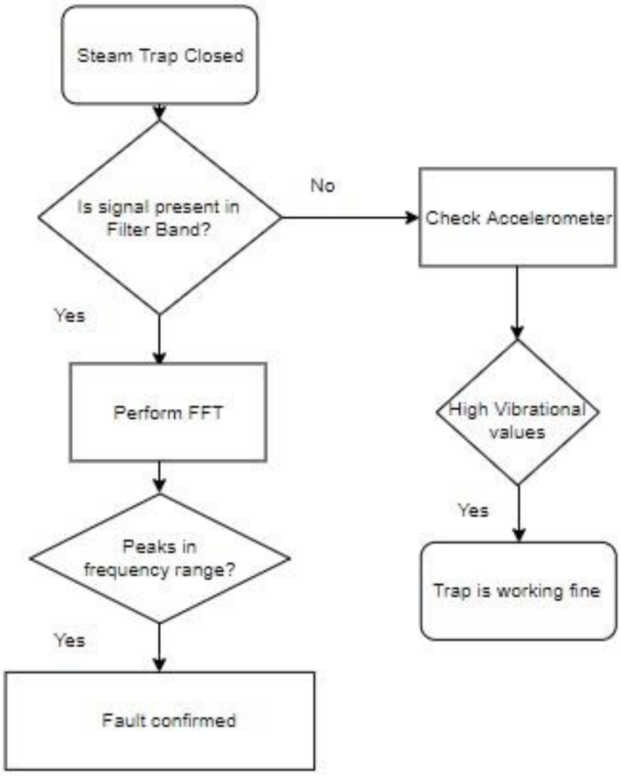


Figure 66. Trap Closed

The next step was to determine the frequency ranges at which the steam traps operates to formulate a method of approach. A research was done regarding this by the University of Campinas, Brazil and frequency ranges were established when steam is travelling at high pressure through small holes or orifices [15]. This article states that in steam traps, the smaller the size of the orifice, the higher the frequency will be. Orifices that were tested were between the ranges of 1mm to 5mm in diameter. The predominant frequency ranges for all of these orifices lie in the region of 4 to 8 kHz with the largest orifice having the lowest frequency and vice versa. At this moment it was decided to implement a bandpass filter. It was decided that if a signal is in the filter range and their initial state is known, then the accelerometer and the Fourier transform could be used in combination to detect fault in the trap.

When the trap is closed or there is a fault and it is closed, the condensate starts collecting. This condensate is still very hot and if not released in time can cause backlogging which can physically damage the equipment around. This prompted the approach that if the condensate is gathering and there is backlogging then, there will be stronger vibrations in the steam trap which could be picked up by the accelerometer. The accelerometer provides a redundancy check to the bandpass filter output.

Now, that this concept has been given a proper structure, the next step will be to implement this on the PSoC Creator which will be the programming interface for the PSoC. The PSoC incorporates both modular and tabular forms of programming where system and off chip components and their interconnections will be available as modules and their operational specifics will be defined by coding. Once the coding has been completed, the next step will be to find access to a facility with steam traps to test them with the system or simulate the behaviour of the steam trap.

3.1 PSoC Creator

PSoC Creator is an Integrated Design Environment (IDE) that enables concurrent hardware and firmware editing, compiling and debugging of PSoC and FM0+ systems. Applications are created using schematic capture and over 150 pre-verified, production-ready peripheral components.

Components are analogue and digital peripherals represented by a symbol that users drag and drop into their designs and configure to suit a broad array of application requirements. Each Component in the Catalogue is configured with a customizer dialog and includes a full set of dynamically generated API libraries. After configuring all the peripherals, firmware can be written, compiled, and debugged within PSoC Creator or exported to leading third party IDEs.

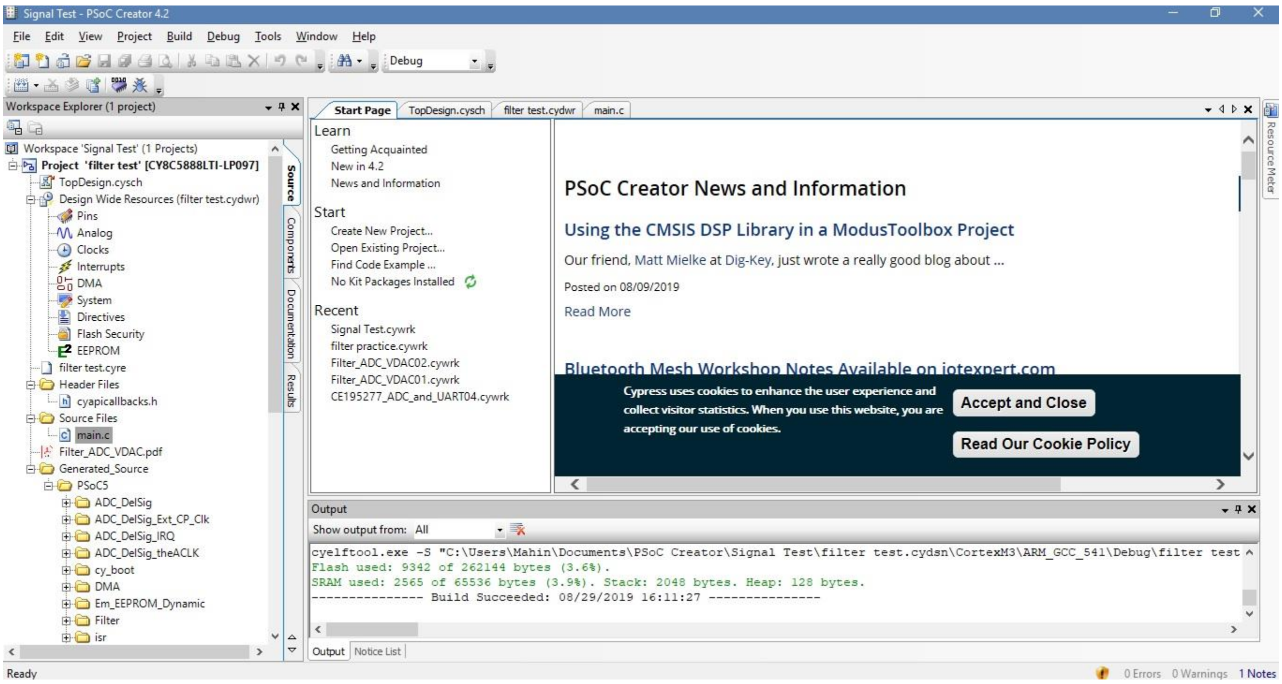


Figure 67. PSoC Creator Interface

3.2 Programming

This section includes the step by step processes that were undertaken so as to acquire the objective of the project. As previously mentioned, the PSoC contains blocks of many on-chip and off-chip components. Once these blocks are placed on the schematic and the program is generated the PSoC Creator loads all the required libraries automatically for programming. The final programming is then done on a 'Main.c" file.

The initial step or the beginning phase is to introduce sampling. Since the sound signal will be analog, it is very important that it be converted to a digital signal so as to enable proper processing. A Delta-Sigma ADC has been utilised for this case. Its Sample Rate has been set to 48000 Samples per Second (SPS). Furthermore, an Op-Amp is also introduced so as to provide maximum input swing.

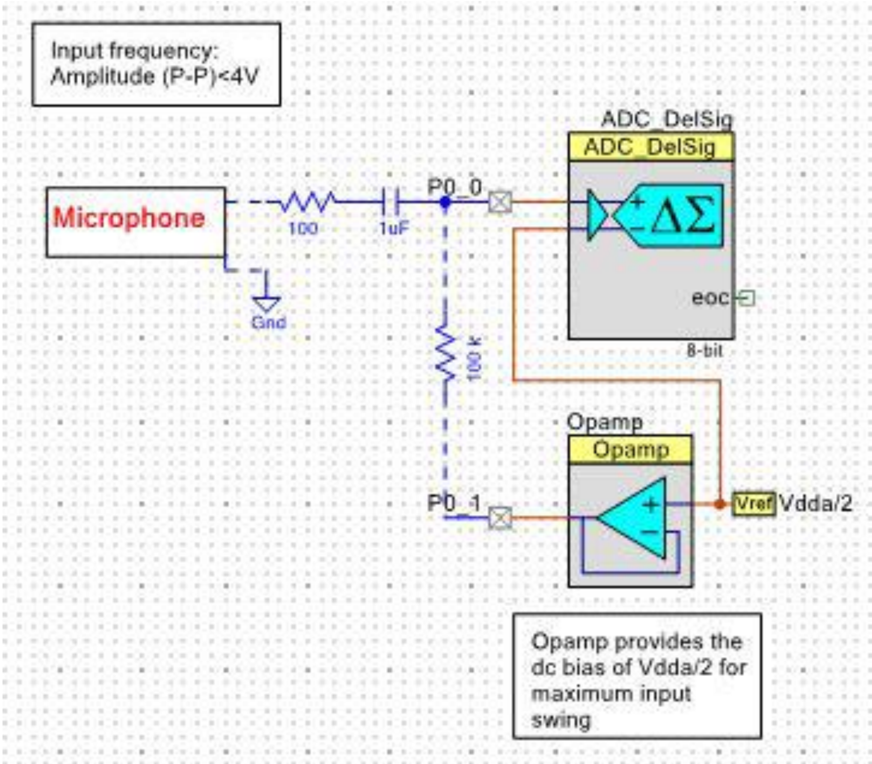


Figure 68. Sampling and ADC

The next step is to introduce a bandpass filter. The PSoC creator has a 'Digital Filter' which provides access to the Digital Filter available inside the PSoC 5LP. This filter can be configured in many different ways and its properties configured according to the requirements. It can be configured as a low-pass, high pass and band pass filter with FIR and IIR filter class options. For this schematic, the sampling frequency of the filter is set to 48000 samples per second and the Centre Frequency is set to 8 KHz with low cut-off frequency at 5 KHz and high cut off frequency at 11 KHz. An important fact to be taken into consideration is that the filter frequency ranges are programmable and can be changed according to requirements or if need be. Furthermore, the option of a dual filter is also available adding further functionality for future applications.

To pass information to the filter a Direct Memory Access (DMA) block has to be introduced. The DMA component allows data transfers to and from memory, components, and registers. The controller supports 8, 16 and 32-bitwide data transfers, and can be configured to transfer data between a source and destination that have different endianess. A DMA component is useful when you want to unburden the CPU of the task of transferring data or when data needs to be transferred in a predictable way that can be set up beforehand.

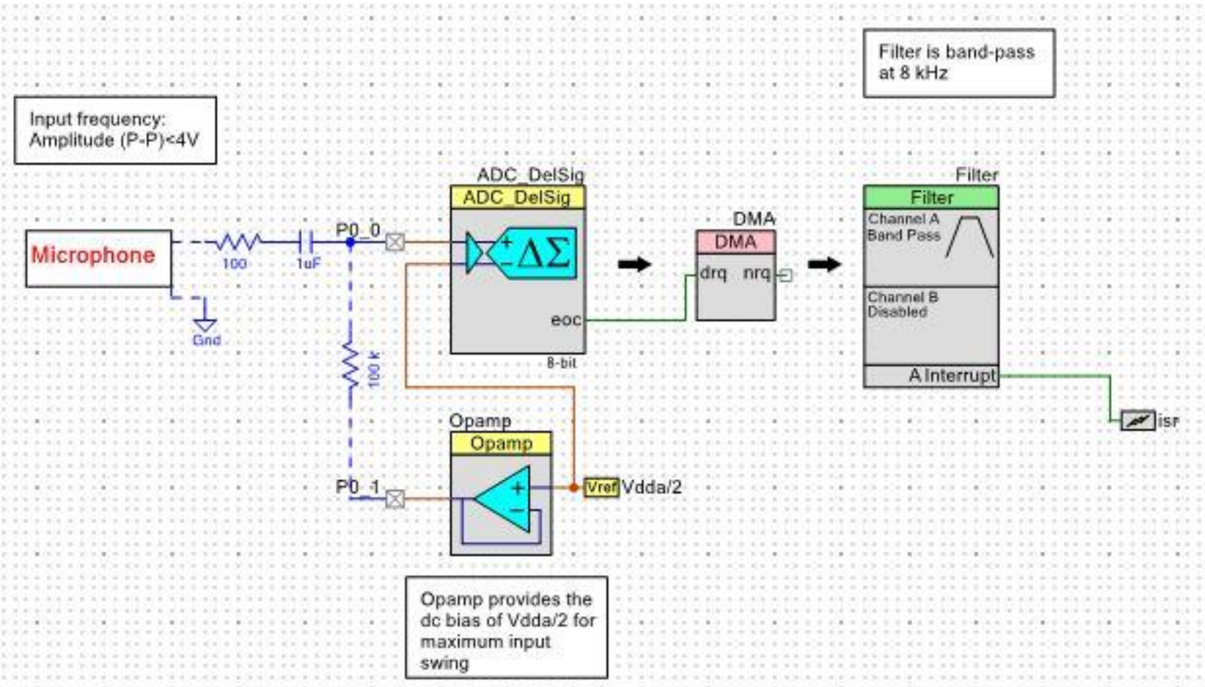


Figure 69. Filter Implementation

The next step is to introduce the Fast Fourier Transform ’FFT’. This is the second and final redundancy check applied to the system. Fourier analysis converts a signal from its original domain (often time or space) to a representation in the frequency domain and vice versa. Since there is no specific block available for FFT in the PSoC creator, the process of FFT has to be coded manually. Furthermore it is to be kept in consideration that since the input signal is sound and not a constant signal, the FFT will display peaks in a range of frequencies and not just one exact peak.

. The concept once again in short is as follows:

- Take readings from the microphone sensor.

- Check the Pre-determined state of the trap.

- If the trap is supposed to be open and there is signal in the filter frequency range, then the trap is functioning normally. Perform the FFT and confirm this by obtaining higher peaks in the frequency range. If not then there is a fault.

- Check the reading from the accelerometer. If the accelerometer displays high values of vibration than usual, then the fault is confirmed.

- If the trap is supposed to be closed and there is no signal in the filter frequency range, then the trap is functioning properly. If not then there is a fault. Perform the FFT and confirm this by obtaining higher peaks in the band-pass frequency range.

- Check the readings from the accelerometer. If the accelerometer displays lower values of vibrations than usual, then the fault is confirmed.

3.3 Results

This section covers the results obtained after providing data and real life conditions to the system. It will further explain the conditions and environment that were set up to test this system and will display some analysis related to it.

The prototype is now ready to be tested in real life conditions. However there are a few constraints. Primarily, the fact that there is no access to steam traps. However, this system is versatile and all the components individually programmable as per the specifications. As such, a similar environment to the steam traps was implemented. This was done with the help of pressure cookers.

Readings based on two conditions were monitored from the pressure cooker. The first condition was when steam is being released by the pressure cooker. This was introduced to simulate the condition of a faulty steam trap not releasing steam. Audio was captured starting from 5 seconds before the steam being released to 10 seconds after the steam was released. If the system is working as it should be, then it should detect signal in the bandpass filter range which has an upper limit of 11 kHz. This would mean that when this system is applied on a steam trap and the initial condition is open but the steam trap is faulty and is closed, then this signal will be present in the bandpass filter range thus proving that the steam trap is faulty.

The second condition is when the water is boiling with steam and liquid both present inside the pressure cooker. This was introduced to simulate the condition of a faulty steam trap releasing steam. Audio was captured in the same manner as the previous condition. If the system is working fine then there should be no signal in the bandpass region. However, the previous condition at this point will be that the trap is supposed to be open so since there is no signal in the bandpass frequency region, it will confirm that the steam trap is faulty.

These conditions were set up in order to simulate as close as possible, the behaviour of the steam traps under these faulty conditions. Other analysis were also done to observe the behaviour of the system and how it responds to real-life conditions.

The results of the FFT for the first condition (faulty steam trap releasing steam) are shown below.

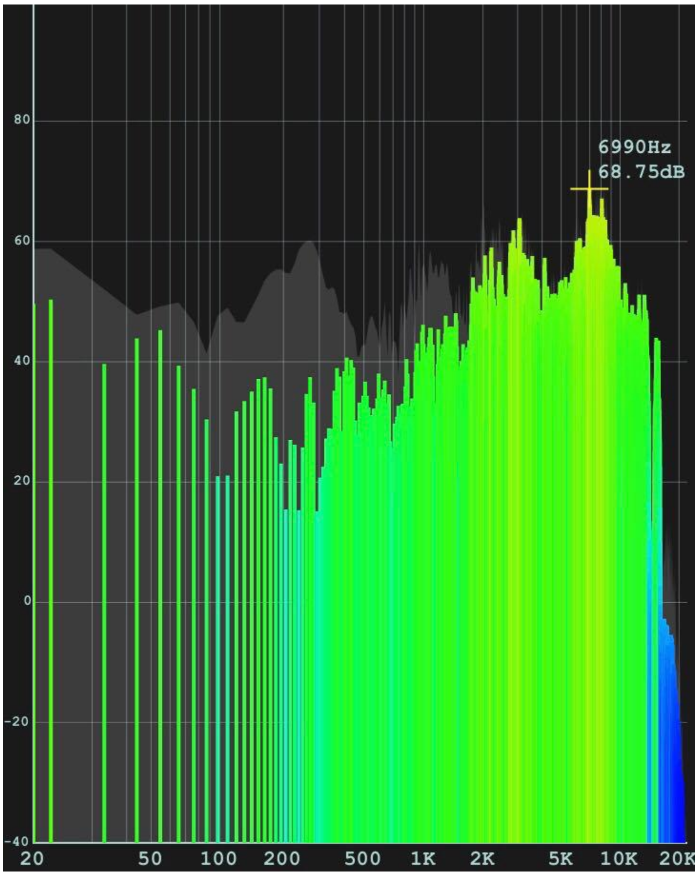


Figure 70. Spectrum when trap is open

The previously mentioned hypothesis and references are all verified with this test. The frequency range is around 7 KHz as per expectations. For further analysis the Power Spectral Density (PSD) is also taken for this condition and analysed using Matlab. If the peaks of the PSD are out of this range then it signifies that the targeted band is not active. It is to be kept in consideration that the normalized power of the filter is taken and this particular normalization is done with ambient conditions. The PSD is also presented.

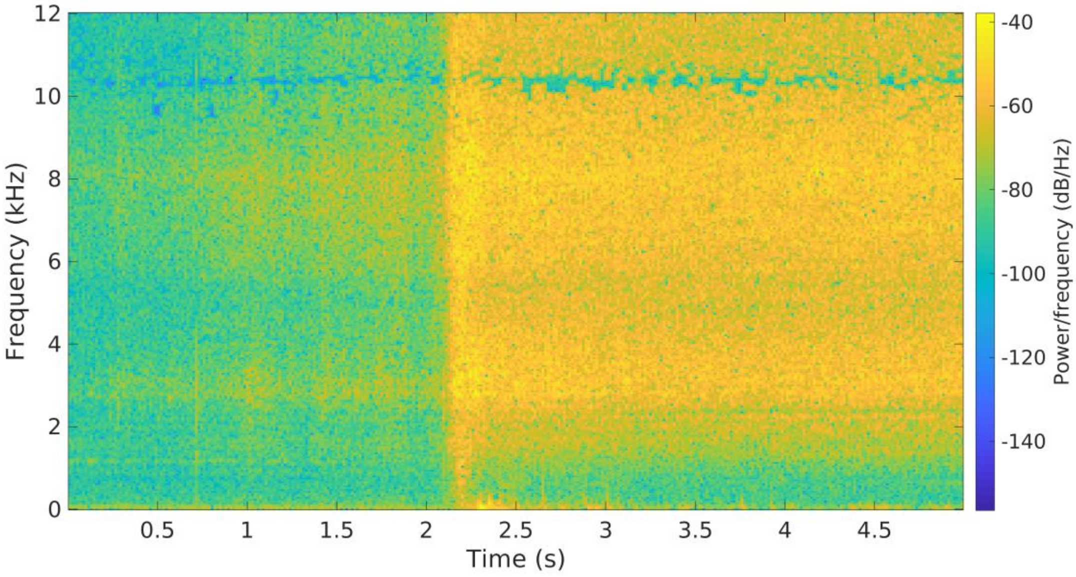


Figure 71. PSD When Trap Is Open

The shift in frequencies is clearly observable in the spectrum at the 2 second mark which is where the steam starts being released i.e. trap closed and steam leaking through orifice. The FFT for the second condition (faulty steam trap releasing steam) are shown below.

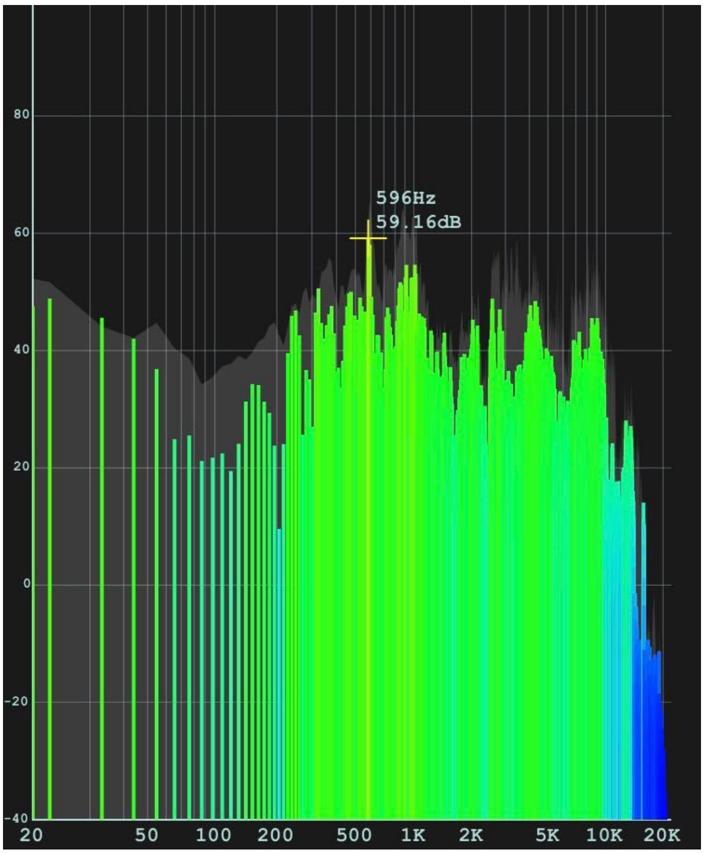


Figure 72. Spectrum When Trap Is Closed

This also verifies the previous hypothesis and tests and states that when the trap is closed and there is a mixture of steam and water present, the frequency range shall be below 4 kHz [15]. The Power Spectral density also observes no specific changes and is constant throughout.

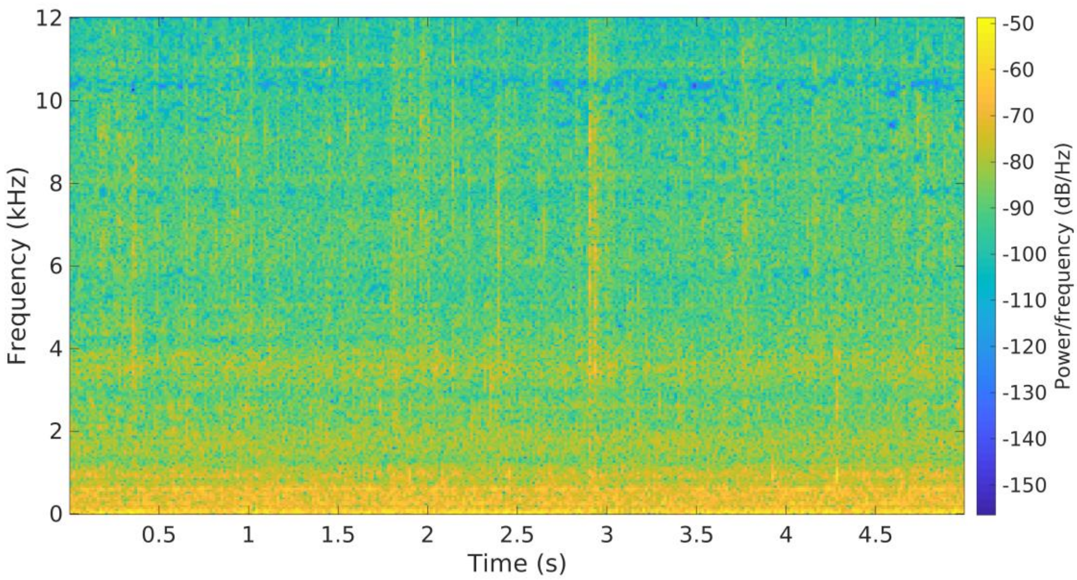


Figure 73. PSD when Trap Is Closed

In conclusion, it is observed that both the faulty conditions are being detected by the system. When the trap is faulty and not releasing steam, the signal is spotted in the bandpass filter frequency range and when the trap is faulty and releasing steam no signal is spotted in the bandpass filter region. The system when implemented on actual steam traps will work in the same way. It will check acquire the signal and cross-reference it with the initial state and process the data to generate results. The results obtained in this section verifies and solidifies the basic concept and hypothesis that was implemented with quantifiable values.

4. Conclusion

As mentioned in the beginning, the aim of this project is to develop an algorithm or a system that can monitor and detect faults in the steam traps. The project started with first developing an understanding of the functionality of the steam traps and then progressed to selecting the components required, building a physical prototype, developing a methodology and a way of approach to the problem, formulating the code and then implementing it on the system. Finally the results were then analysed, processed and the methodology that was adopted verified.

In doing so, the goal to propose a system that provides a solution for autonomously monitoring and detecting faults in steam traps by utilising low power programmable system on chips I achieved. Furthermore, this system is energy efficient and eliminates the need to hire a third party to personally check the steam traps. It also has a two tier redundancy check to increase the accuracy of fault detection thus reducing operational costs.

In future, this technology can be used in other disciplines also. It can be implemented to check the proper functioning of turbines. The accelerometer and microphone can sense the vibrations and internal noise of the turbine to determine its smooth functioning. It can also be used in security systems for motion detection. Furthermore, it has high functionality in wearable electronics for pulse sensing, orientation, speech recognition and can be used in medical equipment too. The PSoC's versatility also enables to provide the system with completely programmable specifications for each and every PSoC component involved thus enabling flexibility and customisations tailor made according to the situation.

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Appendix

Code for Fault Detection

```
double norm_power(double filtered_signal_array[16],double max_value_of_signal,int
walve_state)
//function details
{
	double normpower = 0;
	int fault_status = 0;

	for(int i=0;i<16;i++) // This loop finds out the average power contained in the input
signal
	// For frequencies outside bandpass range, this will return small values
	{
		filtered_signal_array[i] = filtered_signal_array[i]/max_value_of_signal;
		normpower = normpower + filtered_signal_array[i]*filtered_signal_array[i];
	}
	normpower = normpower/16;
	// There are total 16 samples in the signal, so we are taking average over 16
	// If you decide to change number of samples, change this too



	double decision_threshold = max_value_of_signal*max_value_of_signal/2;
	// Decision threshold is half the supposed maximum power. For 4 volts peak to peak,
its 2
	// (amplitude squared/2: 2*2/2). You can change this threshold for more sensitivity,
for example,
	// instead of half power, you can go for 1/3

	if(walve_state==0) // walve is closed
	{
		if(normpower<decision_threshold) // the steam whistle is not detected (band
power is lower than threshold)
```

```
		// since valve is closed, so we should not hear steam whistle, no fault
		{
			fault_status = 0;
		}
		else // the steam whistle is detected (band power is higher than threshold)
		// since valve is closed, so we should not hear steam whistle, fault
		{
			fault_status = 1;
		}
	}
	else
	{
		if(normpower<decision_threshold) // the steam whistle is not detected (band
power is lower than threshold)
		// since valve is open, so we should hear steam whistle, fault
		{
			fault_status = 1;
		}
		else // the steam whistle is detected (band power is higher threshold)
		// since valve is open, so we should hear steam whistle, no fault
		{
			fault_status = 0;
		}
	}
	return fault_status; // fault status is returned
};
```