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“Development of foreign body detection methodology in industrial food preparation process”

Master’s thesis

Supervisor

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ABBREVIATIONS

FB	Foreign body
NIR	Near infrared
FTIR	Fourier transform infrared
NDT	Non-destructive technique
NMR	Nuclear magnetic resonance
MRI	Magnetic resonance imaging
FEM	Finite element modelling
SPICE	Simulation program with integrated circuit emphasis
FE	Finite element
FEA	Finite element analysis
SONAR	Sound navigation and ranging

INTRODUCTION

In Today's world, packed food and beverages are widely consumed. Technological advancement become an important factor for rising of the food science and technology sector. Most packaged beverages and food comes in plastic, aluminium, glass and paper packaging. Canned food is now widely available for sale and its consumption has risen significantly in recent times.

Consumer may become a victim of a disease or get injured due to the presence of foreign bodies in food. Foreign bodies, which come from the raw materials used in the food product or packaging materials, are called intrinsic while extrinsic foreign bodies originated from an external source. Foreign bodies in food constitute one of the most serious causes of consumer complaints and can result in substantial losses and brand damage. Especially for the food products, which targets younger kids and babies, FB in food can cause worst problem to them.

The sorts of physical contamination present in food vary largely depending on the type of food in question, the different contaminant materials incorporate wood, plastic, metal, glass, animal origin, paper and cardboard and many more. Sources for such contaminants incorporates raw materials, poor maintenance of an equipment, improper manufacturing procedure and poor employee practice [1]. It is naturally desirable for manufacturer that all foreign bodies are found and removed before they reach the consumers.

The aim of this thesis is to analyse the detection possibilities of foreign bodies in pumped liquid foods using ultrasound technique by simulation or Finite Element Modelling. FEM simulations can be done using any simulation software available in today's market. Such simulation allows to study and optimize the system before it is physically constructed. Thus it saves cost and amount of time required in building up system. COMSOL Multiphysics 5.2 is used for this thesis work. Simulation results can be able to give information on the FB detection capability by using ultrasound, In addition, It allows to modify system dimension and physical properties such as diameter of food pipe, location of ultrasound transducer, flow rate of food and many more.

1 LITERATURE OVERVIEW

1.1 Techniques

Now a day's various methods and techniques are available for the detection of FB. The optimal approach depends upon the nature of the food and possible FB materials present in it.

A) Metal detection

Metal detection is a standout amongst the most widely recognized and most seasoned form of foreign body detection although it remains a huge reason for worry in the food industry. The operation of metal detectors is based upon the principles of electromagnetic induction [2].

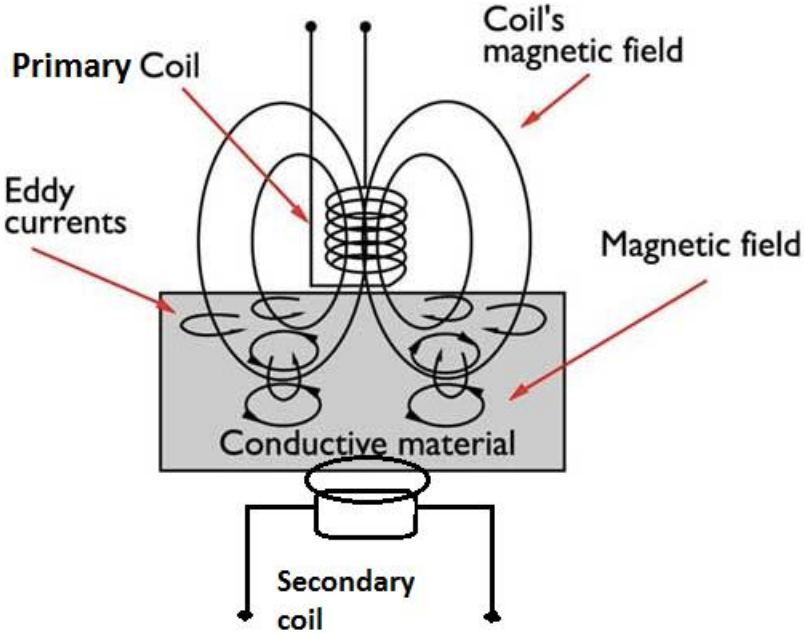

Figure 1. Schematic diagram of electromagnetic induction principle

It comprises of two coils, transmit coil and receive coil. The transmitted magnetic field interacts with metal and produces eddy current, which in turn produces a weak magnetic field. This regenerated magnetic field is captured as a voltage signal at receiver coil. All metals have characteristics that will cause an alteration in the transmitted signal, because of their conductivity and magnetic properties. Non-metallic material does not interfere with the transmitted magnetic field. In a food processing line, metal detector will compare the signal received with the expected signal and identify the presence of a contaminant if a variation is observed [3].

Table 1. Detection capability of metal detectors [4].

Aperture height	Dry product	Wet product	Wet Product
	Ferrous & non-ferrous	Ferrous	Non-ferrous
Up to 50 mm	1.0 mm	1.5 mm	2.0 mm
Up to 125 mm	1.5 mm	2.0 mm	2.5 mm
Up to 200 mm	2.0 mm	2.5 mm	3.0 mm

Limitation:

- Only detects conductive materials.
- Conductive food products add an extra strong signal to the signal of contaminant but using digital signal processing technique, one can remove that extra signal caused by the food product itself

B) X-ray Imaging

X-ray is a form of electromagnetic radiation. This technique uses the absorption/transmission of X-rays to produce images. Two and three dimensional images can be constructed using computed tomographic imaging. X-rays has a capacity to differentiate materials on the basis of their varying densities which makes possible for X-ray imaging technique to be utilized for recognition of contaminants such as metal, stone, glass, dense plastics and calcified bone [2].

Applicability to liquid in pipes:

X-ray Imaging System can be attached to the pipe which carries liquid food. There exist on the market pipeline X-ray systems for the continuous assessment of pumped items [2].

Capability [5]:

Table 2. Detectable contaminants

Contaminant type	Density (take water density as 1.00)
Iron	7.15
Steel	7.86
Stainless steel	7.93

Table 3. Possible detectable contaminants

Nylon	1.15
PVC	1.38
Teflon	2.19
Calcified bone	2.20
Stone	2.50
Glass	2.50
Aluminum	2.71
Dense rubber	1.52

Pros and uses [2]:

- Can penetrate inside the sample travelling through packaging
- Non-destructive technique, non-contact technique

Cons and limitation [2]:

- More instruments needed for spectrum analysis.
- Solid state detectors are expensive.
- Focus only on a small area at a time.

- Hard to detect insects, wood, hair, cardboard and paper

C) RAMAN SPECTROSCOPY

Raman Spectroscopy is a form of vibrational spectroscopy. It provides information on rotational and vibrational modes or low frequency modes in materials which are unique to that substance.

Applicability to liquid in pipes:

It is easy to obtain Raman spectra of a liquid but its inhomogeneity and fast moving can make it difficult.

Pros and uses [2]:

- Non-contact and non-destructive type

Cons and limitations [2]:

- No commercial solution available in market for food.
- Fluorescence can make it difficult to identify Raman spectra.
- Hard to expand this technique in this application.

D) NEAR INFRARED SPECROSCOPY

NIR spectroscopy uses the near infrared region of the electromagnetic spectrum (from about 800 nm to 2500 nm).

Applicability to liquid in pipes [2]:

Diameter of pipe should be small enough for the NIR signal to penetrate. Water in liquids absorbing the NIR signal can cause a problem.

Pros and uses [2]:

- Easier maintenance than X-ray machine.
- Non-ionizing radiation (safer than X-ray)
- Non destructive

- Good applicability to dairy products and fruit

Cons and limitation [2]:

- Short penetration length
- Strong absorption in water limits the use

E) MICROWAVE

Food product can be scanned by microwave. It works the same way as an X-ray imaging. The technical setup of transmitter at one side and receiver at the opposite side of food product, allows to obtain 2D signal. Through the use of more than one transmitter placed at different position, we can get 3D signal. Detailed description of this method is given in "Food radar system" [6]. The transmission of the microwave radiation is subject to the permittivity of the transmission medium. The presence of a foreign objects change a materials permittivity and the detected radiation can thus be monitored for contamination. This is applicable to liquids and emulsions.

It is claimed that glass (10 mg pieces), metal filings (5 mg), plastics, stones, wood and other organic materials can be detected with microwave techniques [6].

Pros and uses [2]:

- Non-contact, non-destructive
- Wide range of contaminant materials detectable at their microwave impedance.
- No limits on speed of flow through the food-processing system
- No radiation or other 'field' that could affect the subject material.

Cons and Limitation [2]:

- Expensive equipment

F) ULTRASOUND

Ultrasound is a mechanical wave and propagates by vibration of the particle of the medium. The amount of energy reflected and transmitted through the material depends on their relative acoustic impedance. Foreign bodies in food have different acoustic impedance compared to the food itself, so reflection, refraction and scattering takes place which indicate the presence of a foreign body. Ultrasound with frequency from 20 KHz to several gigahertz can beused to detect and locate foreign body [2].

Different types of ultrasound transducers are available and the main advantage is that it can be small as a catheter tip of 1.2 mm of diameter. Conventional ultrasound measurement uses coupling by means of oil or gel between the transducer and the target medium. There is a possibility of contamination in food because of the coupling material. Air coupled transducers are mostly used as no chemical agents like oil and gel used there. In this type of transducer, the transmitted signal is dependent upon temperature, humidity and the flow rate of air. Instability of these properties can cause errors in the velocity and thickness measurements [3]. Cho, et al [7] shows the study of instability of an air column due to varying temperature and the presence of different foreign objects.

Ultrasound technique has been shown to detect and identify stone (5*10*20 mm), glass (2*5*7 mm), 10 mm of wood, plastic, bone and steel in homogeneous food sample testing at 20-75 mm probing depth while for non-homogeneous food sample at 50 mm probing depth [8]. These foreign bodies have been detected in cheese using pulse echo transducer by recording the amplitude of the reflected wave. In addition, the alignment of the transducer with respect to the food container plays an important role in the detection of a foreign body.

Reference [9] shows the design of an ultrasonic transducer setup with an auto-alignment system. The variation in reflection amplitude is analysed as a function of the ultrasound beam incident angle to a beverage container surface. Basically two aspects, the coupling method and incident angle control found to be crucial in the detection of a foreign body in a glass jar. Author found it difficult to detect a foreign body in case of a curved container surface. They analysed water and five different types of juices with or without pulp and noticed that food with higher attenuation (like tomato) has higher probability to give false warnings than food with low attenuation (like water) using pulse echo method. Higher attenuation of ultrasound by food medium dramatically reduce the amplitude of the echo signal caused by FB so it is good to use through transmission method so we get high signal to noise ratio where subjected food material has a higher attenuation. There is a one problem with using this technique, namely that small glass fragments in a bottle may be settled down on the bottom or can get stuck to the inner wall of the glass jar, thus masking the echo signal with the inner wall signal and as a result – escape detection.

Reference [10] explains the technique for the detection of small object occluded in a glass bottle. The author proposed an algorithm to facilitate this kind of detection. Glass bottle is being scanned by the ultrasound with the help of a computer program called Labview. This program positions the sensor at a different location on the bottle and numbers of images are obtained. First, all the images were being processed vertically by the short time Fourier transform algorithm then they were being processed horizontally using differentiation. From that information corresponding frequency index obtained then the magnitudes at that index were lined up according to their sequential order to form a new signal. It is important to remember that high frequency has a high spatial resolution but limited depth of penetration while low frequency has a greater depth of penetration but lower spatial resolution.

Pros and uses [2]:

- Fast
- Non-destructive and online
- Low power usage
- Relatively cheap

Cons and Limitation [2]:

- Resolution and penetration are inversely related.
- Requires good contact between object and transducer

G) ELECTRICAL IMPEDANCE

It is considered as one of the simplest methods to detect a foreign body by means of observing the change in measure impedance.

Pros and uses [2]:

- Non-destructive

- Simple experimental set-up
- Can detect anything that has different impedance properties to its surroundings, so applicable to glass, rubber, plastic, metal etc.

Cons and Limitation [2]:

- There is a challenge in defining the change in a measurement signal which shows corresponds to the presence of contaminant as there is a wide range of material types and sizes of foreign bodies.

H) Nuclear Magnetic RESONANCE

NMR is a phenomenon in which nuclei in magnetic field absorb and re-emit electromagnetic waves. MRI is an application of NMR to detect source of the resonance from the target material. These techniques are perfect for the discovery of the bone parts and other foreign materials in meat. Both can also distinguish foreign bodies in whole fruits and vegetables for examples worms and holes. Furthermore, NMR has a capability to discover any disorders in fruits or vegetables while MRI can identified Internal browning, bruising, ripening, maturity, scald, rotten areas, fungal infection and even sugar content [11].

Pros and uses:

- Non-contact and non-destructive
- Powerful tool in detection and assessment of food items.

Cons and limitations:

- High cost and setting up magnetic field is difficult
- Can be performed only offline

1.1.1 Conclusion

Based on the section 1.1, the following techniques can be recommended as most promising and applicable at the manufacturer sites are metal detection, X-ray inspection, ultrasound technique and microwave.

Using ultrasound in detecting foreign bodies in food is less expensive. Additionally it is more secured than X-ray. Furthermore, ultrasound detection systems are non-intrusive and non-dangerous to food products. They are less demanding to work under different conditions and surroundings. These systems are also hygienic which conforms to food production and quality standards. Ultrasound system provides fast and easy examining of food products that helps to maintain high production rate of the packaged food. As ultrasound sensor has narrow scanning window, one can place more than one sensor around the pipe containing food to cover whole pipe [11, 12].

To sum up, ultrasound technique looks more promising compared to other techniques. In addition it has lots of application in various filed, as discussed below.

1.2 Basics of ultrasound

Ultrasound wave needs a medium for propagation. It can propagate in solids, liquids and gases. It can propagate as longitudinal wave, shear wave, surface wave and plate wave. The waves originate from a vibration source and move through a medium by its particles oscillation. [13]. As a nature of a wave, ultrasound wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave. The following equation shows this relationship [14].

$$\lambda = \frac{\nu}{f} \tag{1}$$

Where, λ, ν , f presents wavelength, velocity and frequency respectively.

Typically low power ultrasound is used for non-invasive analysis and monitoring of various food materials and foreign bodies during processing and storage to ensure high quality and safety [15]. Low power, high frequency ultrasound can also be used to discriminate and quantify some basic mechanical or structural properties of solids and liquids.

During the propagation in a medium, ultrasound starts to lose energy. Absorption and scattering are the main forms of attenuation. Attenuation takes place because energy is wasted for activating vibration of the particles of the medium. The attenuation coefficient (α) is defined by,

$$A = A_0 e^{-\alpha x} \qquad (2)$$

Where A_0 and A are the initial and final amplitude of the wave respectively, x is the distance travelled by the ultrasonic wave in a medium.

When sound moves through an inhomogeneous medium, scattering occurs. There are various reasons behind scattering. Sometimes when a sound beam transfers its energy to a medium particle, the particle gets expanded and contracted which in turn acts as a sound source. This effect is also called thermal scattering. Sometimes density difference between medium particles also generates scattering [13]. It should be noted that scattering is especially sensitive to the frequency of sound. It is also dependent upon the incident of an ultrasonic wave and angle of observation [15, 16]. During absorption, the energy of a mechanical wave converts into heat. It's very different from scattering, where the wave energy is scattered into different directions. Scattering may only happen in heterogeneous medium, while absorption happens in both heterogeneous and homogeneous media. The reason behind absorption of ultrasound in fluids are thermal conduction, viscosity and molecular relaxation [17]. The amount of energy absorbed by the medium is related to the frequency of ultrasound [18].

When an acoustic beam encounters an interface, it is partly transmitted and partly reflected.

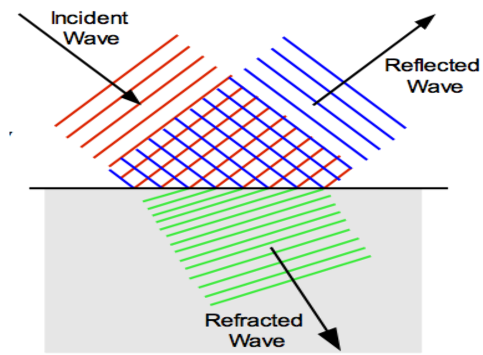

Figure 2. Refraction and reflection of acoustic waves [19]

The acoustic impedance of the materials at the two sides of the interface determines the ratio of the reflected wave and the refracted wave. Acoustic impedance is defined as a product of sound velocity and density passing through the boundary of different materials. Acoustic impedance measures generated sound pressure by the vibration of particles of a medium at a given frequency. Acoustic impedance is frequency dependent. Materials with different densities will have different acoustic impedance, which causes reflection at the boundary between that two materials. [20]

1.2.1 Applications

Ultrasound has lots of applications. In medical field, it is used for diagnosis and therapy. It is also used as a surgical tool. Ultrasonography, a technique of building 3 dimensional images with the help of ultrasound is used to locate tumour and in pre-parturition check-ups. Ultrasonography helps a doctor to measure the size of foetus and estimate the expected birth date. SONAR is famous as a navigation tool, which also uses ultrasound. Ultrasound is used to detect cracks and other flaws in a material, generally called as Non Destructive Testing of the material. Ultrasonic processors are used as homogenizers, which help to reduce small particles in a liquid to improve stability and uniformity. Ultrasound is also used to disperse solids into liquids. It is done by the high shear force generated by ultrasound. For grinding purpose, ultrasound is an efficient means. Ultrasonic milling is suitable for processing micron and nano size materials, such as calcium carbonate, ceramics and metal oxides. In sonochemistry, ultrasound is used to create high pressure and temperature to promote chemical reaction. Ultrasound is also used in to purify water, it kills bacteria present in water. In general high power, low frequency ultrasound is used in material processing while low power, high frequency ultrasound is used to detect defects in material. Both high and low power ultrasound can be used in communication [21, 22].

Our area of interest of the ultrasound application for this thesis was the NDT technique. Ultrasonic NDT technique based on reflection, diffraction and scattering of ultrasound wave by defects like inclusion causing amplitude and/or phase variations of the output signal. NDT involves the use of an emitting transducer and a receiving transducer. In the case of pulse echo technique, one transducer is used both as the emitter and the receiver. The emitter generates the ultrasound wave, which propagates in the test sample. For optimal transmission of ultrasound in to test material, a coupling medium is used between the transducer and the material. Use of coupling media is useful in terms of effective ultrasound propagation but it reduces its application. Mostly air is used as a coupling medium, in which case, part of the ultrasound reflects from the boundary between the air medium and test material. If the wavelength of the transmitted ultrasound is smaller than the object, then it is being reflected. The greater the difference in impedance between food material and object, the greater the amount of energy reflected back.

In pulse echo technique, ultrasound energy should be enough to travel through the medium and get back to the transducer. In pulse echo technique, frequency plays an important role. Generally higher frequencies can't penetrate more compared to lower frequencies of ultrasound wave. In this work, frequency range from 1MHz to 10 MHz was investigated. By carefully measuring time between the transmission of the transmit pulse and reception of echo from the object as well as from back wall, it is possible estimate position of the object in the material [23].

This thesis work doesn't include modelling of the ultrasound transducer itelf, but it uses a boundary condition which generates and receives ultrasound and its echoes from the material. In simulation ultrasound propagate as a plane wave in a material.

2 FINITE ELEMENT MODELLING

2.1 Introduction

Finite element modelling is a numerical analysis technique to get approximate solutions to a wide variety of physics and engineering problems. Finite element modeling enables us to analyze mechanical systems by deriving differential equations relating the variables through basic principles such as equilibrium, conservation of energy, conservation of mass, laws of thermodynamics, Maxwell's equations and newton's laws of motion. The basic concept behind FEM is the subdivision of the mathematical model into non-overlapping components of simple geometry called finite elements. The response of each element is expressed in terms of a finite number of degrees of freedom characterized as the value of a function, at a set of nodal points. By assembling the collection of all elements, we get the response of the entire mathematical model [24].

There is a large number of simulation software are available on the market like Simulink, Ansys, ADINA. COMSOL is often compared with Ansys. There are various advantages in using COMSOL over other simulation softwares. COMSOL module allows to deal with much more fields of physics than the Ansys allows. It contains various physics interface and tutorials of various models. The models in COMSOL can be manipulated by scripts written in MATLAB.

COMSOL multiphysics 5.2 was used for simulation in this thesis work. COMSOL contains many types of modules, our area of interest was the acoustic module. Some complex models require high processing speed and a large amount of operating memory from the computer.

2.2 Literature Overview

Propagation of ultrasound can be simulated using FEM. Reference [25] gives information on a two dimensional FEM model, designed in COMSOL. Which has been simulated for ultrasonic wave propagation in an isotropic solid medium. The purpose was to optimize the FEM parameters to get very close solution to the real one. Steel was used as the material to study the longitudinal wave propagation of 20 kHz ultrasound. Study was carried out to see the change in the shape of the incident wave, the amplitude and frequency with respect to the change in length of the element and time steps. A simple rectangular geometry was chosen such that side wall reflection didn't reach to the observation point during the given time. Length of the triangular elements ranging from the half of the wavelength to the sixteenth of the wavelength was being simulated with the time step less than the tenth of the ultrasound time period.

There are different element types are available to mesh the geometry. 3D elements are tetrahedrals, hexahedrals, prisms and pyramids while 2D elements are triangular and quadrilateral. Tetrahedrals and triangles are the default element type for most of the physics as any 3D and 2D volume can be meshed. Other elements are not always able to mesh a particular geometry. Use of brick and prism elements helps to reduce the no. of element in the mesh. The choice of elements for mesh depends upon the motivation behind the application. Bricks or prisms used in the application where physical property doesn't change significantly. The primary motivation in COMSOL for using brick and prism elements is that they can significantly reduce the number of elements in the mesh. [26]

One of the main application of ultrasound is Non Destructive Testing. Reference [27] explains a 2D simulation of a single sided air coupled ultrasound pitch-catch technique for NDT using COMSOL. A thin layer of air separates the transducer and the material instead of traditional coupling media like water, glue or grease. Both the transmitter and the receiver are set in oblique angles on the same side of the inspected material as it can be accessible from one side only. 2D geometry has 6 subdomains: A test sample made of aluminum, 3 air domains, and a borehole filled with air, sound absorbing material between the transmitter and the receiver- to block the reflection coming from the air-aluminum interface. In addition, a boundary condition called perfectly matching layers added to eliminate unwanted reflections thus we can be able realize infinite media.

Boundary condition at the interface between the test material and air represent continuity of the normal displacements and stress components. Stress free conditions are applied to all boundaries excluding the active surface of the transmitter. Meshing is carried out in such a way that accurate solution can be possible to achieve within an acceptable computation time. Maximum element size in test material is kept larger than maximum element size in air. After defining the mesh, the model is solved over a relevant range of source frequencies. This simulation model and results are compared to experimental results and verify the agreement with the experimental results.

The design of the transducer is important because it affects the whole ultrasonic system performance. Reference [28] explains designing, modelling and validation of multilayered ultrasonic transducers using the acoustic and piezoelectric modules of COMSOL. The model simulates the generation and longitudinal ultrasonic wave propagation in the probe during pulse-echo measurement mode. Geometry of the model has 3 subdomains. The piezoelectric transducer, backing material and a buffer rod. Bismuth titanate is used as the piezo electric material. "Normal acceleration" boundary condition is applied at the interface between the piezoceramic crystal and the surrounding material. In the pulse echo mode, the same element sends and receives the ultrasound signal. Boundary condition plays an important role to operate the piezo element both as an actuator and sensor simultaneously so as a result a floating potential boundary has been applied on the upper and lower surfaces of the piezoelectric material. This has been done by using a SPICE circuit in which the piezoelectric model made of a voltage source, a resistor and a piezo component.

Furthermore, a transient analysis with a time dependent solver has been performed. At the end the model was solved in the range of 0-40 µs, with 10 ns step. A prototype transducer was developed and its echo signal results were compared with the simulation results; they were found in agreement with each other.

Ref [22] shows another way to design an ultrasonic transducer. It also shows the importance of validation and its way to perform. Their COMSOL model contained water tank, a piezoelectric disc with a coupling plate and an aluminum cylinder. Simulation was carried out in transient acoustic –structure interface and the piezoelectric device interface model. The piezoelectric disc with the coupling plate make an ultrasound transducer. In addition, it was configured with two electrodes. One attached to the coupling plate for grounding purpose while the second one attached to uppermost surface that was driven by 100 V at 485 KHz for 10 µs duration. This forces to excite maximum output of the transducer and produce nearly eqaul to five ultrasonic cycles.

Mapped type mesh was applied to transducer and water in contacts with the transducer while Triangular mesh was applied to the aluminum cylinder and to the water in contacts with it. Size of the mesh was chosen to be much smaller than the wavelength to obtain better simulation. Solution time was set between 0 µs and 50 µs with 50 ns time step. Here time step is much lower than the period of ultrasound that fulfills requirement for better results.

For Validation purpose, the author have used Schlieren visualization experiments that emits 500 KHz into a water tank with glass wall including aluminum cylinder. FE model found to be close with the Schlieren visualization experiment. Furthermore, it also include comparison of result of poorly-configured FE model and well-configured FE model.

3 SIMULATION SETUP

3.1 Prerequisite

The more convenient and speedy way to check for a FB in a food using ultrasound pulse echo technique is to place an ultrasound transducer on a food pipe, where prepared food is ready to go into a package. In a food pipe, food should be continuously moving, this technique is applied to the liquid and fluid food. Food should be checked before it goes for packaging. In addition, food pipe and transducer system should be isolated from the external vibration. In modelling, diameter of food pipe is taken as a 65 mm. Velocity of flowing food is 1200 litter per hour. Temperature is assumed 293.15 K. Pressure exerted on the attached transducer due to flowing fluid is assumed to be zero Pa.

3.2 Simulation in COMSOL

Setting up a Finite element model in COMSOL multiphysics is rather straightforward. The whole process can be divided into two main steps.

1. Pre-processing

   Pre-processing includes several steps. It starts with defining space dimensions. User can choose 0D, 1D, 2D, 3D and axis symmetric. After that, an important step is to choose physics from the list and type of the study. Since simulation environment contain graphical user interface, it makes very simple for user to add parameters and to design the geometry. It is also possible to import geometries constructed with the help of other software. After creating geometry, the next step is to specify the settings for the underlying physics and equations in the model. Built in physics modes can be used. Boundary conditions can be set according to the application.

   Then, the structure should be discretized into small elements. This subdivision into elements is called meshing. The mesh nodes enables the discretization of the geometry into small units of simple shapes. There are two ways to generate a mesh. One way is to use the built in mesh generator which automatically generates standard mesh by choosing physics controlled mesh in the sequence type box. It is also called as free meshing and it's very simple. User can use it for all types of geometries regardless of the shape. User can control the size of the mesh elements. Another way is to choose user controlled generating mesh. User can choose different types of mesh elements and can also set the size of the element. Availability of mesh elements depends upon the dimension of the geometry. For 1D geometry, mesh generator discretizes the domains into smaller intervals. Mesh edge is used. For 2D geometry, the mesh generator discretizes the domains into triangular or quadrilateral mesh elements while the boundaries in the geometry are discretized into mesh edges. Large no's of mesh elements are available for the 3D geometry. The mesh generator discretizes domains into tetrahedral, hexahedral, prism or pyramid mesh elements. The boundaries in the geometry are discretized into triangular or quadrilateral boundary elements. The geometry edges are discretized in to edge elements [29, 30].

2. Post-processing

   After running the simulation, the result can be studied graphically in COMSOL, for example plotting. Results can also be exported to another program like Matlab or in the form of animation. It is also possible to export result in video format. With the help of this feature, we can see propagation of ultrasound wave including its reflection, scattering at the object interface via animation [30].

3.2.1 Global Definitions

It helps to add features applicable to entire model. Features can be parameters, variables, functions and groups.

In this model, the following parameters were added.

Table 4. Parameters

Name	Value	Description
Frequency	1E6 Hz	Frequency of the ultrasound
C	1482 ms^{-1}	Speed of sound in water
wavelength	(C/Frequency)	Wavelength of ultrasound in water
h_mesh	(wavelength/5)	Size of the mesh element

T	(1/Frequency)	Time period of ultrasound
Duration	(T*3)	Duration of ultrasound excitation
timestep	(T/10)	Time step

Rectangle function is also defined under the global definitions. It is denoted as rect1. It is used to simulate a signal for predefined time interval. Since we have defined duration of ultrasound as 2 µs. The rectangle function's lower limit is defined as 0.1*Duration while the upper limit is defined as 0.9*Duration. If we plot the rectangle function (rect1) it will look like below

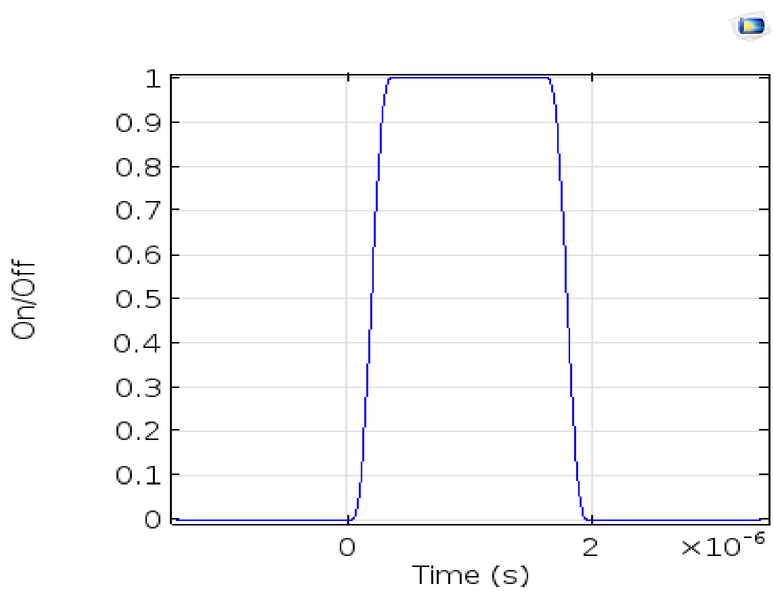

Figure 3. Time graph of "duration" parameter

COMSOL solver gives numerical stability with smoothed rectangle function. In addition, it helps to avoid artificial oscillations of the transducer.

Starting from time = 0 s to 2E-6 s, the transducer will transmits an ultrasound wave of 1 MHz frequency.

3.2.2 Geometry

Geometry of this model includes a 60 mm diameter sized circle, which represents the food pipe. To represent an ultrasound transducer, a 20 mm rectangle is mounted on the top of the circle. The rectangle is mounted in such a way that the surface of the transducer fits on the circle, thus the surface of the transducer is not flat but curved. A foreign body is designed as a small circle of 2 mm radius in below figure.

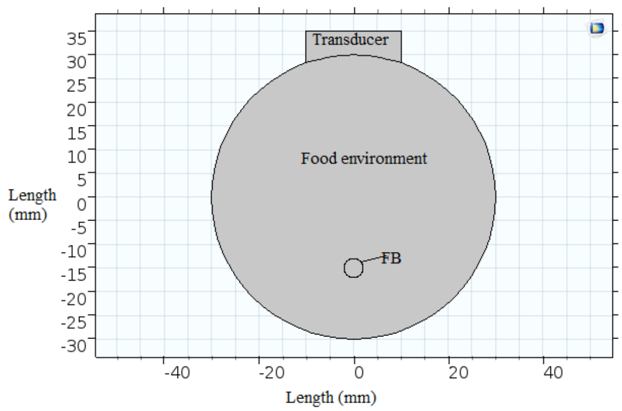

Figure 4. Design of a food pipe with transducer and FB

3.2.3 Materials

COMSOL contains a number of databases with a broad collection of elastic, solid mechanics, electromagnetics, fluid, chemical, thermal, piezoelectric and piezoresistive properties of materials. It is also possible to create user defined material by entering properties of the material.

It is not required here to choose material for a transducer as ultrasound waves are being generated by applying boundary condition although PZT-5H is chosen as a material of the ultrasound transducer. Liquid food is at the centre of focus for this modelling. For foreign body material- acrylic plastic, silica glass, wood, metallic FB like iron, steel can be used

3.2.4 Meshing

Table 5. Meshing properties

Domain	Mesh size	Type of mesh
Foreign Body	(wavelength/5)	Triangular

Food material	(wavelength/5)	Triangular

Free Triangular type nodes are used for meshing of FB as well as for the food material. The size of the mesh is depends upon the ultrasound wavelength used. Since Plane wave radiation boundary was used to generate the ultrasound wave, the transducer part is modelled for a visual purpose only, thus there is no meshing required.

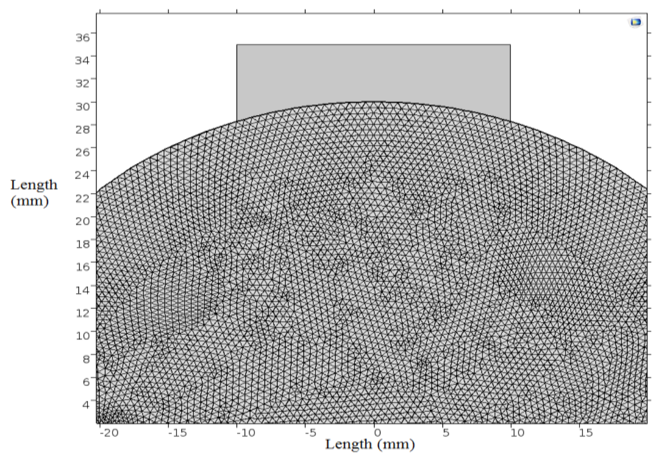

Figure 5. After meshing

This is how the model will look like after meshing.

3.2.5 Physics

Acoustic module in COMSOL was used for this project. The area of interest is to see changes of the pressure of the ultrasound wave at the transducer surface. Since the pulse echo technique is time dependent analysis, time dependent simulation is required. Pressure acoustic, transient interface physics suits very well for this application. The physics interface solves the scalar wave equation in the time domain. The wave equation describes the nature of the wave in form of a mathematical equation. It is second order linear partial differential equation.

$$\frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2} + \nabla.\left(-\frac{1}{\rho}(\nabla p - q_d)\right) = Q_m \tag{3}$$

For the acoustic pressure $p = p(x, t)$. Here c is the speed of sound and ρ denotes the equilibrium density, t is the time while q_d and Q_m are the dipole and monopole sources, respectively. This physics interface is available for all types of dimensions [30].

This physics interface comes with default nodes, which are Transient pressure acoustics model, Sound hard boundary (wall), and Initial values. Transient pressure acoustic model node adds the scalar wave equation. In this node, user can set temperature of the fluid and can choose a fluid model from linear elastic fluid, viscous fluid, thermally conducting fluid, thermally conducting and viscous fluid and Ideal gas fluid. In this application temperature is chosen differently while fluid properties are kept as linear elastic fluid.

The sound hard boundary (wall) make a selected boundary behave like a wall. It makes the normal component of acceleration zero for zero dipole source and constant fluid density, meaning the normal derivative of pressure becomes zero at the boundary [30].

The initial value node is used for nonlinear solver by adding initial values of acoustic pressure and its time derivative. It is also possible to add more than one initial values. In this application, it kept as a zero value.

Generation of ultrasound required a wave radiation type boundary condition at the surface of the transducer. There are three different type of wave radiation boundary available in COMSOL, Plane wave radiation, spherical wave radiation and cylindrical wave radiation. Plane wave radiation boundary condition is opted to generate plane acoustic wave. Now pressure of the acoustic wave is defined by using Incident pressure filed sub node by using the following equation.

$$p_i = \sin 2\pi f t . rect1 \tag{4}$$

Where, p_i is the pressure of a wave in Pa. The waveform of the sound wave is chosen to be a sine wave. $f$and t represent frequency and time, respectively. $rect1$ is a rectangle function used to simulate a signal for predefined time interval.

Now to be able to receive ultrasound at the surface of the ultrasound transducer, component coupling is used. In COMSOL, component coupling establishes couplings between different parts of the model components. A component coupling is defined by a coupling operator. Here in this application, Integration operator is used. Integration couplings are useful for evaluating integrated quantities. To evaluate the total acoustic pressure across a transducer surface, intop1 is defined with a source selected as a surface of the transducer. Intop1(p) integrates acoustic pressure over the source, where p denotes acoustic pressure.

3.2.6 Time dependent study

Since our interest is to see the propagation of ultrasound in the food material and possible reflection, scattering from FB including its detection at the ultrasound transducer surface, time dependent study suits well. Pulse echo technique is time dependent. Solving time domain equations is more complicated from the numerical point of view, therefore computational time can be significant even on capable multicore computers.

Time dependent study was used to compute the time varying propagation of the pressure wave. Time dependent study adds a time dependent study node and a time dependent solver. It partitions the total time of the solution into small interims or time steps [22]. As the number of nodes increases, computation time also increases. The important thing is that for more accuracy, time elements should be minimal, which in turn increases the computational time. It generally depends upon the mesh size, which in turn depends upon the wavelength of the ultrasound. It follows the Nyquist sampling theorem [31]. According to the theorem, mesh size should be smaller than half of the wavelength otherwise model will produce a blunder. For finer result, the mesh size is kept as one fifth of the wavelength of the ultrasound.

Since most food materials are made up of water, ultrasound travels at a rate of 1482 ms^{-1}. A rough estimation of time taken by an ultrasound wave to travel through a 60 mm diameter food pipe, from transducer to the opposite wall and back, takes approximately 90 µs. Thus time solver is set to solve for times between 0 µs to 9 µs with the predefined timestep parameter. It is important to note that flow rate of the food is generally taken as a 1200 litters per hour.

$$Velocity = \frac{4 * Flow\ rate}{\pi * Pipe\ diameter^2} \tag{5}$$

The calculated velocity of food inside 60 mm diameter of the pipe is 0.12 ms^{-1} that means 0.00012 mm per µs. During the scanning with ultrasound (90 µs time period) food travels only 0.010 mm so in the modelling, food is assumed to be stationary.

3.2.7 Post-processing of results

In pulse echo technique we are interested to see the echo from FB, if it exists in food. We are measuring acoustic pressure at the surface of the ultrasonic transducer, which is varying with time. Thus it is needed to draw values of acoustic pressure registered at the surface of the transducer during the defined time period of 0.9 μs.

Result branch in COMSOL was used to plot the graph from the solution. In this model, 1D plot group is chosen to draw time dependent acoustic pressure graph. 1D plot group in COMSOL is used to draw a value that varies with time or frequency. In this model Global type was chosen, which plots the global, acoustic pressure (N/m) vs time (s).

4 SIMULATION METHODOLOGY

4.1 Single transducer

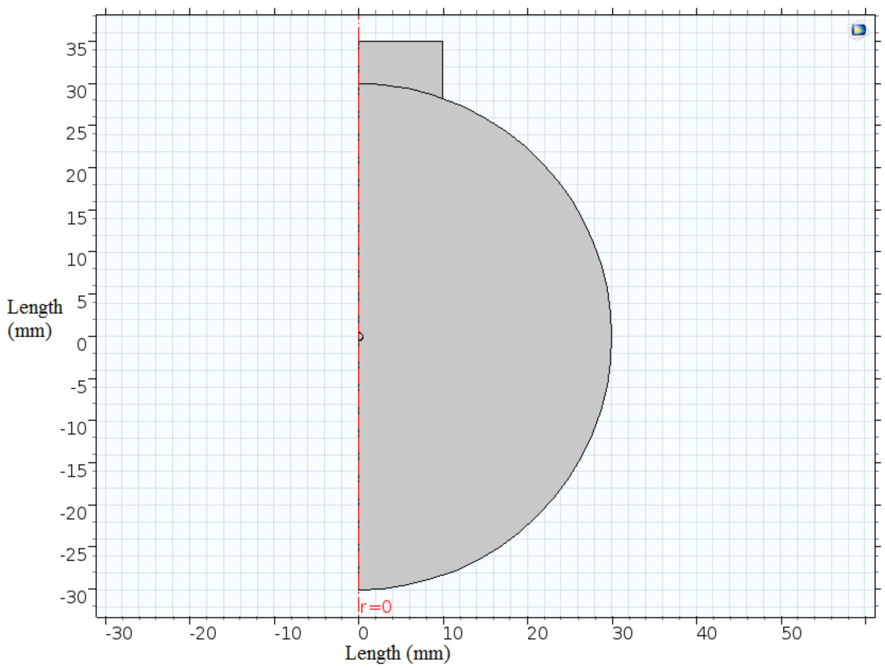

Figure 6. Single transducer 2D axis symmetric model

Space dimension for the model is chosen as 2D axis symmetric. It helps to reduce size and calculation time compared to full 2D model but provides the same results. The food material is assumed as a homogeneous liquid, which has almost same property as a water. Sound propagation is affected by the properties like density and speed of sound in particular material. Liquid food, for example any fruit juice consist 70% to 97% of water, it depends upon type of fruit [32]. The FB of 0.5 mm radius is centrally located and it has circular shape.

4.2 Multiple FBs detection

Figure 7 shows FBs of different material with different sizes in a liquid food environment. There are pine of 0.5 mm* 3 mm, aluminium of 1 mm* 4 mm and nylon of 2 mm size diameter of half circle.

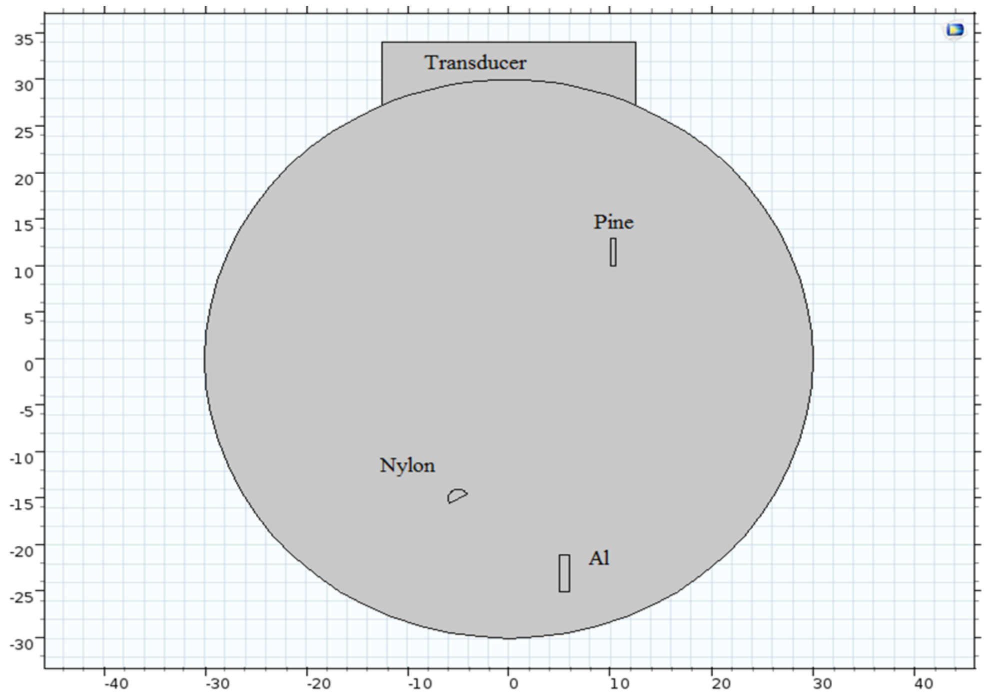

Figure 7. Model includes different FB material with different shape and size

Result of the model described in Figure 7 is shown in Figure 14.

4.3 Multi-transducer system

A practical system should be capable to detect FB at any position inside the food pipe. One curved face transducer is not enough to cover the whole area of food pipe thus it is necessary to include more than one transducer. Here, three transducers are placed in such a way that it covers approximately all the area of the food pipe. More transducers could be attached to cover more area but it could lead to increase the levels of noise.

Time shift operation functions in such a way that one transducer will work for predefined time period by keeping other transducers in off mode. Ultrasound transducers are switched one by one. The reason behind this is acoustic pressure will remain in the food medium after excitation of ultrasound, that can be captured by other transducers, thus increasing the noise. In addition, between switching of the transducers, some amount of time pause is given to settle down the acoustic pressure wave in a food medium.

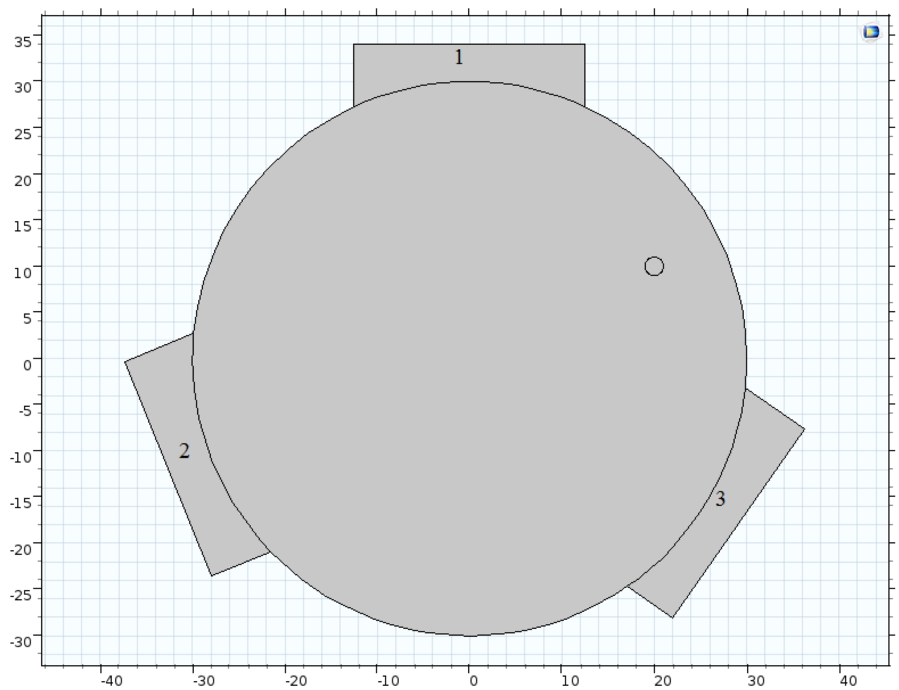

Figure 8. Multi-transducer model

Piecewise function is used for switching. One transducer will work for 90 μs, after that it remaines off till the time reaches to 300 μs. The Second transducer will be active from 300 μs to 390 μs and remained off till the time reaches to 600 μs. After that third transducer will be switched on from 600 μs to 690 μs.

Results includes the time signal graph of transducer 1, 2 and 3 of the model that shown in figure 15, 16 and 17 respectively. It is observed that FB can only be detected by transducer 2.

4.4 FB Detection inside a fruit piece

The model shown in figure 9 is able to detect FB that is occluded inside the food inhomogeneity. It is applicable to some packed food like pickles, juice with pulps and many more. Model includes 1 mm radius of FB inside a 10 mm * 10 mm fruit piece. Surrounding food environment is assumed as a normal fruit juice which contains about 80 % water.

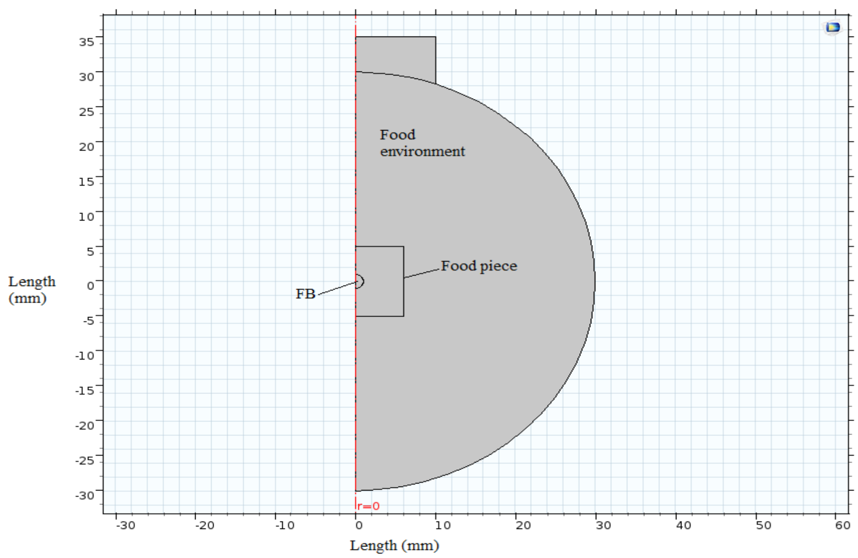

Figure 9. Model shows a fruit piece having FB inside of a fruit juice

Figure 18 shows the result of the model described in figure 9.

4.5 Noise problem

The simulation model doesn’t include external noise which can be present at the manufacturer’s site that might reach the ultrasound system attached to the food pipe. In real world, all the electronic devices produce random signal that spreads uniformly across all the frequencies. This is called noise. Echoes can be masked by the noise, if amplitude of the noise is equal or higher than the amplitude of the echo. It is necessary to reduce the amplitude of the noise relative to the echo, means increasing signal to noise ratio. This can be done by using filters. A filter is an electronic device that removes some unwanted stuff from a signal. There are different types of filters are available today.

One possible way to reduce the amplitude of noise is by expelling noise at all frequencies outside the scope of the frequencies present in the echo signal bandwidth [33]. Furthermore, ultrasound system can be isolated from the external vibration sources.

5. RESULTS

5.1 Response check

After successfully setting up a model, now it is time to check its efficiency for the detection of various shape, size and materials of FB in a food.

Figure 6, shows the model which is being used to check efficiency of pulse echo ultrasound system. Original model is being cut vertically from the centre. Efficiency check experiments is carried out to see following things

1) Does the response changes with respect to different FB size
2) Does the response changes with respect to different FB location

Discussion on efficiency check with time signal graphs are described in Appendix 1. Response check. Results proved model’s efficiency for detection of FB and its sensitivity towards different FB size and location.

5.1.1 Temperature effect

Temperature of the liquid food at manufacturing site can be assumed from 15 °C to 45 °C. Generally, the temperature of a fruit juice will remain at 25 °C or at room level temperature. Dairy products like milk, yogurt will remain lower than the room temperature level. Food temperature beyond 55 °C could damage the ultrasound transducer [34]. In addition, ultrasound propagate in a medium at different rate in a different temperature [35]. It is very interesting to know how temperature of a food medium affects FB detection.

Appendix 2 shows the time signal graphs at different temperature. From the graphs shown in Appendix 2, it is concluded that there is no change in the amplitude of the echo at different temperature level of the same food medium. In addition, in 90 µs time period, there will no significant variation in temperature occur, which could affect detection of echo from the FB.

5.1.2 Back Wall Reflection problem

In pulse echo system, back wall reflection has always higher amplitude than the FB echo. This makes very hard to detect FB, which lies on the surface of the food pipe. Especially for the FB of less than 2 mm diameter, back wall reflection overlaps FB echo that makes hard to distinguish FB echo from the back wall reflection.

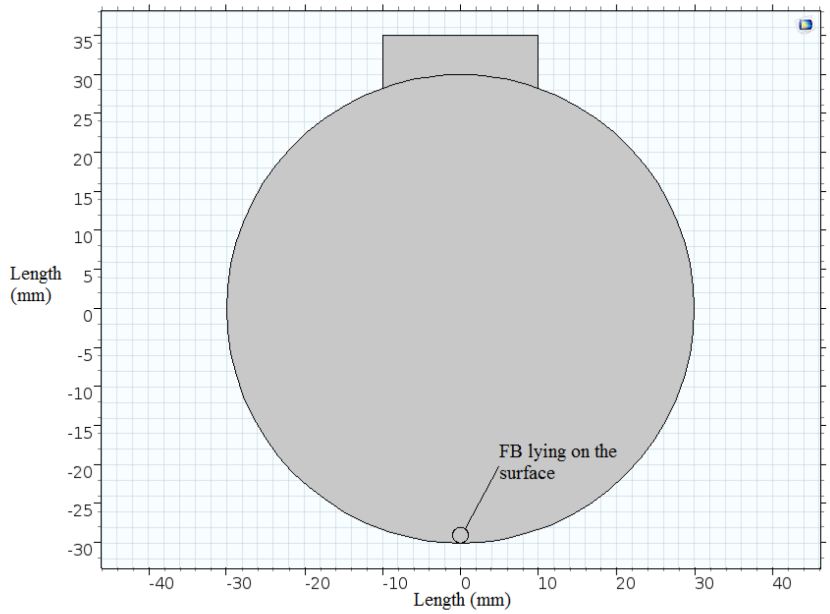

Figure 10. FB lying on the inside surface of the food pipe

This model is able to detect FB of 1 mm diameter, which lies on the surface of the food pipe. For successful detection only one cycle of ultrasound wave is generated instead of the commonly used three cycles. Reference signal derived from the system, which does not include FB can be used for detection by means of comparison.

Figure 11 shows the time graph of the model described in figure 11. Echo from the FB can easily distinguish from the back wall reflection. To make it more visible of FB, teeth inside the wall were designed in order to reduce the intensity of back wall reflection. Appendix 3 shows the design of the model including teeth and its results.

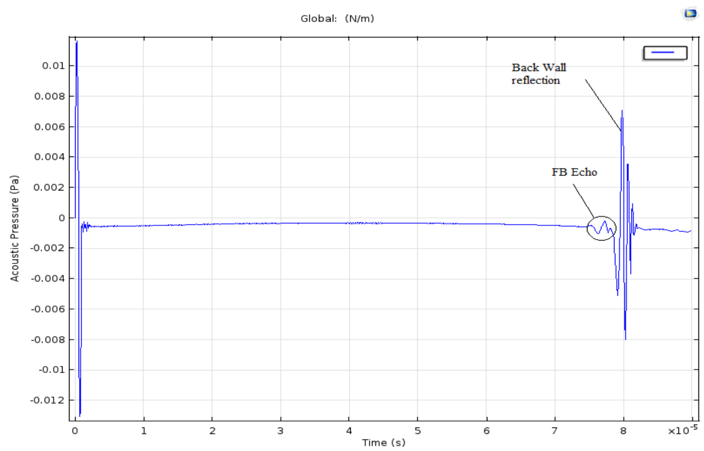

Figure 11. Time signal of single cycle ultrasound corresponds to figure 10

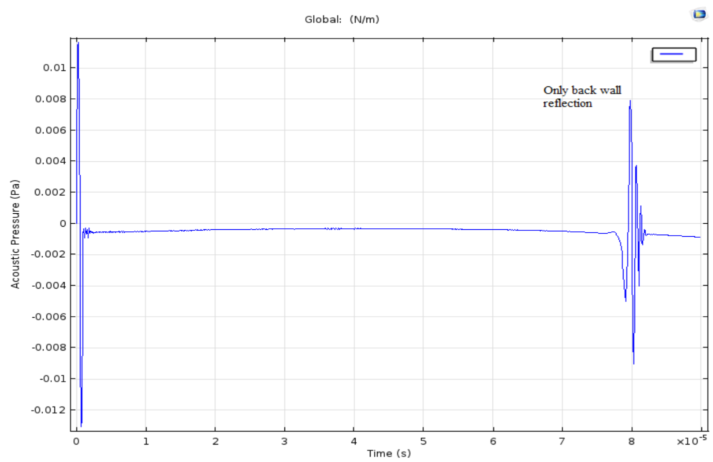

Figure 12. Reference time signal of single cycle ultrasound when there is no FB

5.1.3 Limit of detection

It is important to know the limit of detection of FB by ultrasound system. Frequency plays important role for the detection of FB. As stated in section 1.2, if the wavelength of the transmitted ultrasound is smaller than the object, then it is being reflected. Higher frequencies have smaller wavelengths, thus they are able to detect smaller FBs.

Consider the model described in figure 6 assuming FB of 0.1 mm radius located centrally inside the food pipe. For this simulation air was taken as a material of FB so it is generally an air bubble of 0.1 mm radius. A range of frequencies like 1 MHz to 5 MHz were tested to see echo from the FB. All the results are presented in Appendix 4.

From the figure no. 42 to 46 in appendix 4, it is clearly seen that increasing frequency of the ultrasound improves resolution. It is also important to know that higher frequency has shorter wavelength which makes mesh element size even smaller. This kind of simulation uses more time and power of a processor.

5.2 Multiple FBs detection

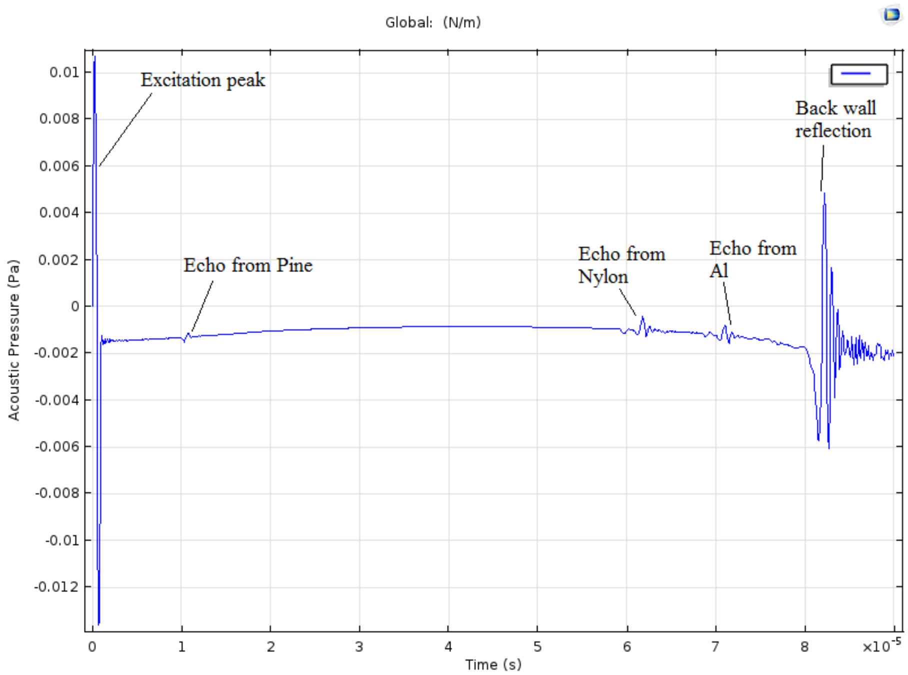

Figure 13. Time signal graph of the model shown in figure 7

Figure 13 shows the time graph of the model described in figure 7. The echoes from the various FBs are clearly visible.

5.3 Multi-transducer results

Transducer 1 result is shown in figure 14. From the figure 8, FB is out of the coverage of the transducer 1 hence there is no echo from the FB found in figure 14.

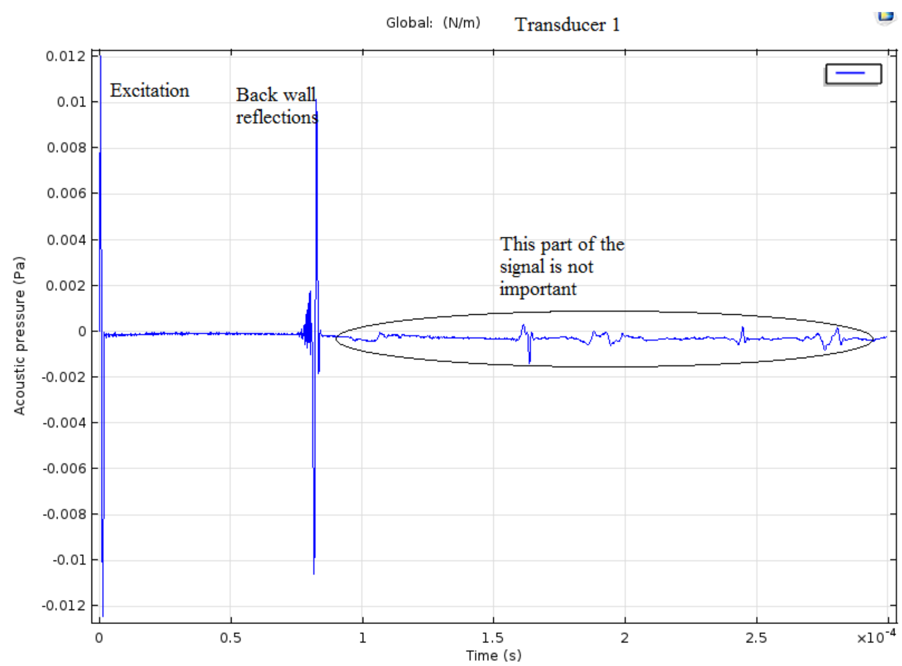

Figure 14. Time signal of transducer 1 of the model shown in figure 8

Time graph of the transducer 2 result is shown in figure 15. It shows echo from the FB.

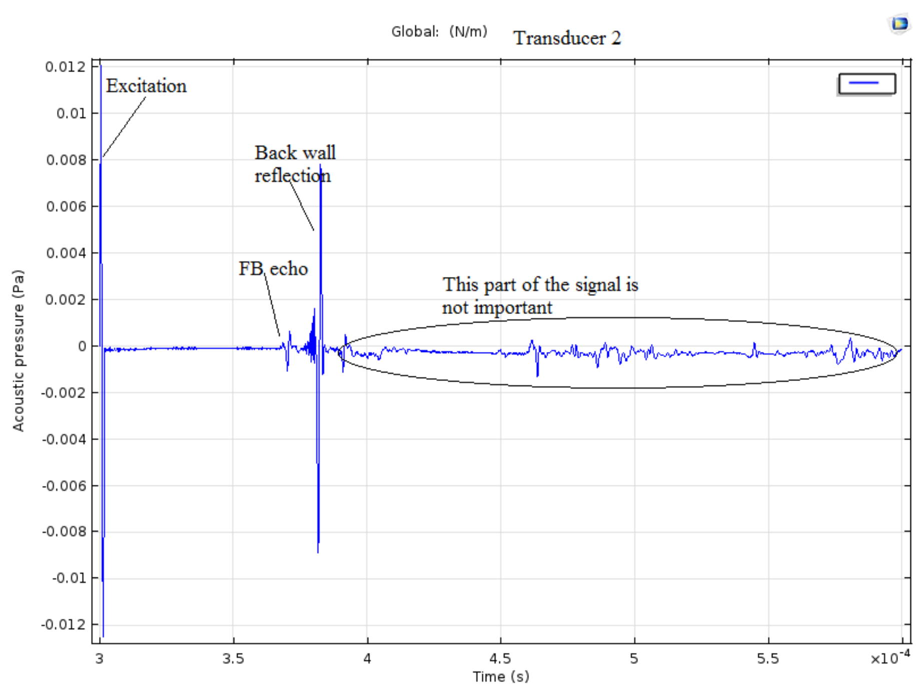

Figure 15. Time signal of the transducer 2 of the model shown in figure 8

FB is also out of coverage for the transducer 3 hence there is no echo from the FB in figure 16.

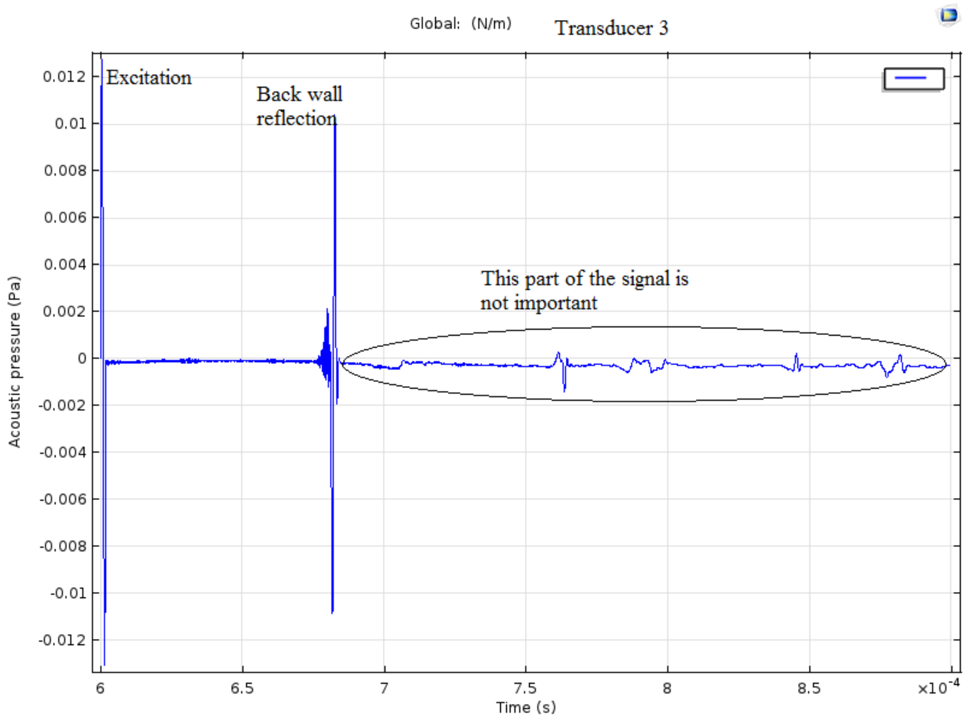

Figure 16. Time signal of the transducer 3 of the model shown in figure 8

5.4 FB detection in fruit piece

Figure 17 shows Echo from the fruit and FB occluded inside the fruit.

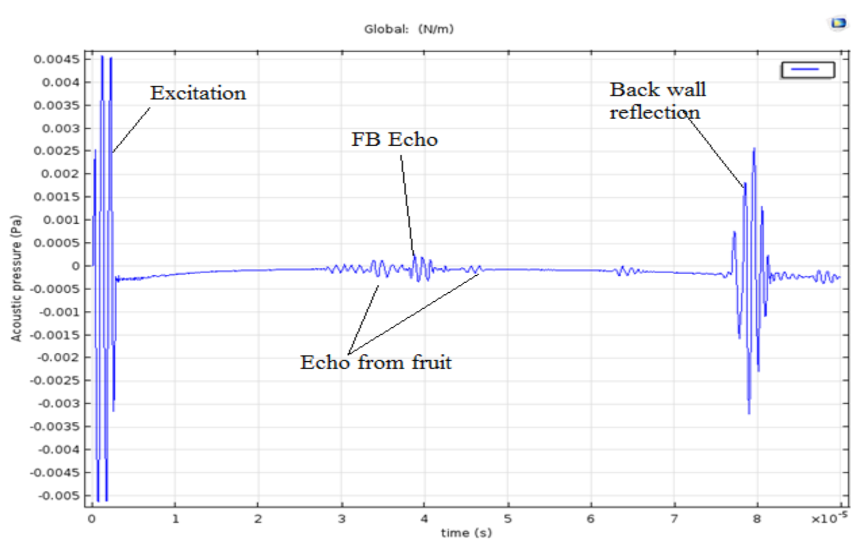

Figure 17. Time signal of the model shown in figure 9

5.5 Visualization of ultrasound propagation and reflection

It is also possible to see how ultrasound propagates and get reflected from FB and wall with time in COMSOL and allows to export results as a video in flash or AVI format. Figure 18, 19 and 20 shows the current position of ultrasound waves at particular time described in the figures.

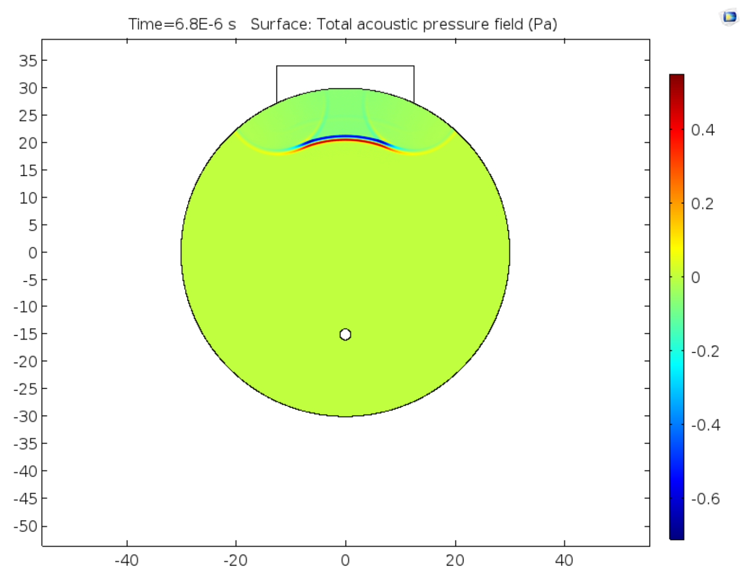

Figure 18. Propagation of 1 MHz frequency of ultrasound at 6.8E-6 s

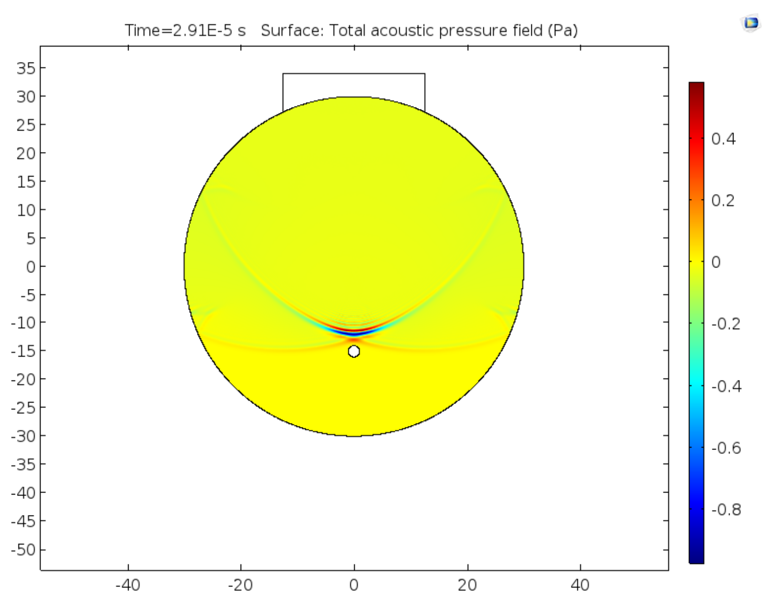

Figure19. Ultrasound approaching to the FB at 2.91E-5 s

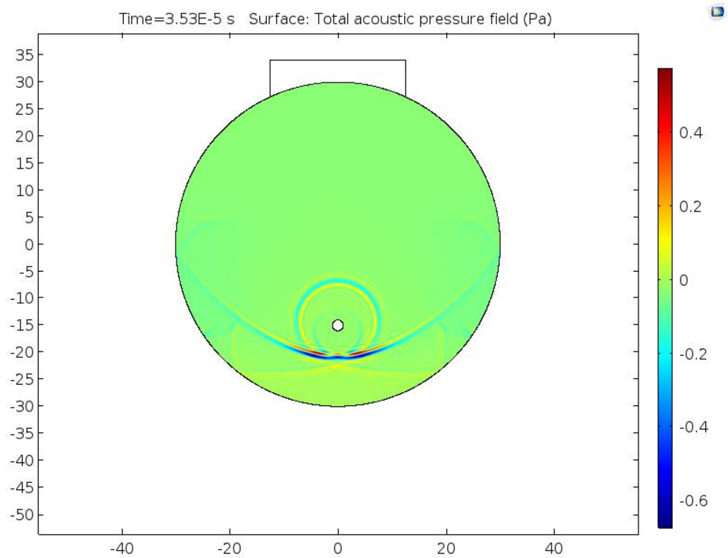

Figure 20. Reflection and propagation of ultrasound at 3.53E-5 s

5.6 Validation

To verify the feasibility of the approach suggested by the simulations, an experimental test using medical ultrasound systems was performed. Figure shows the experimental set up. GE Logiq 7 ultrasound system at 10 MHz and Siemens Acuson S2000 ultrasound at 20 MHz operating frequency were used in this experiment.

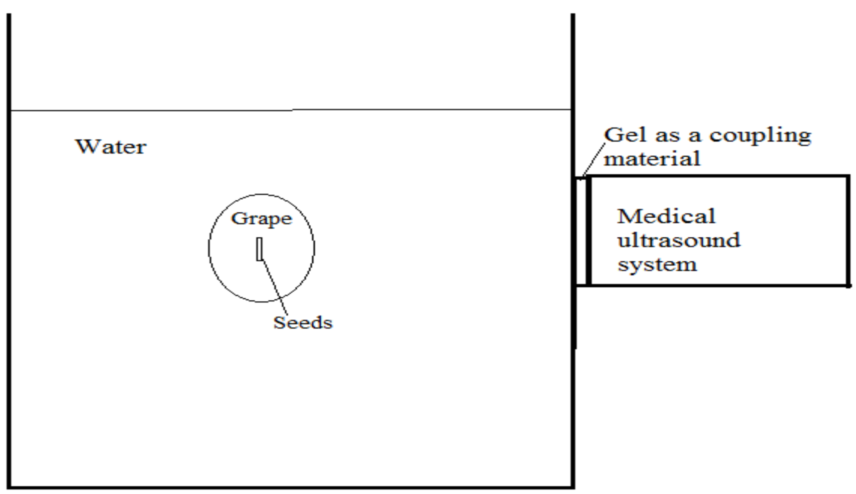

Figure 21. Experimental setup to test medical ultrasound system

A plastic container with a diameter of 75 mm was filled with water and grape was being put inside of it. Medical ultrasound transducer was attached to the container using gel. The experiment was carried out at 25 °C, seeds inside grape could be clearly seen in the image when viewed at 20 MHz and the grape was within 40 mm from the transducer. In addition, a toothpick was also inserted in the fruit, the sharp tip of it was also clearly recognizable in the image at 20 MHz. However, the image lost most of the details when the grape was moved close to the opposite wall of the container. At 10 MHz, the seeds were still distinguishable inside the grape when located near the opposite wall. Moreover, when placed close to the side walls of the container, the grape was not detected in the image at all.

The results shows the capability of an ultrasound to detect different material (FB) within a material, however, a compromise has to be made between resolution and penetration depth, when selecting the operating frequency and transducer location.

6 CONCLUSION

The model of the food pipe of 30 mm radius with the ultrasonic transducer on the top of it were successfully designed and run in COMSOL 5.2. The simulation results showed that the ultrasound pulse echo technique is capable of detecting small foreign bodies in liquid food. According to the modelling results, the system is able to detect object starting from 0.1 mm radius using frequencies starting from 2 MHz. It is noticed that FB should have a notable difference in density from the food medium in order to become detected. The simulation results showed that several objects made of different materials can be detected concurrently. While one transducer is incapable of covering the whole tube, the application of a larger number (3 or more) of time shifted ultrasound transducers can virtually cover the whole food pipe cross-section area. Previously reported as difficult to detect objects near the opposite wall could be detected by applying just a single pulse instead of conventional three. The design and the result of the simulation are expected to be used in the development of a real detection system.

7 SUMMARY

Title: "Development of foreign body detection methodology in industrial food preparation process"

Summary

Several techniques for the detection of the FB in food were studied and the advantages and disadvantages of each technique were analyzed. Among all the available techniques, ultrasound technique was found to be most promising in the detection of FB. The system for the FB detection using ultrasound was based upon pulse echo technique and was analyzed by the means of simulation, using COMSOL multiphysics 5.2 software. The model includes food pipe, transducer and possible FBs inside the liquid food. The applicability of ultrasound to the detection of FB as small as 0.1 mm in radius was established, temperature and frequency dependence was studied. A multiple time shifted transducer scheme was designed to cover maximum area of the food pipe.

Keywords:

Simulation, Foreign body in food, Ultrasound, COMSOL Multyphysics 5.2

CERCS codes:

P190: Mathematical and general theoretical physics, classical mechanics, quantum mechanics, relativity, gravitation, statistical physics, thermodynamics

T110: Instrumentation technology

T210 Mechanical engineering, hydraulics, vacuum technology, vibration acoustic engineering

T430: Food and drink technology

8 KOKKUVÕTE

Pealkiri: “ Võõrkehade tuvastamise süsteemi disainimine toiduainetetööstusele ”

Kokkuvõte

Analüüsiti ja võrreldi erinevaid meetodeid, mida võiks kasutada võõrkehade vedelast toidust tuvastamiseks. Meetodite eeliseid ja puudusi hinnates valiti edasiseks uurimiseks ultraheli-tuvastus. Simulatsioonid viidi läbi lõplike elementide meetodil COMSOL Multiphysics 5.2 tarkvara kasutades, keskendudes pulsi-kaja tehnikale. Mudel koosnes toidu pumpamise torust, mis oli täidetud vee sarnase materjaliga, ultraheli muundurist ja erinevast hulgast, erinevast materjalist ja paigutusega võõrkehadest selle sees. Simulatsioonid näitasid, et võimalik on tuvastada võõrkehasid, mis on vähemalt 0.1 mm raadiusega, eeldusel et materjali tihedus erineb vee tihedusest. Analüüsiti muunduri töösageduse ja keskkonna temperatuuri mõju. Toru ristlõike võimalikult suure osa katmiseks koostati mitmest aja-nihkega töötavast muundurist süsteem.

Võtmesõnad

Simulatsioon, võõrkehad toidus, ultrahli, COMSOL Multyphysics 5.2

CERCS code

P190: Matemaatiline ja üldine teoreetiline füüsika, klassikaline mehaanika, kvantmehaanika, relatiivsus, gravitatsioon, statistiline füüsika, termodünaamika

T110: Instrumentatsioonitehnoloogia

T210: Masinaehitus, hüdraulika, vaakumtehnoloogia, vibratsioonakustiline tehnoloogia

T430: Toiduainete ja jookide tehnoloogia

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10 APPENDICIES

Appendix 1. Response check

Different FB size

In this experiment, Aluminium is taken as a FB. FB of 0.25 mm, 0.5 mm, 1.00 mm and 1.5 mm diameter were simulated.

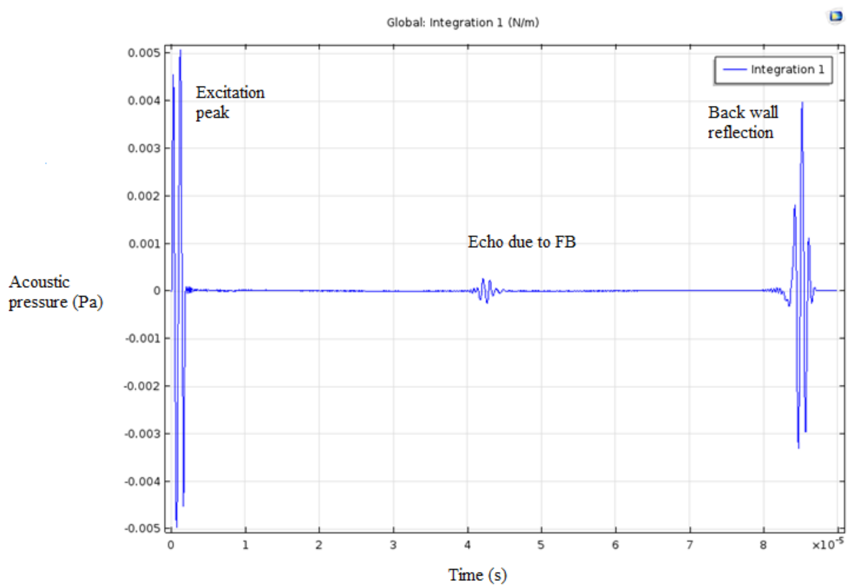

Figure 10. Time signal for a FB of 0.5 mm radius

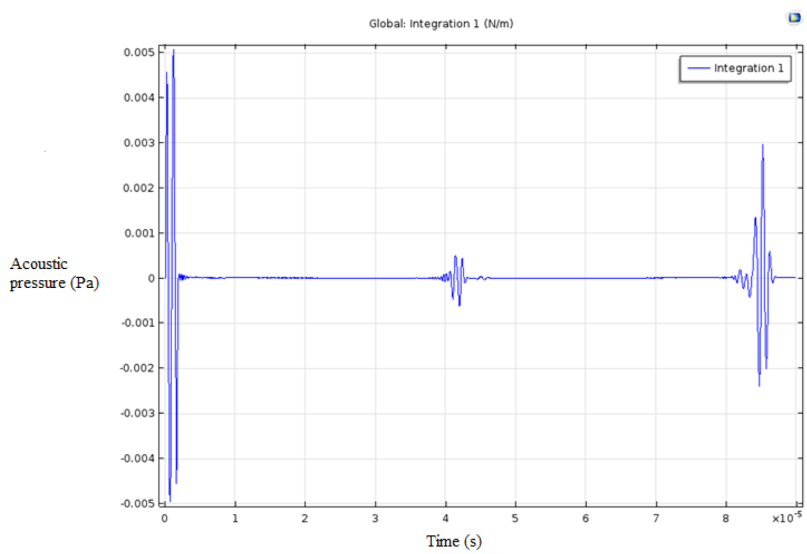

Figure 11. Time signal for a FB of 1 mm radius

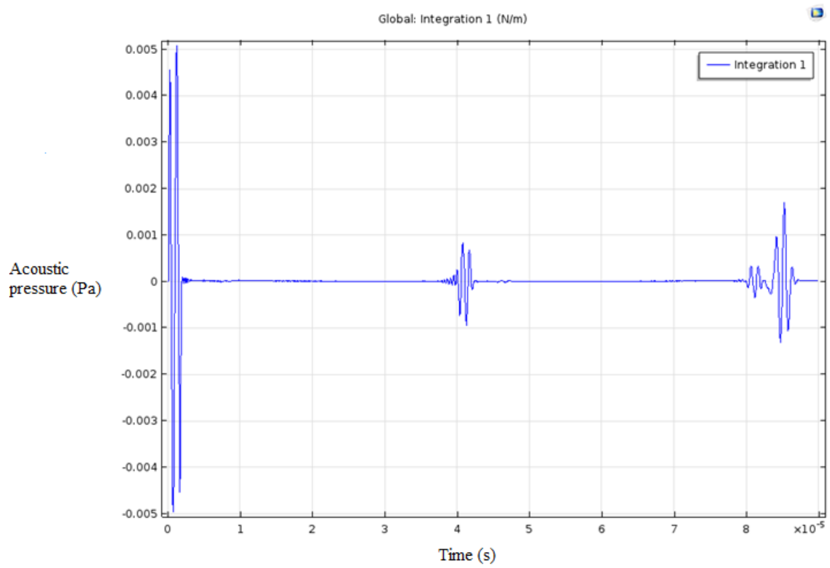

Figure 12. Time signal for a FB of 1.5 mm radius

By comparing above graphs, it is clearly seen that amplitude of echo due to FB increases with the size of the FB. Which means pulse echo system is sensitive to the size of the FB.

Different of the FB location

In this experiment location of FB with respect to its distance from ultrasound transducer is varied and receiving of echo from FB with respect to time is being measured. For meaning comparison same FB material with same size and shape is being used.

Following model shown in figure 25 has been designed

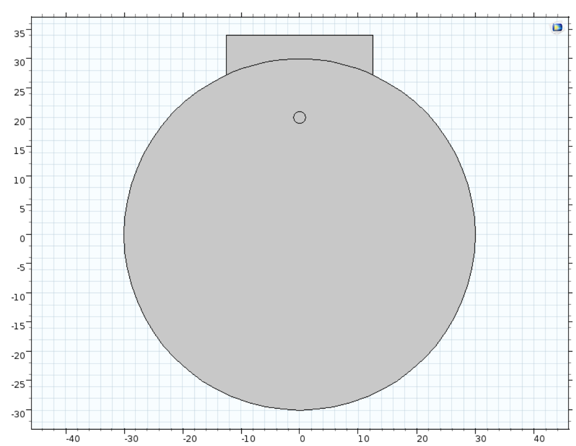

Figure 13.FB located near to the transducer

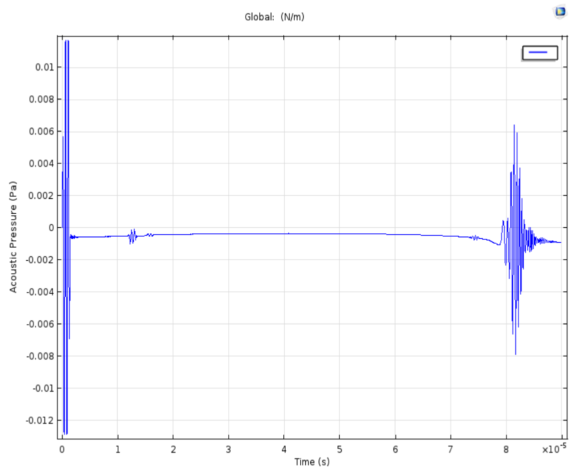

Figure 14. Time signal corresponds to Figure 25

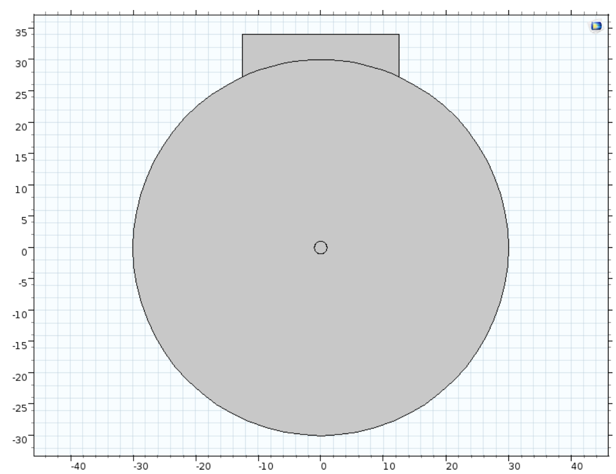

Figure 15. FB located in a center

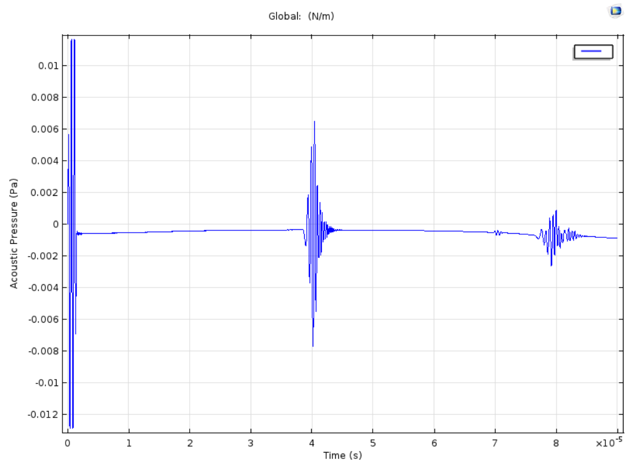

Figure 16. Time signal corresponds to figure 27

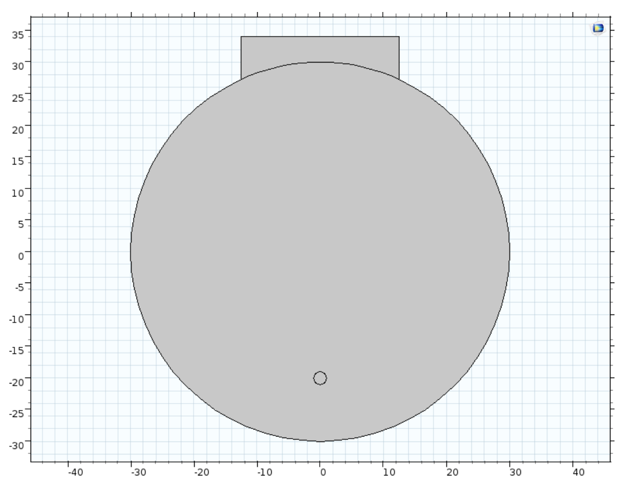

Figure 17. FB located far from the transducer

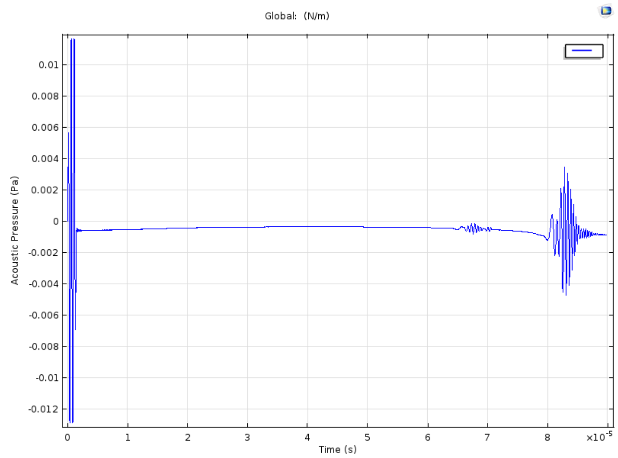

Figure 18. Time signal corresponds to figure 29

From the figure 26, 28 and 30,it is also possible to identify location of FB in the food with respect to the transducer.

Appendix 2. Temperature effect

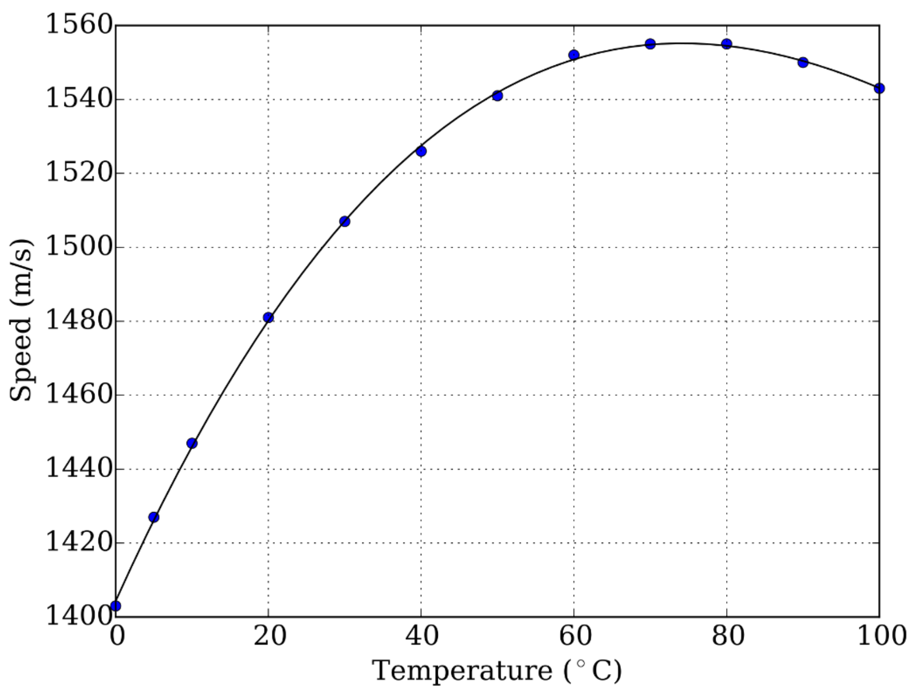

Figure 19. The temperature dependence of speed of the sound in water [36]

Figure 31 shows speed of the sound in pure water at different temperature.

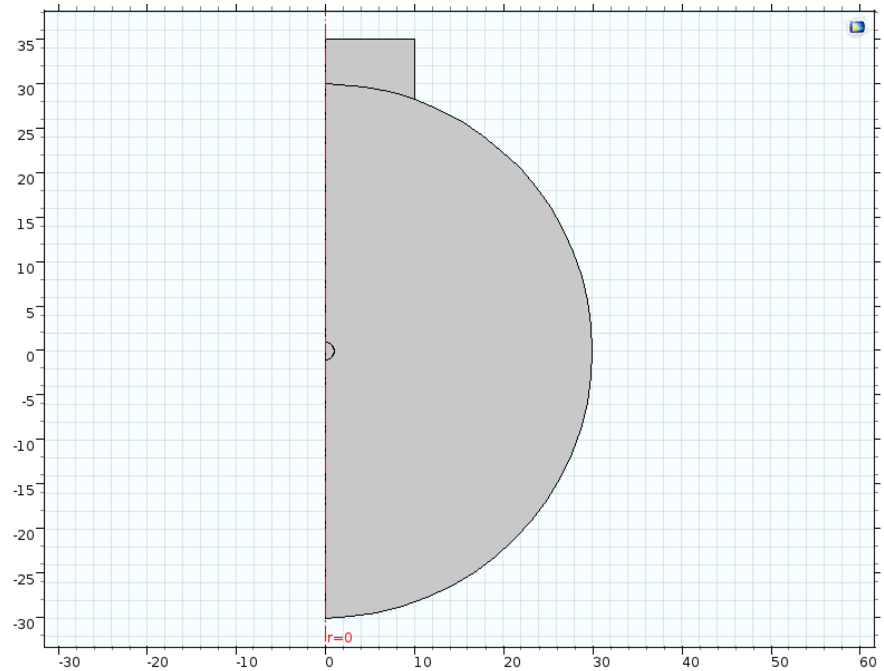

Figure 20. Model used for different temperature of food analysis

Figure 32 shows location of FB. Here in first case temperature of food medium is taken as a 10 °C. Time signal is shown in figure 33.

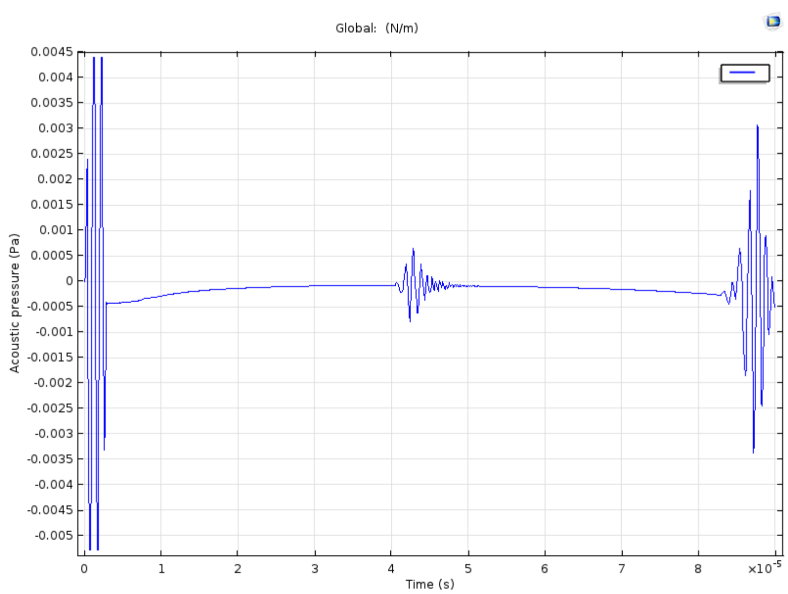

Figure 21. Time signal for Food medium at 10 °C

Now changing the temperature to 20 °C. Figure 34 shows the result at 20 °C

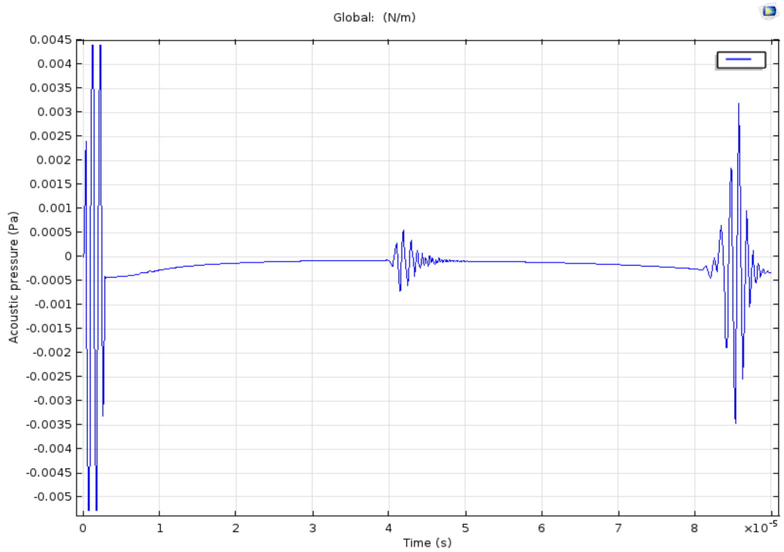

Figure 22. Time signal for food medium at 20 °C

Let's set the temperature as a 40 °C. Figure 35 shows the result at 40 °C

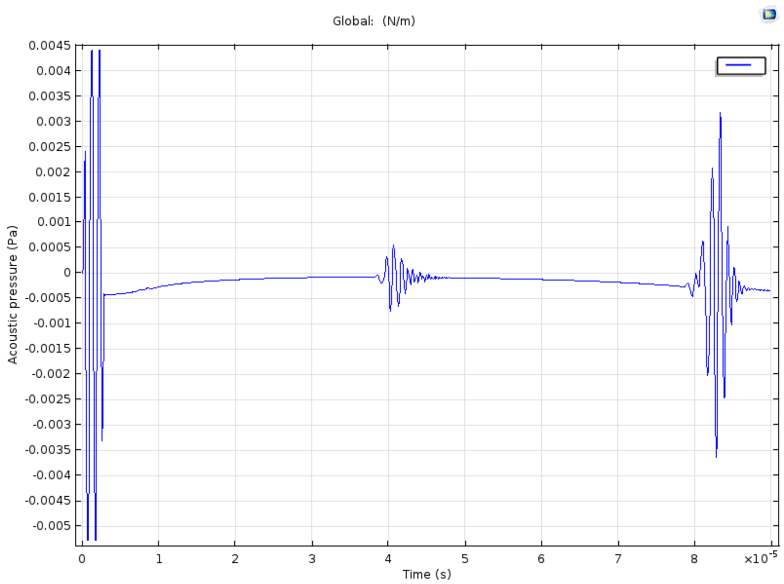

Figure 23. Time signal for food medium at 40 °C

And at the last, for 50 °C temperature, result is shown in figure 36.

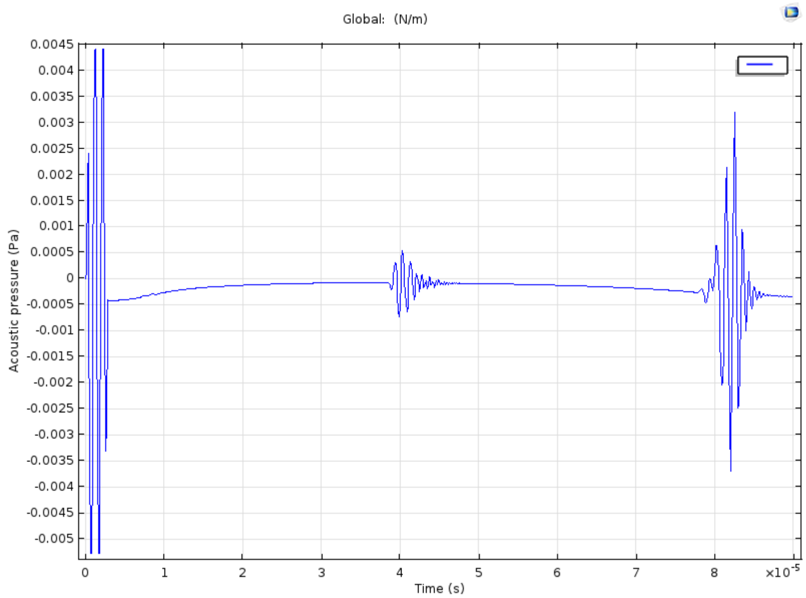

Figure 24. Time signal for food medium at 50 °C

From the above figures 33, 34, 35 and 36, it is concluded that there is no change in the amplitude of the echo at different temperature level of food medium.

In addition, in 90 µs time period, there will no significant variation in temperature occur, which could affect detection of echo from the FB.

Appendix 3

To reduce the intensity of back wall reflection, design of food pipe is modified in such a way that it scatters ultrasound wave to all possible direction. This kind of design reduce the intensity of back wall reflection reached at a transducer.

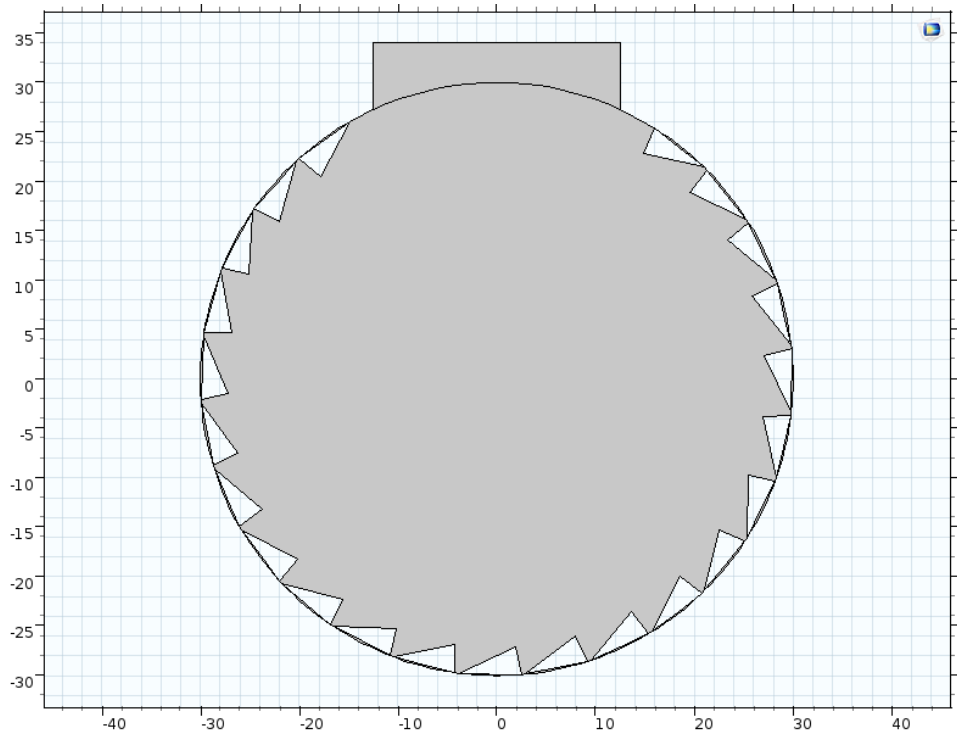

Figure 25. Food pipe having tooth's inside

Below figures shows the comparison of time signal of a normal design and saw tooth design food pipe, when there is no FB inside.

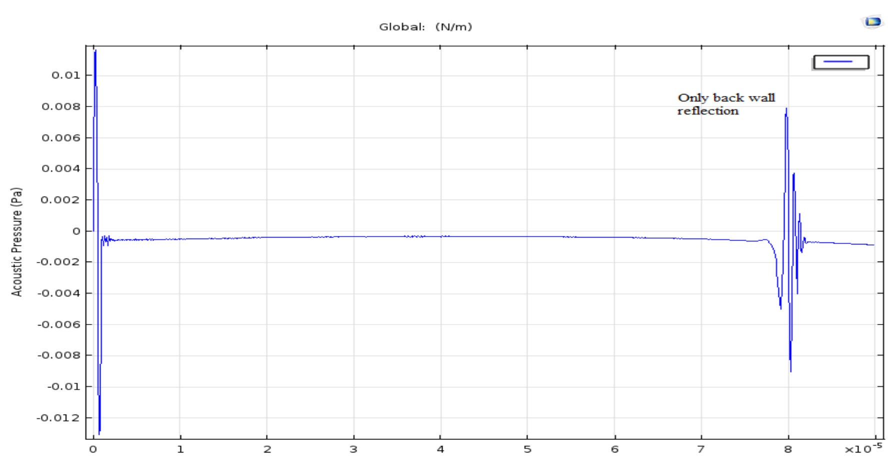

Figure 26. Time signal for a normal model

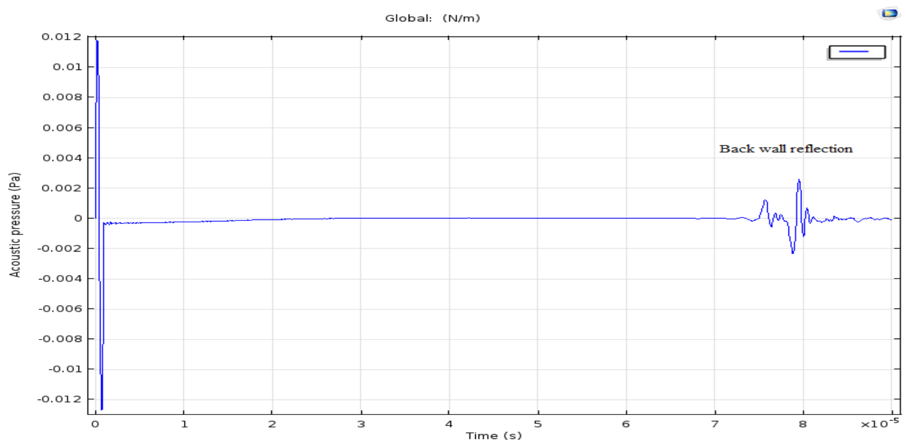

Figure 27. Time signal for a model having tooth's inside

Let’s see what happened when there is a FB of 1 mm diameter lying on the surface of the toothed food pipe.

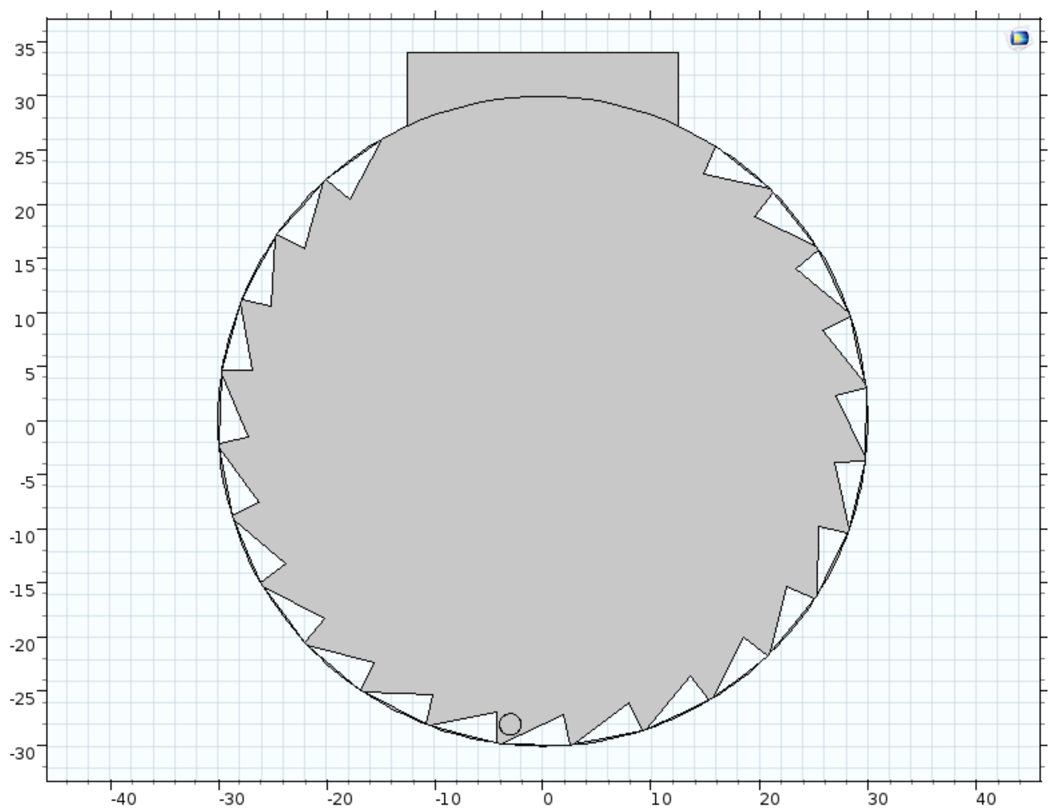

Figure 28. FB lying on the inside surface of the food pipe having tooth's inside

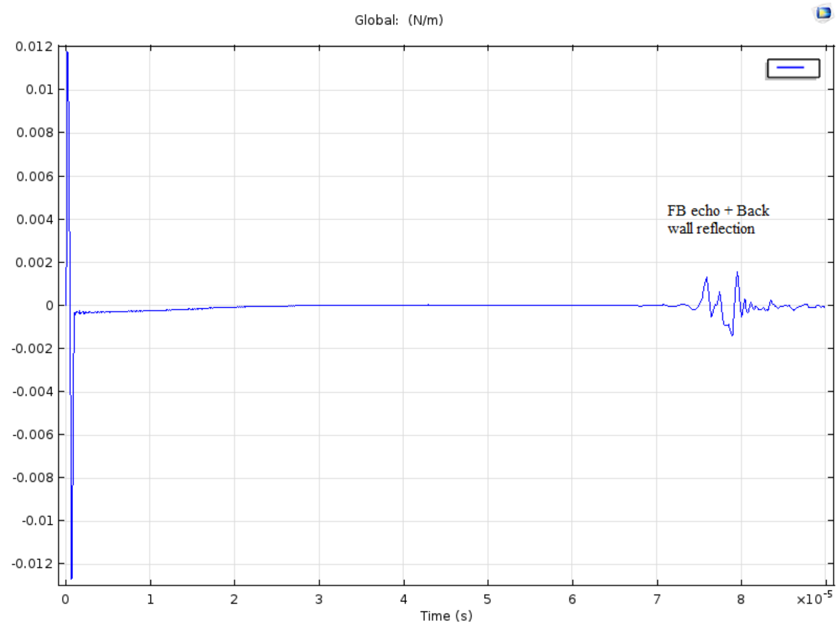

Figure 29. Time signal corresponds to the figure 40

If comparison is made with reference time signal, the peak from FB and back wall reflection are not distinguishable. Thus there is no advantage on having toothed inner wall of food pipe.

Appendix 4 Limit of detection

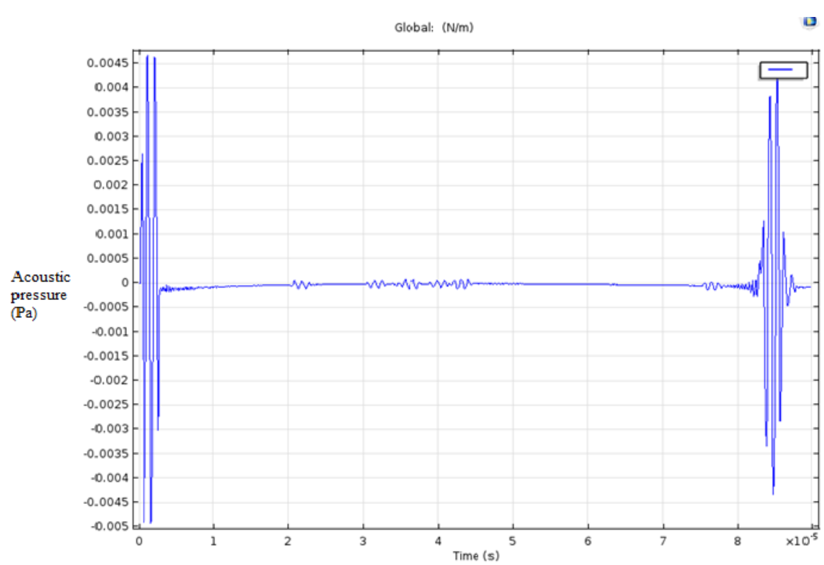

Figure 30. Time signal using 1 MHz frequency

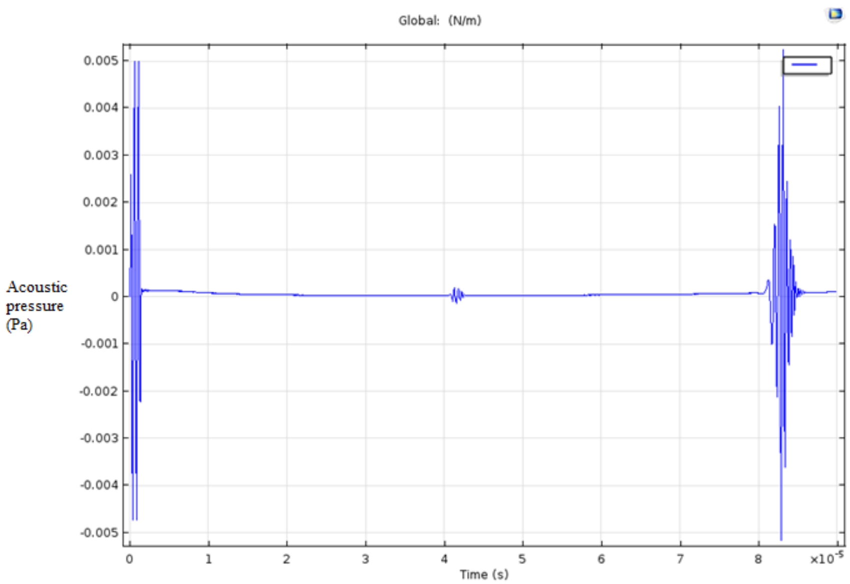

Figure 31. Time signal using 2 MHz frequency

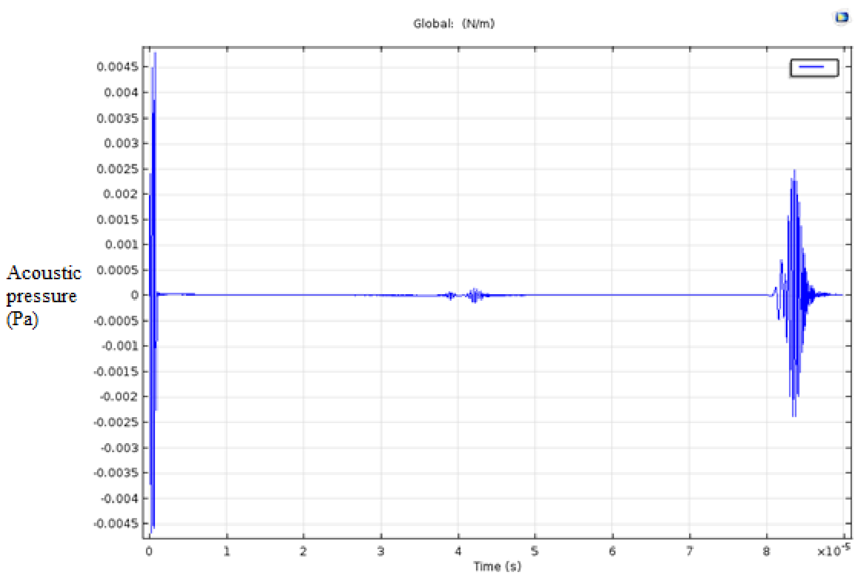

Figure 32. Time signal using 3 MHz frequency

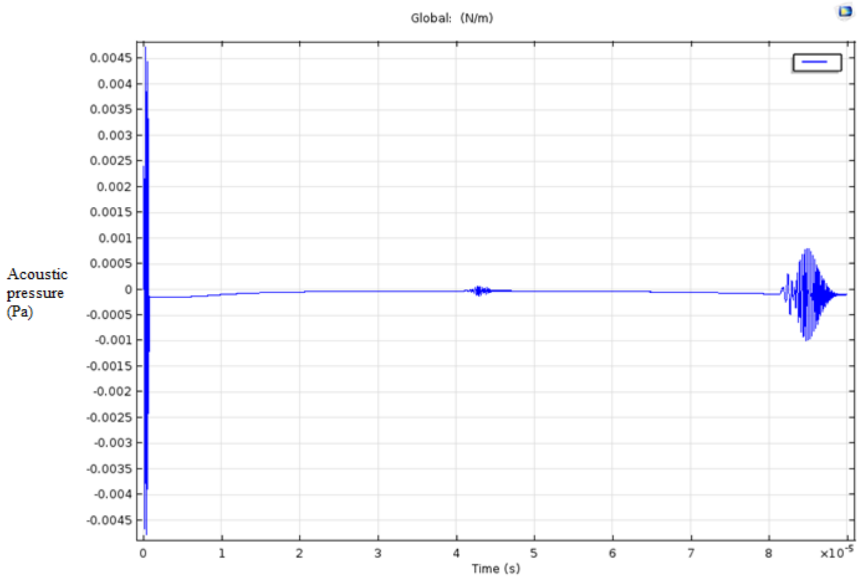

Figure 33. Time signal using 4 MHz frequency

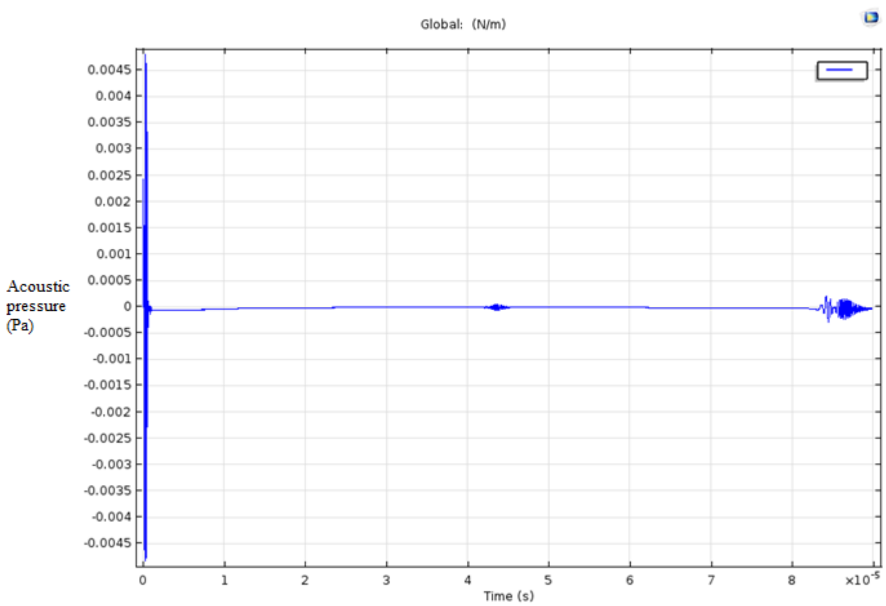

Figure 34. Time signal using 5 MHz frequency

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