

République Algérienne Démocratique et Populaire
Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

École Nationale Polytechnique d'El Harrach – Alger

Département de Génie Mécanique



Final Year Project Thesis

In partial fulfillment of the requirements for the degree of State Engineer in
Mechanical Engineering

Thesis Title:

**“The Force Generated by The Entry of a Moving Compressible Fluid
Induces an Impinging Acoustic Wave”**

Presented by: **Rayhan Brik.**

Supervised by: **Prof. Hamid SEDJAL / Prof. Antonio CARCATERRA**

Defense Date: 17, July

Jury Members:

- President: Prof. Nouredine AMOURA
- Examiner: Prof. Ammar ZEGHLOUL

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Mémoire de Fin d'Études

Présenté en vue de l'obtention du diplôme d'Ingénieur d'État en Génie
Mécanique

Titre du mémoire :

**“La force générée par l'entrée d'un fluide compressible en mouvement
induit une onde acoustique incidente”**

Présenté par : **Brik Rayhan.**

Encadré par: **Prof. SEDJAL Hamid / Prof. CARCATERRA Antonio**

Date de soutenance : 17 Juillet

Membres du jury :

- Président: Prof. AMOURA Noureddine
- Examineur: Prof. ZEGHLOUL Ammar

الملخص:

يتناول هذا البحث دراسة توليد وانتشار الموجات الصوتية في مائع قابل للانضغاط نتيجة تفاعل هذا المائع مع جسم صلب ثابت داخل قناة. الهدف هو فهم كيفية توليد موجات الضغط والانعكاسات، وظواهر الرنين نتيجة تطبيق سرعة متذبذبة عند المدخل. تم أولاً بناء إطار نظري يشمل مفاهيم أساسية مثل الجريان الصوتي (Acoustic Streaming)، الضغط الإشعاعي، ونموذج Ffowcs Williams and Hawkings (FW-H) بعد ذلك، أجريت محاكاة عددية باستخدام برنامج ANSYS Fluent لتحليل تأثير معالم مثل الطول الموجي (λ)، الطور (φ)، ونصف قطر الجسم الصلب (R) شملت النتائج تحليل إشارات الضغط الزمني، طيف SPL، والمخرجات الصوتية من نموذج FW-H.

الكلمات المفتاحية:

انتشار الموجات الصوتية، سائل قابل للانضغاط، محاكاة باستخدام ANSYS Fluent، تفاعل المائع مع البنية.

RÉSUMÉ :

Ce travail porte sur la génération et la propagation des ondes acoustiques dans un fluide compressible en interaction avec un corps solide fixe. L'objectif est de comprendre comment des oscillations imposées à l'entrée d'un domaine confiné peuvent produire des phénomènes acoustiques tels que des ondes de pression, des réflexions et des effets de résonance. Une base théorique a été construite en s'appuyant sur les notions clés de l'acoustique des fluides, telles que le streaming acoustique, la pression de radiation et le modèle FW-H de Ffowcs Williams et Hawkings. L'analyse numérique a été réalisée avec ANSYS Fluent à travers des simulations transitoires, en faisant varier des paramètres comme la longueur d'onde (λ), la phase (φ) et le rayon du cylindre (R). Les signaux de pression moyenne, les spectres SPL et les données acoustiques FW-H.

MOTS-CLÉS:

Propagation des ondes acoustiques, Fluide compressible, Simulation avec ANSYS Fluent, Interaction fluide-structure.

ABSTRACT:

This research analyzes generation and propagation of the acoustic waves in a compressible fluid due to interaction with an immovable solid body. The objective is to identify the process by which inlet-driven oscillations in a confined space lead to the formation of acoustic phenomena such as pressure waves, reflection, and resonance. A theoretical background was initially established by going through significant terms of fluid acoustics, like acoustic streaming, radiation pressure, and the Ffowcs Williams–Hawkings (FW-H) model. Numerical simulation was then performed through ANSYS Fluent, where time-dependent simulations were executed to determine the impact of parameters such as wavelength (λ), phase (φ), and cylinder radius (R). Mean pressure signals, SPL spectra, and FW-H.

KEYWORDS:

Acoustic wave propagation, Compressible fluid, ANSYS Fluent simulation, Fluid–structure interaction.

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Finally, I warmly thank everyone who, directly or indirectly, contributed to the realization of this thesis.

Dedication

"To the one who said I can, and did it.

To the one who believed it was impossible, and still brought it to life."

Today, I embrace a moment I've long dreamed of. A journey filled with trials and long nights has brought me here to success that was once out of reach, yet now rests in my hands.

To my beloved mother AICHA,

You were the prayer that accompanied me, the gentle voice that lifted me, and the haven I ran to when the road felt heavy. Thank you for every heartbeat of patience and unconditional love.

To my dearest father MOHAMMED ALI,

You were my first strength, my solid ground. You taught me discipline, perseverance, and pride. Your sacrifices were the silent pillars of this journey. I hope I've made you proud.

To my two wonderful sisters RADIA, DHIKRA,

And to my three amazing brothers SAMI ,HOUCINE DHIA

You have always been my joy, my safety, and the loudest supporters
of my dreams. Your presence made the path lighter.

To my dear sister-in-law LILA,

Your kindness, support, and sincere encouragement meant more than
words could express. Thank you for being part of this journey with
your constant positivity and warmth.

To my nieces and nephews, especially the precious girl who fills our
days with laughter, and to my sister's son May your futures be as
bright and limitless as the love you bring.

To my dear friends ABIR, WALA, BARAA, AMEL, RANIA, IMEN,
DOUAA, ISRA.

You were the laughter in my darkest days, the helping hand when
things got hard, and the reason I never gave up. Thank you for
walking beside me.

And finally,

To myself Rayhan BRIK,

This success is yours. For the times you cried in silence, stood up
alone, and never gave up. You did it.

All praise and thanks to God for every beginning and every end.

Alhamdulillah.

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NOMENCLATURE

Symbol	Description	Unit
ρ	Density	$kg \cdot m^{-3}$
P	Pressure (total or acoustic)	$Pa (N \cdot m^{-2})$
p'	Acoustic pressure fluctuation	Pa
u	Fluid velocity vector	$m \cdot s^{-1}$
u_0	Mean fluid velocity	$m \cdot s^{-1}$
u'	Velocity perturbation	$m \cdot s^{-1}$
v	Fluid particle velocity	$m \cdot s^{-1}$
v_n	Surface-normal velocity component	$m \cdot s^{-1}$
e	Internal energy per unit mass	$J \cdot kg^{-1}$
E	Total energy	J
F	Body force per unit volume	$N \cdot m^{-3}$
c or c_0	Speed of sound in the medium	$m \cdot s^{-1}$
μ	Dynamic viscosity	$Pa \cdot s$
δ	Thickness of the boundary layer (Stokes)	m
D	Characteristic length (e.g., diameter)	m
f_s	Vortex shedding frequency	Hz
T	Temperature	K
a_0	Reference speed of sound	$m \cdot s^{-1}$
Q_0	Acoustic constant	Pa
P	Total pressure	Pa
P_0	Ambient pressure	Pa
T_{ij}	Lighthill stress tensor	Pa
p_{ij}	Compressional stress tensor	Pa

C_p	Constant specific heat	$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$
ω	Angular frequency	$\text{rad} \cdot \text{s}^{-1}$
φ	Phase shift of the sinusoidal wave	rad
λ	Wavelength	m
k	Wave number	m^{-1}

GREEK SYMBOLS :

<i>Symbol</i>	Description	<i>Unit</i>
α	Absorption coefficient	m^{-1}
β	Tilt or angle (often radian)	rad
δ	Boundary layer thickness or Dirac delta	m
γ	Ratio of specific heats (adiabatic index)	
S	Strouhal number	
∇	Gradient operator	
$\delta(f)$	Dirac delta function	
$H(f)$	Heaviside function	

GENERAL INTRODUCTION

In compressible fluid dynamics, the interaction of fluid flow with solid bodies creates a plethora of complex physical phenomena, among which the creation of acoustic waves is a significant area of interest in scientific and technical applications. Whether it is aeronautical ducts, biomedical ultrasound machines, or industrial noise control, understanding the creation of acoustic waves, their propagation, and interaction with barriers is crucial to develop efficient and effective solutions.

The current study is interested in the case when a stationary solid body is located inside the domain of compressible fluid and a sinusoidal time-dependent flow is imposed on the inlet. This type of configuration is representative of many real cases when waves are created by oscillating boundary conditions rather than due to bodies moving, e.g., pulsatile flow in medical devices or pressure waves in ventilation systems. The wave passes through the domain and strikes the solid geometry, causing reflection, refraction, and acoustic pressure building up around the body.

The primary goals of this work are the following:

- Implement numerical methods to simulate and analyze acoustic wave generation and propagation in a compressible medium.
- Assess the impact of major parameters like wavelength (λ), phase (φ), and cylinder radius (R) on acoustic responses.
- Compute the sound pressure level (SPL) and its time and space variation and determine any potential resonance or amplification effect.

To this end, a methodology of computational fluid dynamics (CFD) was utilized with ANSYS Fluent for solving compressible Navier-Stokes equations under unsteady flow conditions. The acoustic analogy of Fowcs Williams and Hawkings (FW-H) was also utilized to get far-field pressure data at receiver points. Several scenarios were examined numerically, and the major outputs such as pressure contours, SPL spectra, and time-domain signals were studied.

The research comprises six chapters, one of which is devoted to a very relevant topic area of the research.

Chapter 1: Basic of Acoustic Waves

This chapter explains the elementary ideas on acoustic waves, such as their nature, kinds, mathematical representation, and physical parameters governing their behavior in liquids and solids.

Chapter 2: Acoustic Wave Generation and Propagation in Liquids

It discusses how acoustic waves are produced in compressible fluids and how it is particularly relevant to sources such as turbulence, vortex shedding, shock waves, and thermal effects. The chapter then discusses wave propagation properties such as compressibility, dispersion, reflection, and refraction.

Chapter 3: Acoustic Streaming.

This chapter discusses the process of steady flow caused by high-frequency acoustic waves. Rayleigh and Eckart streaming are discussed theoretically, including governing equations and their application in microfluidics and biomedical systems.

Chapter 4: Acoustic Radiation Pressure.

Stresses the loading that acoustic waves put on particles and boundaries. This characterizes radiation pressure, discusses its principles, and demonstrates how it can be applied in order to move objects and generate flow patterns in a number of applications.

Chapter 5: Numerical Simulation of Acoustic Wave Generation in a Compressible Fluid using ANSYS Fluent

This chapter defines the computational approach. The fluid domain, boundary conditions, mesh, solver settings, and turbulence/acoustic models (e.g., FW-H) are discussed. Simulations are carried out with changing parameters like wavelength (λ), phase (ϕ), and cylinder radius (R).

Chapter 6: Results and Discussion

Simulation results are given in the form of contour plots, time-domain pressure signals, SPL (Sound Pressure Level) analysis, and comparative studies. The influence of the parameters of study on acoustic behavior is explained and compared with theoretical expectations.

Chapter 1: FUNDAMENTALS OF ACOUSTIC WAVES

1.1. Scope of acoustics in mechanical engineering

Acoustics is an important discipline in mechanical engineering, comprising topics such as noise and vibration control, aeroacoustics, ultrasonics, structural acoustics, computational acoustics, and automotive acoustics. Engineers in noise and vibration control use damping materials and active noise cancellation techniques to reduce undesired sounds in industrial machinery, buildings, and transportation systems.¹ Aeroacoustics analyzes sound generation caused by fluid flow, such as jet engine noise, wind turbine noise, and flow-induced vibrations in pipelines and HVAC systems.² In mechanical engineering, ultrasonic applications include non-destructive testing (NDT) to detect material defects and acoustic emission monitoring to assess structure integrity.³ Structural acoustics investigates how vibrations travel through solid structures, influencing sound insulation and underwater acoustics, which are essential for submarine communication and sonar technology.⁴ Computational acoustics, which uses techniques like finite element analysis (FEA) and computational fluid dynamics (CFD), allows engineers to simulate and forecast acoustic wave behavior in complicated situations.⁵ Acoustics is critical in the automobile industry for optimizing vehicle cabin noise, lowering engine and exhaust noise, and eliminating tire-road interaction sound. These applications demonstrate the relevance of acoustics in the design of quieter, safer, and more efficient mechanical systems, with continual advances in materials and modeling techniques driving further innovation.

1.2. Early history

In the sixth century BCE, Pythagoras discovered the relationship between the length of the vibrating strings and the variable-pitch musical sounds they produced. More than two millennia later, in 1643, Torricelli demonstrated that sound does not propagate in vacuum, thus establishing the need for media for sound propagation. Half a century later, in 1701, Sauveur introduced the term “acoustics” to describe the science of “sound,” thereby pitching the two terms as synonyms to each other. A century later, in 1802, Chladni brought acoustics to the spotlight by introducing it as a separate branch of physics. With the development of acoustic resonators in 1859, also known as Helmholtz resonators, are founded on the resonance of sound waves within a cavity. They were later applied to sound amplification or

silence in loudspeakers or mufflers, respectively. Kundt studied the speed of sound propagation via a tiny powder-filled tube in 1866 to identify the acoustic pressure nodes of standing waves. As classical acoustics progressed by the end of the nineteenth century, Rayleigh summed up the state of the art at the time in his book *The Theory of Sound* (1896), which is still relevant today.^{6 7 8}

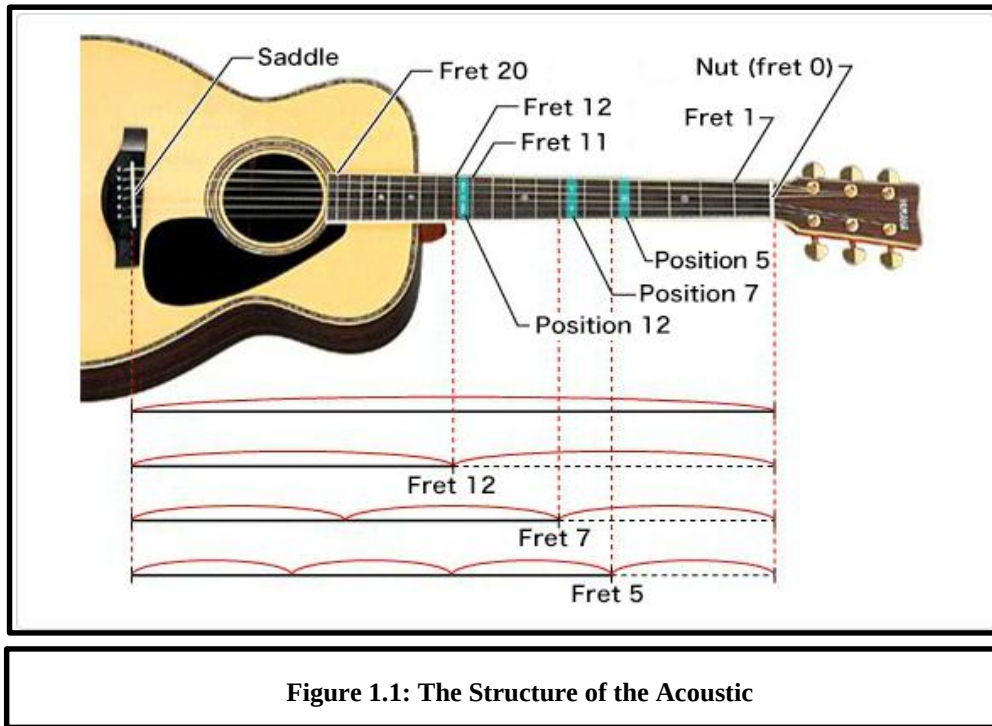


Figure 1.1: The Structure of the Acoustic

1.3. History of acoustic streaming

Acoustic streaming, which is the continuous fluid motion caused by acoustic waves, has been investigated for more than a century. Lord Rayleigh (1884) was the first to theoretically define the phenomena, studying how oscillating sound waves cause fluid motion due to viscosity and wave attenuation.⁹ His study set the groundwork for understanding the conversion of acoustic energy into continuous flows, which proved useful in a variety of engineering and biological applications.

In the mid-20th century, Eckart (1948) expanded on Rayleigh's theory by giving a more thorough framework for acoustic streaming in various flow regimes, such as boundary-layer-driven streaming (Rayleigh streaming) and bulk flow streaming (Eckart streaming)¹⁰. These research shed light on how viscosity, sound frequency, and intensity influence streaming behavior.

Further progress was made in the 1960s and 1970s, when researchers investigated acoustic streaming in ultrasonic applications. Nyborg (1965) created mathematical models to characterize streaming effects in ultrasonic fields, which were crucial for applications including ultrasonic cleaning, sonochemistry, and biomedical procedures.¹¹ During this time, acoustic streaming was also seen in microfluidics and bioengineering, allowing for fine control of small-scale flows.

Researchers developed greater insights into the mechanics of auditory streaming as computational fluid dynamics (CFD) and high-resolution experimental techniques became more prevalent in the late twentieth and early twenty-first centuries. Lighthill (1978) and later Westervelt (1981) made important contributions to the theoretical and numerical modeling of streaming effects in nonlinear acoustic environments.^{12 13} Recent advances have focused on applications such as lab-on-a-chip devices, acoustic tweezers, energy harvesting, and biomedical fluid transport.

Acoustic streaming is still a fast expanding subject today, with researchers using numerical models and experimental methodologies to enhance fluid transport and wave-driven motion for biomedical, industrial, and aerospace applications.¹⁴

1.4. What Is an acoustic wave?

Everyday sounds come from many sources. People chuckle, telephones ring, crickets chirp, and keyboards click. Most people understand the information included in these sounds automatically. Most people prioritize understanding the sounds they hear over understanding sound waves and their propagation.

Geoscientists and anyone who need to understand the information contained in sound waves flowing through the Earth, however, must first understand what sound waves are and how they move.¹⁵

1.4.1. Definition

An acoustic wave is an elastic wave in which a medium is required to carry disturbances within the displacement, velocity, and pressure fields in order to transmit energy from one point in space to another. The medium qualities play an important role in regulating energy transmission. Examples of such waves include ripples on the surface of water, vibrations on a guitar string, and seismic activity that causes earthquakes.¹⁶

1.5. Classification of acoustic waves

Acoustic waves are mechanical waves that propagate through the solid, liquid, or gaseous states of matter by displacing the particles of the medium. Their classification is not simply scholarly; it reflects the variety in the way these waves propagate, the extent of frequencies they cover, and the distinctive features conferred by the medium itself.

1.5.1. Classification by particle motion

a. Longitudinal waves

Longitudinal waves are perhaps the most basic type of acoustic propagation, which includes particle displacement in the direction of the wave. Due to this orientation, they are most common in gaseous mediums, particularly air, where sound waves compress and rarefy molecules upon their trajectory.¹⁷

b. Transverse waves

Transverse waves are distinct from longitudinal waves since they transport particles in a direction perpendicular to the direction of wave propagation. These waves are not typically present in fluids but are present in elastic solids where shearing motions allow such directional displacements.¹⁸

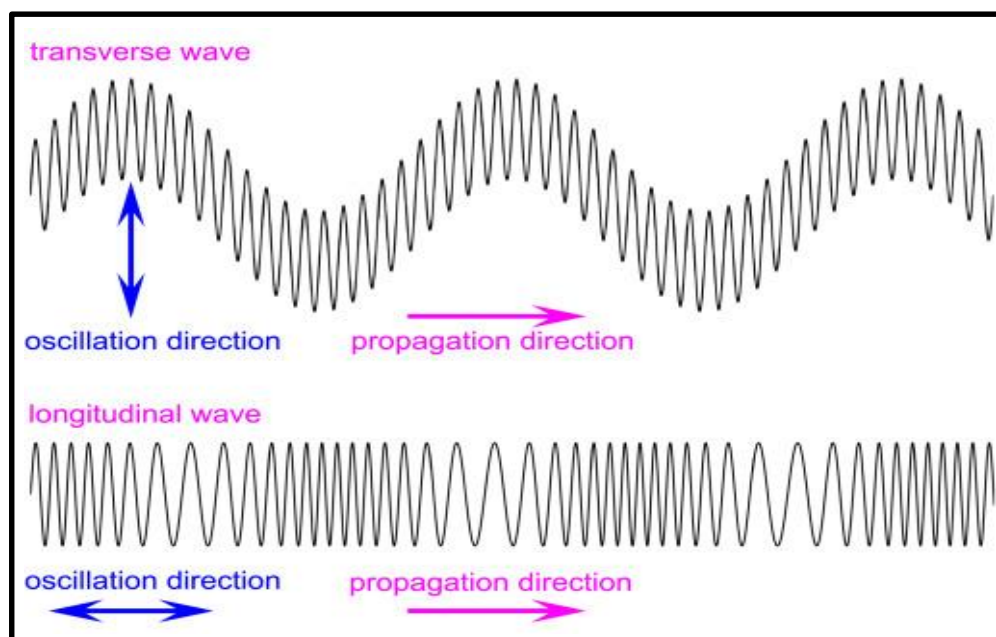
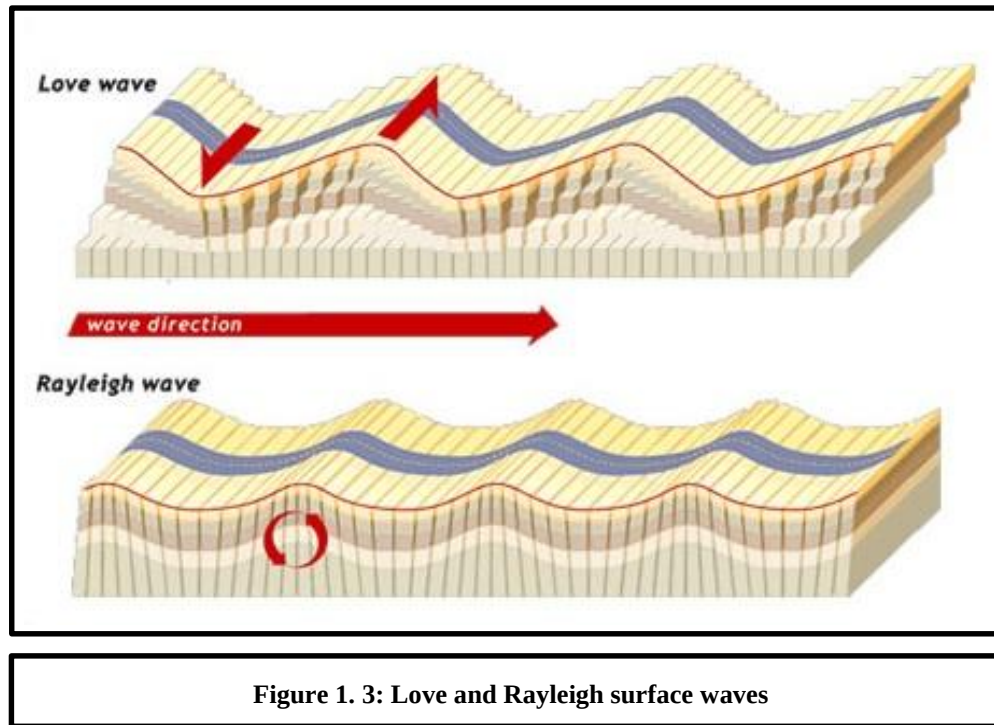


Figure 1. 2: Transverse and Longitudinal acoustic waves

c. Surface waves

Surface acoustic waves, such as Rayleigh and Love waves, travel along the interface and decay exponentially with depth. These waves are important in geophysics and non-destructive testing, where surface interactions are dominant.¹⁹



1.5.2. Classification by frequency

a. Infrasonic waves

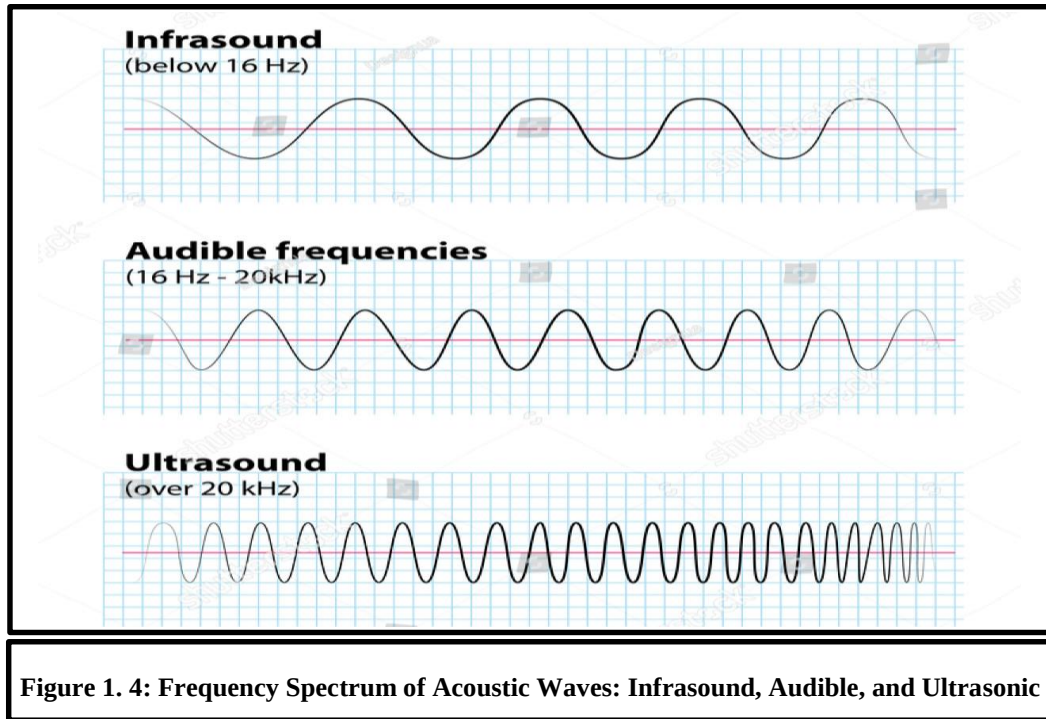
Infrasonic waves, which operate at low frequencies of less than 20 Hz, are inaudible to the human ear but have substantial applications in environmental science, seismic surveys, and macro-scale structural diagnosis.²⁰

b. Audible waves

This band is 20 Hz to 20 kHz—what we refer to as "sound." This band contains voice, music, and general noise, which constitute the foundation of human acoustic experience.²¹

c. *Ultrasonic waves*

Ultrasonic waves (>20 kHz) exceed the auditory threshold and serve a variety of activities, including imaging tissues in medical diagnostics, welding metals, and cleaning precision instruments in industrial applications.²²



1.5.3. *Specialized acoustic waves*

a. *Shock waves:*

Shock waves are defined by their abrupt, nearly instantaneous pressure, density, and temperature changes. They are created by explosions or objects traveling at supersonic speeds and nonlinear behavior. They are utilized both for destructive and diagnostic applications.²³

b. *Pressure waves:*

Pressure waves, or longitudinal waves, play a crucial role in acoustic transmission within fluids. Their repeating compressions and rarefactions transport energy and information across great distances, such as sonar in the ocean or echo in a canyon.

c. *Ultrasound waves:*

These high-frequency waves, while encroaching on ultrasonics, are worthy of note for their critical use in medicine. Whether monitoring prenatal development or shattering kidney stones with lithotripsy, ultrasound technology demonstrates precision through vibration.

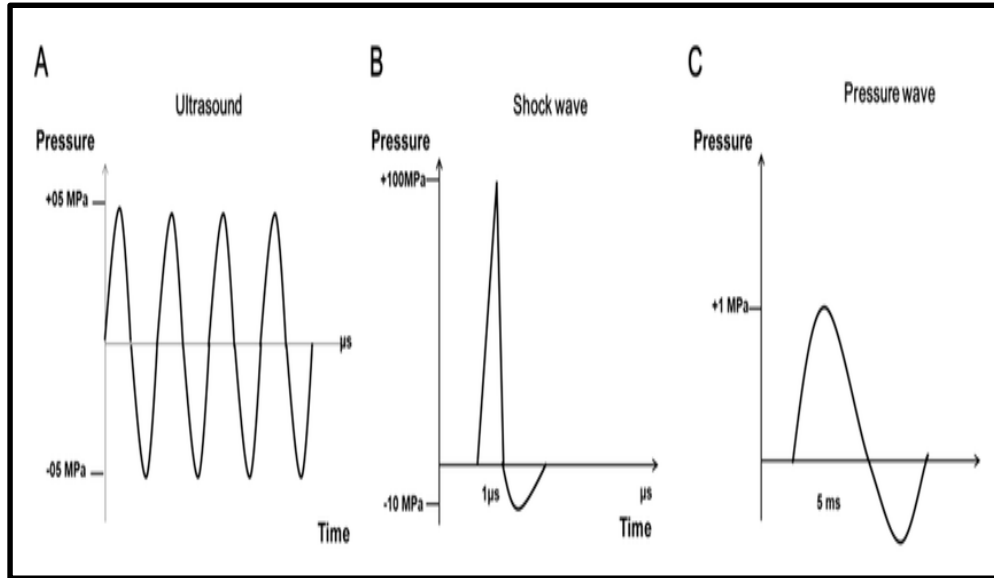


Figure 1. 5: Specialized acoustic waves: Shock, Pressure, and Ultrasound

1.6. Mathematical formulation of acoustic waves

Acoustic waves can be mathematically described on the basis of simple fluid dynamic equations under minimal disturbance assumptions, linear response, and ideal fluid conditions. The behavior of acoustic waves is governed primarily by three equations: equation of state, continuity, and momentum (Navier-Stokes).

1.6.1. Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \dots \dots \dots (1)$$

Here, $\rho = \rho(x, t)$ is the mass density (or just density) and $u = u(x, t)$ is fluid velocity. This equation connects the rate of change of density at a point and the outward or inward mass flux at that point.

1.6.2. The Euler model

The Euler model is named after Leonhard Euler, who developed the mass and momentum conservation equations. The conservation equations for momentum, and energy are:

$$\rho \frac{Du}{Dt} = -\nabla \cdot \mathbf{p} + \mathbf{F} \dots\dots\dots (2)$$

$$\rho \frac{De}{Dt} = -\mathbf{p} \nabla \cdot \mathbf{u} \dots\dots\dots (3)$$

e is the internal energy and F is the external body force density.

The momentum equation (2) explains how a particle's velocity is influenced by external forces and pressure differences, with higher pressures pushing it towards lower pressures.

According to the energy equation (3), a particle's internal energy decreases when it expands and increases when it compresses.

1.6.3. Linearized Governing Equations

Assuming small perturbations in a quiescent fluid, we define:

$$\mathbf{p} = \mathbf{p}_0 + \mathbf{p}' \dots\dots\dots (4)$$

$$\rho = \rho_0 + \rho' \dots\dots\dots (5)$$

$$\mathbf{u} = \mathbf{u}_0 + \mathbf{u}' \dots\dots\dots (6)$$

where $\mathbf{p}_0$, ρ_0 are mean (equilibrium) values and $\mathbf{p}'$, ρ' , $\mathbf{u}'$ are small perturbations.

1.6.4. Linearized Equation of State (Isentropic Approximation)

$$\mathbf{p}' = c^2 \rho' \dots\dots\dots (7)$$

where c is the speed of sound in the medium.

1.6.5. The linear acoustic wave equation

$$\frac{\partial^2 \mathbf{p}'}{\partial t^2} - c^2 \nabla^2 \mathbf{p}' \dots\dots\dots (8)$$

This partial differential equation depicts how pressure waves propagate over space and time.

Chapter 2: GENERATION AND PROPAGATION OF ACOUSTIC WAVES IN FLUIDS

2.

2.1. Mechanisms of wave generation

Acoustic waves find their sources in fluids and solids via a broad array of physical processes. They encompass but are not restricted to shock waves, turbulence, and vortex shedding. They are all driven by dynamic matter-energy interactions, and their contributions are highly dependent on the flow regime, medium compressibility, and boundary conditions. Their sources must be known for many disciplines like aerodynamics and biomedical acoustics to be applicable.

2.1.1. Shock waves

Shock waves are nonlinear disturbances with abrupt changes in pressure, temperature, and density. They usually occur when a body moves at a velocity higher than the local speed of sound (supersonic velocities). The waves are created by compressive forces larger than the medium can respond to elastically, resulting in an nearly discontinuous change known as a shock front.

Shock waves are of importance in high-speed aerodynamics, explosions, and jet propulsion. The Rankine-Hugoniot conditions are mathematical descriptions of such discontinuities.²⁴

2.1.2. Turbulence-induced acoustic waves

Acoustic waves caused by turbulence are a consequence of the intricate interactions in turbulent flows, resulting in the emission of sound. Lighthill's acoustic analogy supplies a mathematical model for the phenomenon based on the treatment of turbulent flow as a sound-sourcing source within a passive medium.

Lighthill continues this analogy in his 1954 book, highlighting the quadrupole character of sources of turbulent flow and contrasting the efficiency of sound generation processes. He also describes the limits of comparability, particularly when flows have low Mach numbers and dipole sources may be prominent.²⁵

2.1.3. Vortex shedding

Vortex shedding takes place when fluid flows over a bluff body, creating alternating low-pressure vortices downstream that cause periodic force variations. Alternating flow is an

extremely intense coherent source of sound, which is known as tonal noise. It is found to be of huge utility in pipes, chimneys, heat exchangers, and even in living things like insect wings and voice cords.

The Strouhal number (S) provides the frequency of vortex shedding:

$$S = \frac{f_s D}{U} \dots \dots \dots (9)$$

Where f_s is the Vortex shedding frequency in units of hertz (cycles per second), D is the characteristic dimension, and U is the flow velocity.²⁶

2.1.4. Flow instabilities and pressure oscillations

In most systems, for instance, in combustion chambers or in jet exhausts, instabilities in the flow field can become coupled with the acoustic field and cause self-sustaining oscillations. These instabilities build up over a period of time and generate high-intensity acoustic waves, an effect known as acoustic resonance.²⁷

2.1.5. Thermoacoustic sources

Heating may cause rapid thermal expansion (e.g., in laser ablation or plasma arcs), producing pressure waves. These are useful for photoacoustic imaging and thermoacoustic engines, which convert periodic heat input into acoustic energy.²⁸

2.2. Effects of compressibility in fluid media

Compressibility, or the ability of a fluid to change density in response to changes in pressure, is a factor in wave propagation, flow dynamics, and energy transmission in fluid media. While incompressible flow assumptions are convenient to simplify many engineering calculations, the inclusion of compressibility is necessary in high-speed, high-pressure, or acoustically active applications where the density changes cannot be ignored.²⁹

Pressure waves propagate at a finite speed in compressible fluids — the speed of sound — with resultant time delay in information transfer. This property is a central aspect of phenomena involving shock wave generation, propagation of acoustic waves, and thermoacoustic instability³⁰ Compressibility effects are small and may be neglected at

subsonic speeds, but with a Mach number above 0.3, variation of density becomes appreciable, affecting the flow field, pressure distribution, and vortex behavior.

Acoustic waves are perhaps the most pervasive side effects of compressibility. When a body moves through a compressible medium, pressure disturbances are radiated in the form of compressional and rarefactional waves. They may be radiated freely or reflect and converge to create complex interference patterns such as impinging acoustic waves, which are particularly significant to aerospace and medical applications.³¹

Besides, compressibility causes nonlinear phenomena in fluid systems. As an example, energy may be stored in compressive regions and then release rapidly, causing phenomena such as shock waves, instantaneous pressure fronts caused by irreversible thermodynamic processes³². This nonlinearity also causes acoustic streaming, which is continuous fluid motion due to transfer of momentum of oscillating waves in a compressible medium³³.

In turbulent flows, compressibility influences the turbulent kinetic energy spectrum and the rate of energy dissipation. Compressible turbulence and the interaction of acoustics is an emerging field, particularly in supersonic aerodynamics and jet propulsion, where acoustic generation from turbulent eddies is a key aspect³⁴.

Finally, compressibility is vital in thermoacoustic systems where acoustic pressure oscillations and temperature gradients coexist. This interaction forms the foundation of thermoacoustic freezers and engines, which have the ability to convert heat into sound and sound back into heat in the absence of mechanical components, due to the compressible nature of the working gas.³⁵

2.3. Influence of viscosity and boundary layers

2.3.1. *The fundamentals of viscosity and boundary layers*

Viscosity can be defined as fluid flow resistance to deformation. In fluid flow dynamics, viscosity plays an important role in the development of boundary layers, which represent a thin region near solid walls dominated by very high viscous forces. The fluid velocity transitions from zero-flow velocity at the surface due to the no-slip condition to the free-flow velocity within those layers. The behavior of the boundary layer is determined by the balance between inertial and viscous forces, and it is often represented by the Reynolds number.³⁶

2.3.2. *Viscosity's impact on boundary layer thickness*

The thickness of the boundary layer is directly proportional to the fluid's viscosity. Higher viscosity results in larger boundary layers as flow resistance by the fluid smooths out the velocity gradient at the surface. This has significant implications in the design of systems requiring accurate control of flow, such as microfluidic devices or tight oil reservoirs.³⁷

2.3.3. *Boundary layers in turbulent flows*

The turbulent boundary layer possesses complex behavior due to the fluctuating and random nature of turbulence. Viscosity controls the formation and stability of turbulent boundary layers, which affect drag and heat transfer. Understanding these effects is significant for aerospace engineering application and meteorology.³⁸

2.3.4. *Variable viscosity effects*

In the majority of practical applications, viscosity is a function of temperature, pressure, and composition. Such dependencies can greatly influence boundary layer behavior, resulting in changes in flow separation points, heat transfer rates, and system performance. Modeling such effects involves sophisticated computational techniques and good knowledge of fluid physics.³⁹

2.3.5. *Applications and implications of viscosity and boundary layers*

a. Aerospace engineering

Boundary layers need to be comprehended in order to have the ability to design airplane surfaces in a manner that reduces drag and increases lift. The aerodynamic performance of flight vehicles is determined by the character of the boundary layer.⁴⁰

b. Mechanical engineering (heat exchangers)

During the design of heat exchangers, the thermal boundary layer has a large impact on heat transfer. The thickness of the thermal boundary layer is responsible for the temperature gradient and thus the rate of heat transfer.⁴¹

c. Biomedical engineering (blood flow)

Boundary layers are utilized to study blood flow behavior near vessel walls. Boundary layer formation in blood vessels influences shear stress distributions, which is relevant to vascular biology and medical device design.⁴²

Chapter 3: ACOUSTIC STREAMING.

3.

3.1. Introduction to streaming

3.1.1. What is acoustic streaming?

Acoustic streaming is the continuous, time-averaged fluid motion that results from the absorption of intense sound waves. Unlike the periodic motion of the particles during sound propagation, streaming is a nonlinear phenomenon resulting in net mass transport of the fluid medium. Streaming is most often seen in high-frequency ultrasonic devices but also in natural systems, microfluidics, and medical devices.⁴³

3.1.2. Types of acoustic streaming

Acoustic streaming can take numerous forms:

- a. *Rayleigh Streaming*: at rigid boundaries when a standing wave encounters a viscous boundary layer.
- b. *Eckart streaming*: due to energy dissipation in the bulk fluid.
- c. *Schlichting Streaming*: Occurs near an oscillating boundary in a viscous fluid.

Each of these is marked by distinct flow patterns and occurs in distinct acoustic environments.⁴⁴

⁴⁵

3.1.3. Applications

Acoustic streaming is being used extensively in ⁴⁶:

- a. *Microfluidics*: for pumping and mixing liquids in lab-on-chip devices.
- b. *Ultrasound treatment*: To improve drug delivery through fluid motion.
- c. *Acoustic levitation*: is observed when particles are stabilized in a streaming field.

3.2. Rayleigh and Eckart streaming

3.2.1. Rayleigh streaming

- a. *Historical background*:

Rayleigh Streaming is the oldest recorded type of acoustic streaming. Lord Rayleigh originally described it in 1884 when examining airflow regimes in Kundt's tubes, where viscous boundary layers contribute to standing sound waves to produce a continuous flow.⁴⁷

b. Physical mechanism:

Rayleigh streaming is seen at rigid boundaries in a fluid region under standing acoustic waves. Wave motion generates oscillatory flow at the boundary, while viscous action within the thin boundary layer transports momentum to the bulk fluid. The nodal planes of the standing wave produce a pair of counter-rotating vortices above and below.

- It is best visible when the sound's wavelength is larger than the fluid's channel.
- Typically, the thickness of the boundary layer is comparable to that of the Stokes layer:

$$\delta = \sqrt{\frac{2\mu}{\rho\omega}} \dots \dots \dots (10)$$

In this equation, μ denotes dynamic viscosity, ρ denotes fluid density, and ω represents angular frequency.⁴⁸

c. Applications:⁴⁹

- Used in acoustofluidics to generate mixing in microfluidic channels.
- Used in particle manipulation techniques in microenvironments.
- Useful in sonochemical reactors for improving reactant dispersion.

3.2.2. Eckart streaming

a. Historical background:

Carl Eckart originally described Eckart Streaming back in 1948. In contrast to Rayleigh Streaming, it addresses bulk motion due to the absorption of traveling acoustic waves by the fluid, and this is particularly applicable for the case of ultrasound in compressible media.⁵⁰

b. Physical Mechanism:

Eckart Streaming is the phenomenon by which acoustic energy gradually diminishes as it passes through a viscous fluid. Nonlinear interaction between velocity, density, and pressure fields creates a constant, one-way flow along the direction of wave travel.

- Higher frequency ultrasound prevails in larger regimes.
- It is not at boundaries but in the bulk fluid as opposed to Rayleigh streaming.

- The energy of the acoustic wave is transferred to momentum, propelling the fluid in a uniform direction.⁵¹

*c. Applications:*⁵²

- Widely applied in medical ultrasound therapy, particularly for the promotion of drug transfer and stimulation of blood circulation.
- Essential to acoustic cleaning methods and ultrasonic atomization.
- Allows contactless pumping in bio-MEMS devices and lab-on-chip systems.

3.3. Governing equations and flow patterns in acoustic streaming

Acoustic streaming is the time-averaged fluid flow generated by acoustic radiation absorption. To describe and describe quantitatively the ensuing flow patterns, one has to resort to the fundamental equations of fluid dynamics, viz., the Navier-Stokes equations, which describe the motion of viscous fluids.

3.3.1. Governing Equations

Acoustic streaming theory is based on the compressible Navier-Stokes equations, which are modified to include acoustic perturbations. The equations include:

*a. Continuity Equation (Mass Conservation):*⁵³

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \dots \dots \dots (11)$$

- Describes the conservation of mass.
- Accounts for changes in fluid density ρ and velocity $\mathbf{v}$ due to wave-induced motion.

*b. Momentum Equation (Navier–Stokes):*⁵⁴

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right) = -\nabla p + \mu \nabla^2 \mathbf{v} + \left(\lambda + \frac{\mu}{3} \right) \nabla (\nabla \cdot \mathbf{v}) \dots \dots \dots (12)$$

- Governs fluid motion.
- Includes the viscous terms and pressure gradient, both crucial in the development of streaming flows.

3.3.2. Flow Patterns

Acoustic streaming exhibits diverse structures depending on the nature of the wave, frequency, and boundary conditions. A few notable flow patterns are:

a. *Rayleigh Streaming Patterns:*⁵⁵

- Occur near fixed boundaries with static waves.
- Vortices develop within the boundary layer and travel through the fluid.
- Typical pattern: counter-rotating rollers with nodes of pressure along them.

b. *Eckart Streaming Patterns:*⁵⁶

- Driven by traveling waves and bulk attenuation.
- Induce a unidirectional drift of fluid in the direction of wave propagation.

c. *Streaming Liching:*⁵⁷

- Wave amplitudes fluctuate along a surface, as observed in the Stokes boundary layer.
- This is especially true with beam-shaped ultrasonic fields in microchannels.

3.3.3. The Fowcs Williams and Hawkings FW-H Acoustic Model

In order to simulate acoustic wave generation in the case of a rigid body kept fixed in an compressible fluid, the Fowcs Williams and Hawkings (FW-H) model provides an appropriate and reliable basis on which far-field acoustic pressure can be determined from near-field flows. It is found to be especially appropriate in numerical simulations where the acoustic source is approximated by a solid surface in contact with an unsteady flow in lieu of a moving source. The FW-H model is Lighthill's acoustic analogy extended to incorporate monopole and dipole source terms, which are formulated over a control surface S that surrounds the body. Under the assumptions of fixed solid boundaries and subsonic flow, the quadrupole (volume) terms may be ignored, simplifying the governing equation to surface integrals only.

The simplified FW-H equation used in Fluent is:

$$\frac{1}{a_0^2} \frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial^2}{\partial x_i \partial x_j} \{T_{ij} H(f)\} - \frac{\partial}{\partial x_i} \left\{ \frac{[P_{ij} n_j + \rho u_i (u_n - v_n)] \delta(f)}{\partial t} + \frac{\partial}{\partial t} \{[\rho_0 v_n + \rho (u_n - v_n)] \delta(f)\} \right\}$$

Where:

u_i : Fluid velocity component in the x_i direction

u_n : Surface velocity component normal to the surface $f = 0$

v_i : Surface velocity components in the x_i direction

v_n : Surface velocity component normal to the surface

$\delta(f)$: Dirac delta function

$H(f)$: Heaviside function

p' : The sound pressure at the far-field, $p' = (p - p_0)$

T_{ij} : The Lighthill's stress tensor, $T_{ij} = \rho u_i u_j + p_{ij} - a_0^2(\rho + \rho_0)\delta_{ij}$

a_0^2 : The speed of sound

p_{ij} : The compressive stress tensor

In your ANSYS Fluent setup:

- The FW-H surface was applied as the solid body (source),
- Multiple receiver points were placed near the body to record pressure fluctuations with time,
- The sound signal and SPL spectrum were accessed by the utilization of "Export Acoustic Source Data" and "Compute Acoustic Signal" options.

This approach provides for the clean acoustic data to be recovered while eliminating the aeroacoustic effects resulting from wave-structure interaction without resolving the full propagation path within the far field. ⁵⁸

Chapter 4: ACOUSTIC RADIATION PRESSURE

4.

4.1. Introduction

Lord Rayleigh (1902, 1905) first researched acoustic radiation pressure, which is the acoustic counterpart to electromagnetic wave pressure. Since then, several scholars have researched this problem, with varying results (see Beyer, 1978).⁵⁹ At the time, Rayleigh and others believed that a vacuum contains "ether," which allows electromagnetic waves to move through it similarly to sound waves. Rayleigh discovered that the acoustic radiation pressure on a perfectly reflecting surface due to a normally incident plane sound wave in a gas is $(\gamma + 1)(E)/2$, where (γ) is the ratio of the gas's specific heats and (E) is the average energy density of the standing wave formed by the incident and reflected waves. The radiation pressure of an electromagnetic wave is denoted as (E) . Unlike the electromagnetic counterpart, the acoustic radiation pressure was determined by the elasticity of the medium denoted by (γ) , which was somewhat disconcerting.

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4.2. Definition

An acoustic field exerts a net force on an object. This force is created by the transfer of wave momentum to scattering or absorbing objects as a result of inhomogeneous wave scattering or reflection from items exposed to the acoustic field. At the interface, the acoustic wave can be partially reflected and transmitted, which can help to generate the radiation force. Several factors influence the ARF in the Mie, Rayleigh, and geometrical scattering regimes, such as the acoustic wave frequency, the scatterer's material qualities, and the object's geometry. The strength of the ARF increases with the Rayleigh, Mie, and geometrical scattering regimes. Rayleigh scattering occurs when the item size is significantly less than the wavelength of the acoustic wave, while Mie scattering happens when the object size is comparable to the wavelength. Geometric scattering occurs when the object size exceeds the wave length, resulting in increased ARF.⁶¹

4.3. General principles

4.3.1. Equation of state

We begin by proposing a model for the adiabatic equation of state of the fluid:

$$P - P_0 = Q_0 \left[\left(\frac{\rho}{\rho_0} \right)^\gamma - 1 \right], \dots\dots\dots (13)$$

Where:

- P_0 is the ambient pressure,
- $P = P_0 + p$ is the total pressure, p is the acoustic pressure
- ρ_0 is the ambient density.
- $\rho = \rho_0 + \rho'$, where ρ' is the excess density.
- γ is a constant.
- and $Q_0 = \rho_0 * c_0^2 / \gamma$, in which. c_0 is the small-signal speed of sound. For an ideal gas, γ is just the ratio of specific heats, in which case $c_0^2 = \gamma * P_0 / \rho_0$, $Q_0 = P_0$, and Eq. (13) reduces to $P/P_0 = (\rho/\rho_0)^\gamma$. For liquids, γ is an empirical parameter.

4.3.2. Acoustic Radiation Stress Tensor

In the Eulerian coordinate system, the momentum equation can be used to obtain the equations of motion for an ideal fluid in tensor form:

$$\rho \left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = - \frac{\partial P}{\partial x_i}, \dots\dots\dots (14)$$

and the continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0, \dots\dots\dots (15)$$

In this equation, u_i represents the i th component of the particle velocity field vector, and x_i represents a component of the position vector. Equations (14) and (15) combine to produce:

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = - \frac{\partial P}{\partial x_i}, \dots\dots\dots (16)$$

For acoustic oscillations can be defined as the time average across one cycle, indicated by $\langle \rangle$. When averaging Eq. (16), the first term on the left side vanishes in steady state. such that:

$$\frac{\partial S_{ij}}{\partial x_j} = 0, \dots\dots\dots (17)$$

Where:

$$S_{ij} = \langle -P \rangle \delta_{ij} - \langle \rho u_i u_j \rangle \dots\dots\dots (18)$$

is called the acoustic radiation stress tensor, which was first derived by Brillouin (1938, 1964), and δ_{ij} represents the Kronecker delta. In Eq. (17), replacing P with $P - P_0$ makes no impact. Since u_i is first order, and $\rho = \rho_0 + \rho'$, Eq. (18) becomes, at second order,

$$S_{ij} = -\langle P - P_0 \rangle \delta_{ij} - \rho_0 \langle u_i u_j \rangle. \dots\dots\dots (19)$$

4.3.3. Mean Eulerian Excess Pressure

In Eq. (19), the number $\langle P - P_0 \rangle$ represents the "mean excess pressure," which is often nonzero at finite amplitudes. It is Eulerian because it is calculated at a fixed location in space, as opposed to Lagrangian pressure. A sound field in an inviscid fluid is irrotational, therefore we can write $u = \nabla \phi$, where ϕ represents the velocity potential. Equation (14) therefore becomes

$$\nabla \left[\frac{\partial \phi}{\partial t} + \frac{1}{2} |\nabla \phi|^2 \right] = -\frac{\nabla P}{\rho}. \dots\dots\dots (20)$$

The first law of thermodynamics states that $dw = T ds + dP/\rho$, where T represents temperature and s and w represent the fluid's entropy and enthalpy per unit mass, respectively. Assuming that the motion is adiabatic, we get $dw = dP/\rho$ or $\nabla w = \nabla P/\rho$. Equation (20) can be integrated once in space, to give

$$w = -\frac{\partial \phi}{\partial t} - \frac{1}{2} |\nabla \phi|^2 + C' \dots\dots\dots (21)$$

where C' is constant in space but can depend on time. The pressure P can be expanded in a Taylor series in w as follows:

$$P = P_0 + \left(\frac{\partial P}{\partial w} \right)_{s,0} w + \frac{1}{2} \left(\frac{\partial^2 P}{\partial w^2} \right)_{s,0} w^2 + \dots, \dots\dots\dots (22)$$

where the subscript $s,0$ means "evaluated at constant entropy and at equilibrium." Since $(\partial w / \partial P)_s = 1/\rho$, we have $(\partial w / \partial P)_s = \rho = \rho_0$, and $(\partial^2 P / \partial w^2)_s = (\partial \rho / \partial w)_s = (\partial \rho / \partial P)_s (\partial P / \partial w)_s = \rho / c^2$, where the fundamental relation $(\partial P / \partial \rho)_s = c^2$ was used, and letting all these quantities take equilibrium values. So Eq. (22)

becomes

$$P = P_0 + \rho_0 \left(-\frac{\partial \phi}{\partial t} - \frac{1}{2} |\nabla \phi|^2 + C' \right) + \frac{1}{2} \frac{\rho_0}{c_0^2} \left(-\frac{\partial \phi}{\partial t} - \frac{1}{2} |\nabla \phi|^2 + C' \right)^2 + \dots, \dots\dots\dots (23)$$

In linear acoustics, $C' = 0$ and Eq. (21) reduces to $w = p/\rho_0 = -\partial \phi / \partial t$. At second order, a finite value of C' is sometimes needed for the solution to satisfy a constraint. We therefore take C' to be a second-order quantity. By time-averaging Eq. (23), at second order we find

$$\langle P - P_0 \rangle = \frac{1}{2} \frac{\rho_0}{c_0^2} \left(\frac{\partial \phi}{\partial t} \right)^2 - \frac{1}{2} \rho_0 |\nabla \phi|^2 + C \dots\dots\dots (24)$$

where $C = \rho_0 \langle C' \rangle$ is a constant in both space and time. At second order, ϕ in the quadratic terms on the right-hand side can be replaced with linear relations. Substituting $u = \nabla \phi$ and $\partial \phi / \partial t = -p/\rho_0$ into Eq. (24), we obtain for the mean Eulerian excess pressure

$$\langle P - P_0 \rangle = \langle P^E - P_0 \rangle = \frac{1}{2 \rho_0 c_0^2} \langle P \rangle^2 - \frac{1}{2} \rho_0 \langle \mathbf{u} \cdot \mathbf{u} \rangle + C = \langle V \rangle - \langle K \rangle + C, \dots\dots\dots (25)$$

Where $\langle V \rangle = \frac{1}{2 \rho_0 c_0^2} \langle P \rangle^2$ and $\langle K \rangle = \frac{1}{2} \rho_0 \langle \mathbf{u} \cdot \mathbf{u} \rangle$ are the time-averaged potential and kinetic energy densities, respectively, and P has been equated to P^E to emphasize that the pressure is Eulerian.

4.3.4. Mean Lagrangian Excess Pressure

During acoustic vibration, fluid particles experience the mean Lagrangian excess pressure, which differs from the Eulerian excess pressure. The superscript L denotes the Lagrangian ξ represents the displacement of a fluid particle from its equilibrium position $\mathbf{a}$. We just need a first-order relationship between ξ and fluid particle velocity, as there is no distinction between the Lagrangian and Eulerian velocities. We therefore write $\mathbf{u} = \partial \xi / \partial t$. An arbitrary Lagrangian quantity $q^L(\mathbf{a}, t)$ is related to the corresponding Eulerian quantity $q^E(\mathbf{x}, t)$, at second order, by $q^L(\mathbf{a}, t) = [q^E(\mathbf{x}, t)]_{\mathbf{x}=\mathbf{a}} + \xi \cdot [\nabla q^E(\mathbf{x}, t)]_{\mathbf{x}=\mathbf{a}}$. So we have $P^L = P^E + \xi \cdot \nabla P^E$, or

$$\langle P^L - P_0 \rangle = \langle P^E - P_0 \rangle + \langle \xi \cdot \nabla P^E \rangle \dots\dots\dots (26)$$

The last term on the right can be evaluated using first-order relations. The linearized form of Eq.(14) is $\frac{\rho_0 \partial u}{\partial t} = -\nabla P$, or $\frac{\rho_0 \partial^2 \xi}{\partial t^2} = -\nabla P^E$. Integration by parts yields $\langle \xi \cdot \nabla P^E \rangle = -\rho_0 \langle \xi \cdot$

$\partial^2 \xi / \partial t^2 \rangle = \rho_0 \langle \partial \xi / \partial t \cdot \partial \xi / \partial t \rangle = \rho_0 \langle \mathbf{u} \cdot \mathbf{u} \rangle$, and thus $\langle \xi \cdot \nabla P^E \rangle = 2 \langle K \rangle$. Substituting both the last relation and Eq. (25) into Eq. (26), we obtain for the mean Lagrangian excess pressure

$$\langle P^L - P_0 \rangle = \langle V \rangle + \langle K \rangle + C = \langle E \rangle + C, \dots\dots\dots (27)$$

where $\langle E \rangle = \langle V \rangle + \langle K \rangle$ is the total mean energy density of the wave. Equations (27) and (25) are referred to as Langevin's first and second relations, respectively (Beissner, 1986). To understand the significance of $\langle P^L - P_0 \rangle$, consider the x component of the stress defined in Eq. (19):

$$S_{xx} = -\langle P - P_0 \rangle - \rho_0 \langle u^2 \rangle. \dots\dots\dots (28)$$

where $\langle P - P_0 \rangle$ is the mean Eulerian excess pressure, and u is the acoustic particle velocity in the x direction. Using Eq. (25) and letting $\langle K_x \rangle = \rho_0 \langle u^2 \rangle / 2$, $\langle K_y \rangle = \rho_0 \langle v^2 \rangle / 2$, and $\langle K_z \rangle = \rho_0 \langle w^2 \rangle / 2$ for the velocity components u, v , and w in the x, y , and z directions, respectively, we may rewrite Eq. (28) as

$$-S_{xx} = -\langle V \rangle + \langle K_x \rangle - \langle K_y \rangle - \langle K_z \rangle + C. \dots\dots\dots (29)$$

If the motion is only in the x direction, then $\langle K_y \rangle = \langle K_z \rangle = 0$, and after letting $\langle K_x \rangle = \langle K \rangle$, comparison with Eq. (27) yields $S_{xx} = -\langle P^L - P_0 \rangle$ for Eq. (29). From the 1-D form of Eq. (17), $\partial S_{xx} / \partial x = 0$, it follows that $\partial \langle P^L - P_0 \rangle / \partial x = 0$, such that

$$\langle P^L - P_0 \rangle = \text{constant}. \dots\dots\dots (30)$$

Equation (30) is not frequently true in two or three dimensions. The 1-D situation has been researched extensively due to its simplicity. Beissner (1985, 1986) emphasized the limitations of 1-D motion as a practical solution. 1-D equations cannot account for oblique and normal reflections of plane waves and diffracting sound beams. Therefore, Eq. (30) has limited practical application.

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**Chapter 5: NUMERICAL SIMULATION OF ACOUSTIC
WAVE GENERATION IN A COMPRESSIBLE FLUID USING
ANSYS FLUNET.**

5.

5.1. Introduction

This chapter provides a numerical simulation in ANSYS Fluent to analyze the generation and propagation of acoustic waves as a result of imposed fluid motion at the intake, which comes in contact with an immersed fixed solid body in a compressible fluid domain.

The primary goal of these simulations is to analyze how the acoustic field evolves and interacts with the rigid fixed body within the duct. In particular, the goal is to calculate the mean acoustic pressure applied to the surface of the fixed solid profile and to assess the forces arising from this fluid-structure interaction.

Furthermore, the simulations analyze how significant parameters like duct width, wave amplitude, and frequency affect acoustic wave propagation and reflection in a confined environment. These parameters are varied to better understand their effect on wave behavior, pressure distribution, and resonance patterns in the computational domain.

5.2. Presentation of ansys fluent software

ANSYS Fluent is a very prominent and well-liked computational program in Computational Fluid Dynamics (CFD). It possesses the ability to simulate and analyze fluid flow, heat transfer, compressible and incompressible gas dynamics, turbulence, multiphase flows, chemical reactions, and acoustic wave propagation.

Created by ANSYS Inc., Fluent computes the Navier–Stokes equations using advanced finite-volume methods. It features a user-friendly interface, robust solvers, and seamless integration with pre-processing and post-processing software such as ANSYS Meshing, SpaceClaim, and ParaView.

- ANSYS Fluent simulates both steady-state and transient flows.
- Both compliant and incompressible fluids are catered for.
- Complex turbulence modeling (e.g., $k-\epsilon$, $k-\omega$, LES, RSM) is provided.
- Acoustic wave propagation for different flow regimes is simulated.
- Dynamic mesh motion is managed, as required for moving geometries.
- Coupling of structural mechanics (FSI) with thermal systems is provided.

Chapter 5: NUMERICAL SIMULATION OF ACOUSTIC WAVE GENERATION IN A COMPRESSIBLE FLUID USING ANSYS FLUNET.

ANSYS Fluent is an important solution for numerical computation of complex processes in mechanical engineering and applied acoustics due to the fact that it possesses a broad spectrum of physical models and high numerical precision.

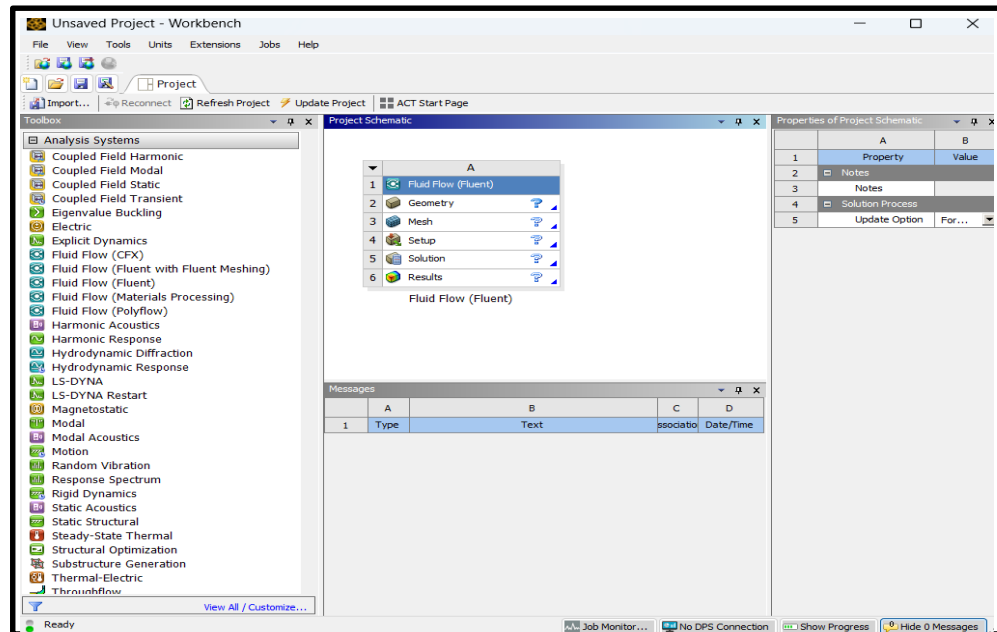


Figure 5. 1: Logiciel ANSYS-FLUENT

5.3. Presentation of the Problem

In the context of compressible fluid dynamics, the interaction between a stationary solid body and a moving flow field can lead to the generation and reflection of acoustic waves. Unlike classical setups where the body itself is in motion, in this study the solid geometry remains fixed within the domain, while the fluid motion is induced from the inlet boundary.

The imposed inlet velocity initiates wave propagation within the compressible medium, and the presence of the solid body—strategically placed at the center of the domain—creates complex patterns of wave interaction, including refraction, reflection, and localized pressure variation.

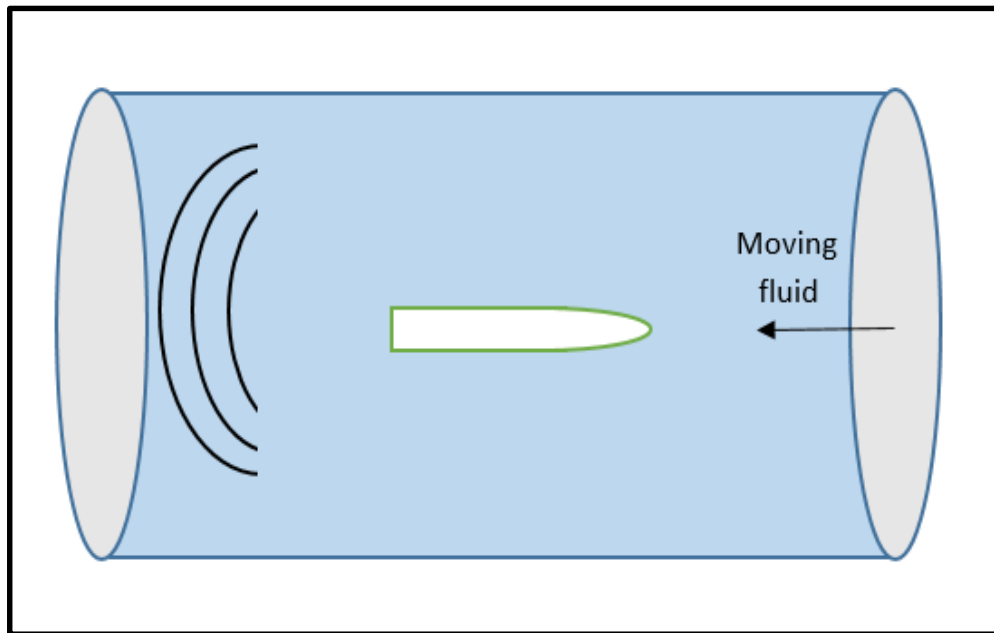


Figure 5. 2: Geometry of the problem

Such a setup is relevant to various engineering contexts, including ultrasound propagation, aeroacoustic analysis of ducts, and non-invasive pressure detection in biomedical systems. The study relies on ANSYS Fluent to numerically resolve the compressible Navier–Stokes equations and to visualize the resulting acoustic field.

5.4. Steps of a CFD simulation using fluent

5.4.1. Drawing geometry on ANSYS WORKBENCH

The computational domain for this investigation is a two-dimensional rectangular channel modeling a compressible fluid medium. Within the domain, there is a solid body at rest with an elliptical shape located in the center as an obstacle and interaction surface for the acoustic waves.

Chapter 5: NUMERICAL SIMULATION OF ACOUSTIC WAVE GENERATION IN A COMPRESSIBLE FLUID USING ANSYS FLUNET.

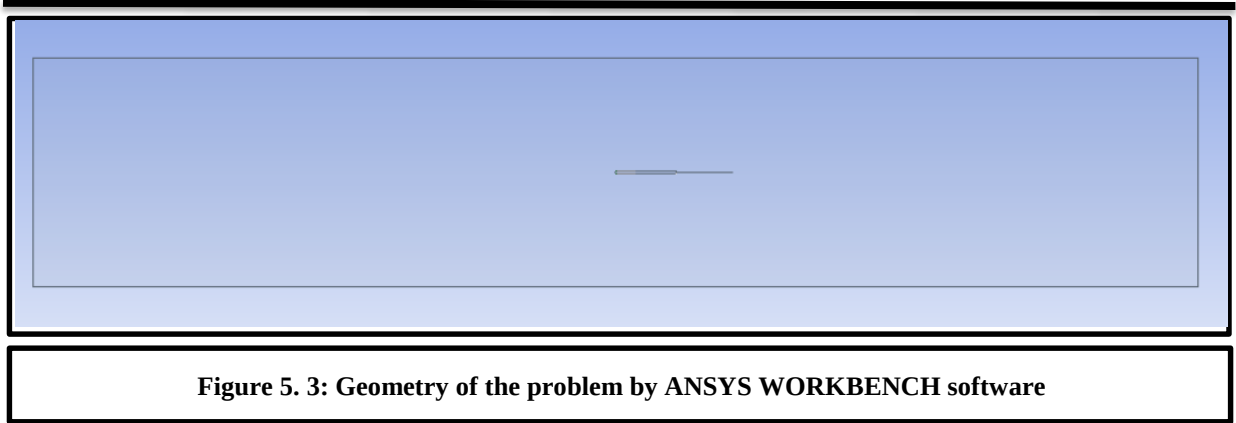


Figure 5. 3: Geometry of the problem by ANSYS WORKBENCH software

5.4.2. Mesh Generation

To be able to solve the governing equations of compressible fluid flow with adequate accuracy, the computational domain was discretized by a structured 2D mesh. Meshing was carried out with ANSYS Meshing, taking special care to have the mesh resolution high enough close to the solid body, where high pressure gradients and wave interaction were expected.

Mesh Characteristics:

- Mesh type is structured quadrilateral.
- In our aeroacoustic simulation, the choice of mesh size was guided by the requirement to adequately resolve acoustic wave propagation throughout the domain. It is well-established that resolving acoustic waves typically requires between 6 to 8 elements per wavelength for accurate representation of both amplitude and phase. However, considering the computational cost and the size of our domain, we adopted a compromise by ensuring a minimum of 4 elements per wavelength. This choice strikes a balance between numerical accuracy and computational efficiency, while still maintaining sufficient resolution to capture the essential characteristics of the acoustic field.

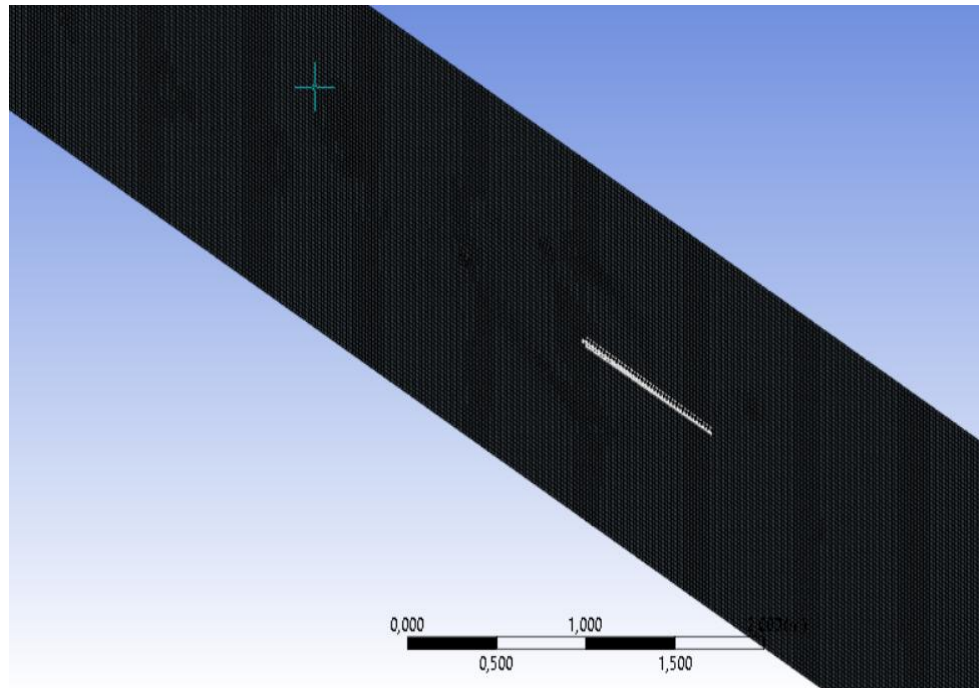


Figure 5. 4: Meshing the geometry of the problem

This well-tuned mesh ensures accurate resolution of acoustic wave propagation phenomena while minimizing numerical dispersion errors, which is especially important for modeling pressure oscillations and wave reflections in compressible media.

5.4.3. Naming of surfaces

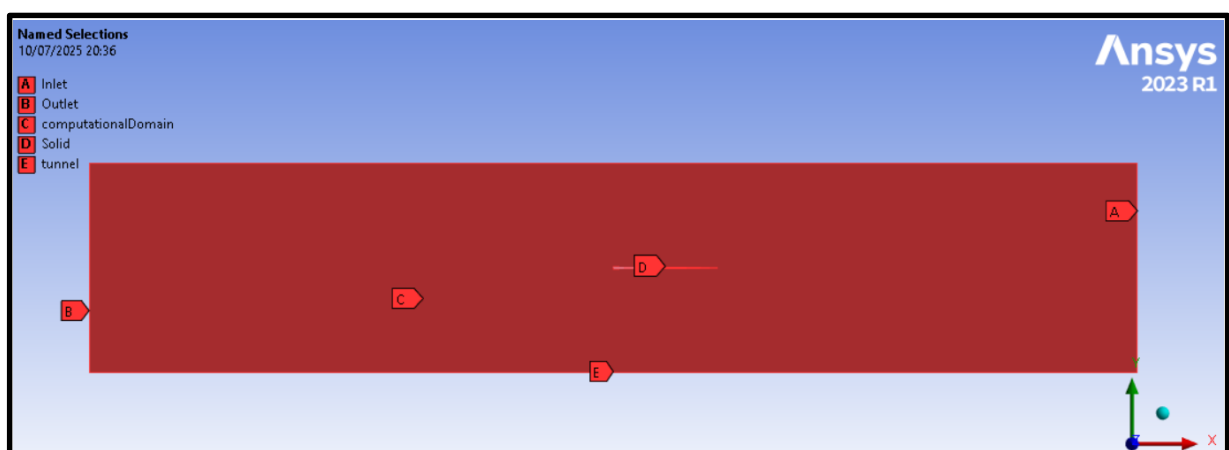


Figure 5. 5: Surface Naming

Chapter 5: NUMERICAL SIMULATION OF ACOUSTIC WAVE GENERATION IN A COMPRESSIBLE FLUID USING ANSYS FLUNET.

Tableau 1. 1: Surface Naming

Numbering	Nomenclature	Description	Boundary condition type
A	Inlet	Left boundary of the domain where flow is introduced	Velocity Inlet
B	Outlet	Right boundary where waves exit the domain	Pressure Outlet
C	ComputationalDomain	The internal fluid domain where the governing equations are solved	interior
D	Solid	Surface of the fixed obstacle located in the center of domain	Wall
E	Tunnel	Bottom and Top boundary of the duct/channel	Wall

5.4.4. Simulation steps

5.4.4.1 General settings

- The transient choice was selected to depict the time-dependent behavior of acoustic wave motion, which changes over time.

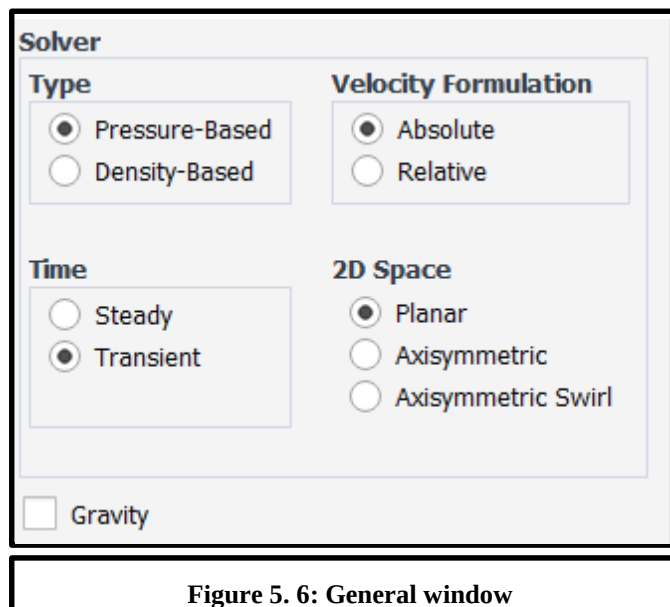


Figure 5. 6: General window

5.4.4.2 Models

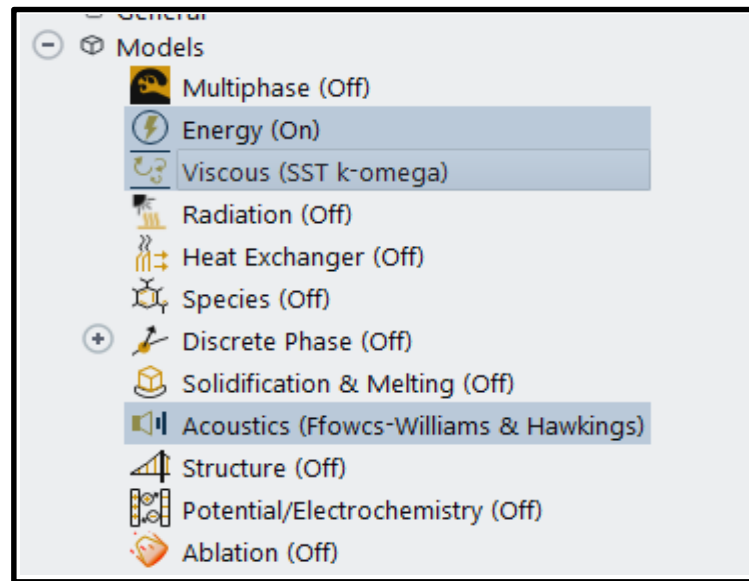


Figure 5. 7: Models window

- The energy equation can now account for thermal effects and pressure-temperature coupling in compressible flow. In acoustic problems, pressure-density-temperature interaction has a significant influence on wave behavior.
- The SST k-omega turbulence model was chosen to represent the turbulence effects in the vicinity of the solid body and within the flow field. This model is appropriate for compressible flows with high velocity gradients and gives excellent predictions of boundary layer behavior and wave interaction. and is excellent for acoustic wave propagation around a fixed obstacle simulation.
- The Fowcs Williams and Hawkings (FW-H) acoustic model was enabled to model far-field sound radiation. The solid body was defined as the acoustic source surface. The "Export acoustic source data in ASD format" and "Compute acoustic signals simultaneously" options were selected. Acoustic pressure signals were captured with 16 receiver locations strategically positioned in the surrounding area of the solid body.

Chapter 5: NUMERICAL SIMULATION OF ACOUSTIC WAVE GENERATION IN A COMPRESSIBLE FLUID USING ANSYS FLUNET.

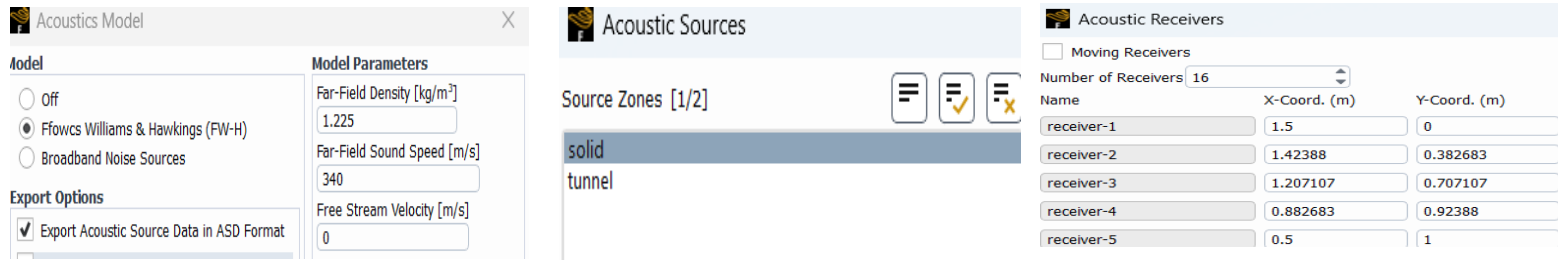


Figure 5. 8: Activation of the acoustic (FW-H) model

5.4.4.3 Materials

- The fluid was characterized as air, using the ideal gas law to represent density. This is a common assumption in compressible acoustics, where air would be treated as an ideal gas under normal conditions. Constant specific heat (C_p) and viscosity were specified using standard air values at ambient temperature (about 300 K).

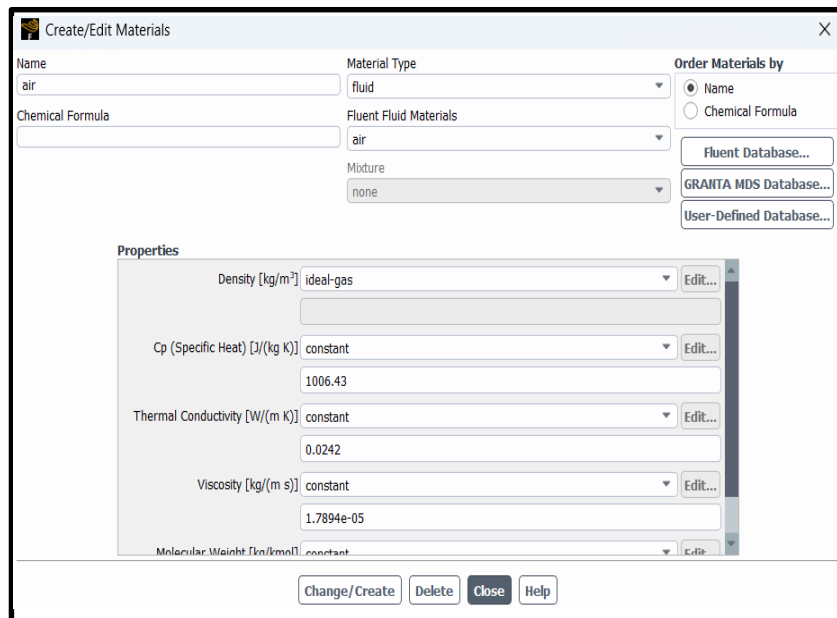


Figure 5. 9: Definition of the physical characteristics of fluids (air).

5.4.4.4 Boundary Conditions

- Inlet (velocity-inlet): This equation $v(t) = v_0 \sin(\omega t + \varphi)$ used a time-varying sinusoidal velocity to imitate an oscillating acoustic source. This enables the creation of pressure waves that travel across the domain.

Tell que:

- velocity amplitude: $v_0 = 4.8 \times 10^{-5} \frac{m}{s}$.
- $\omega = kc_0$ and $k = \frac{2\pi}{\lambda}$; $c_0 = 340.3 \frac{m}{s}$.

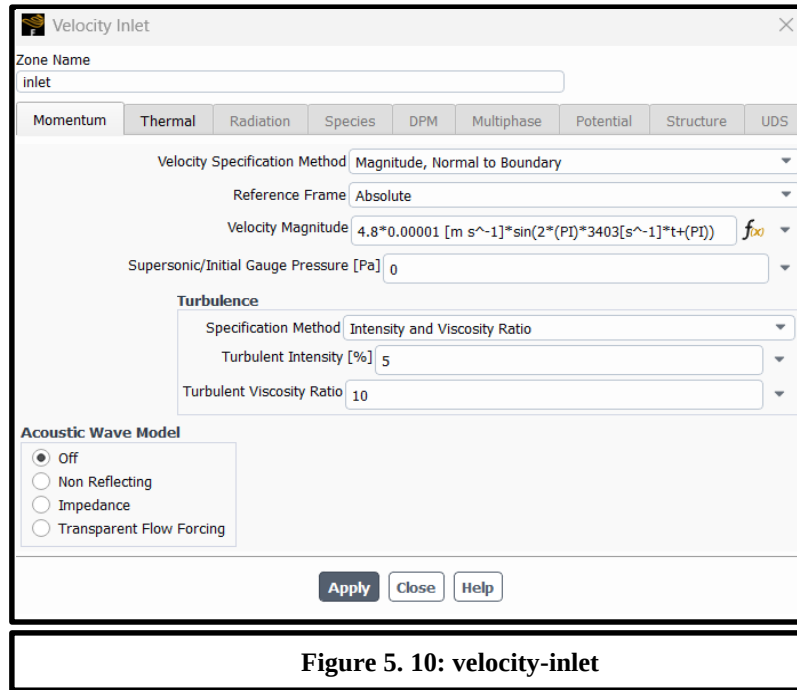


Figure 5. 10: velocity-inlet

5.4.4.5 Solution Method:

PISO (Pressure-Implicit with Splitting of Operators) algorithm was used within the pressure-velocity coupling approach. PISO is very useful in transient, compressible flow computations. This approach allows several steps of pressure correction within each time step, improving the velocity-pressure coupling accuracy, particularly for high-speed or unstable flows.

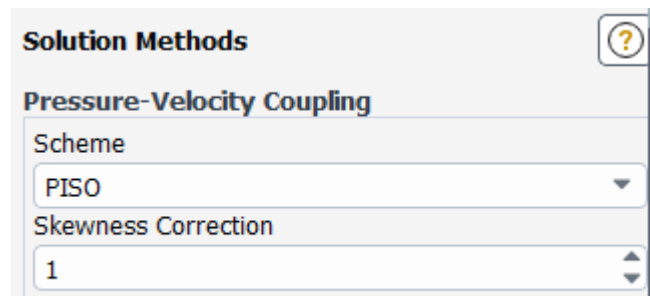


Figure 5. 11: Solution Method

5.4.4.6 Solution Initialization :

Simulation was initiated using the Hybrid Initialization procedure. It gives a good approximation of flow variables everywhere in the domain and increases stability at the start of transient, compressible flow calculations.

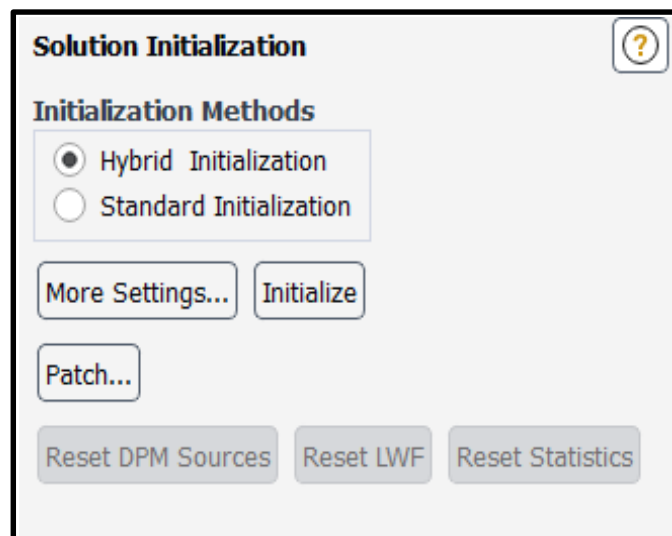


Figure 5. 12: Initialization Methods

5.4.4.7 Run calculation:

To capture the rapid fluctuations of acoustic waves with high accuracy, the time step was calculated using the relation:

$$\Delta t = \frac{2\pi}{\omega};$$

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This ensures that each oscillation cycle is well-resolved in time.

5.4.4.8 Post-Processing:

- SPL (Sound Pressure Level) spectrum collected from fixed probe locations.

To generate the SPL (Sound Pressure Level) spectrum from the simulation results, the following procedure is applied:

- Go to the “Plot” menu.
- Choose the “FFT” (Fast Fourier Transform) option.
- Select the desired receiver (probe) location from the available monitoring points where acoustic data has been recorded.
- Specify the signal (e.g., pressure) corresponding to the selected receiver.
- Execute the FFT to convert the time-domain pressure data into its frequency-domain representation.

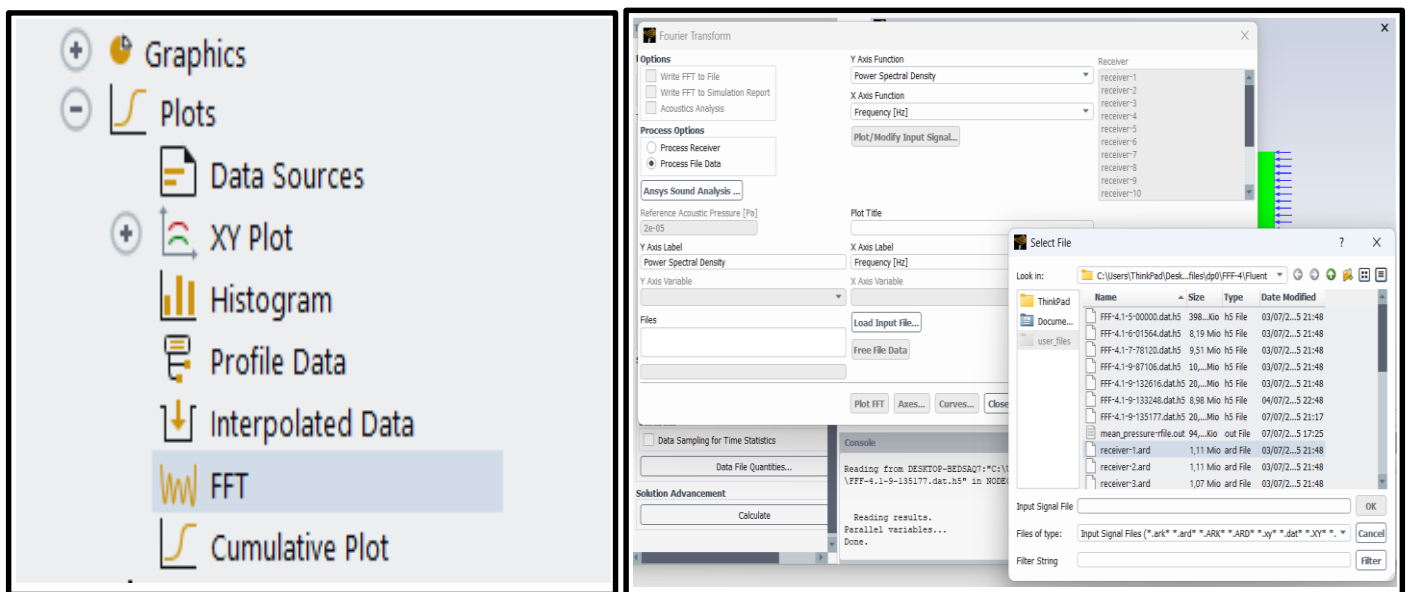


Figure 5. 13:- How to draw a chart SPL (Sound Pressure Level)

- Mean pressure calculated on the obstacle surface.

To calculate and plot the mean pressure on the surface of the solid obstacle, the following steps are performed:

1. Navigate to the "Report Definitions" panel.
2. Click on "New", then choose "Surface Report".

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3. Select "Area-Weighted Average" as the report type. This ensures that the pressure is averaged over the surface area, giving a physically meaningful value.
4. From the list of surfaces, select the solid obstacle (or the specific wall/solid zone of interest).
5. Confirm and name the report definition accordingly.
6. The defined report can now be plotted over time or exported for further analysis.

This approach provides the area-weighted mean pressure acting on the surface, which is important for evaluating the net acoustic loading and for analyzing wave-body interactions

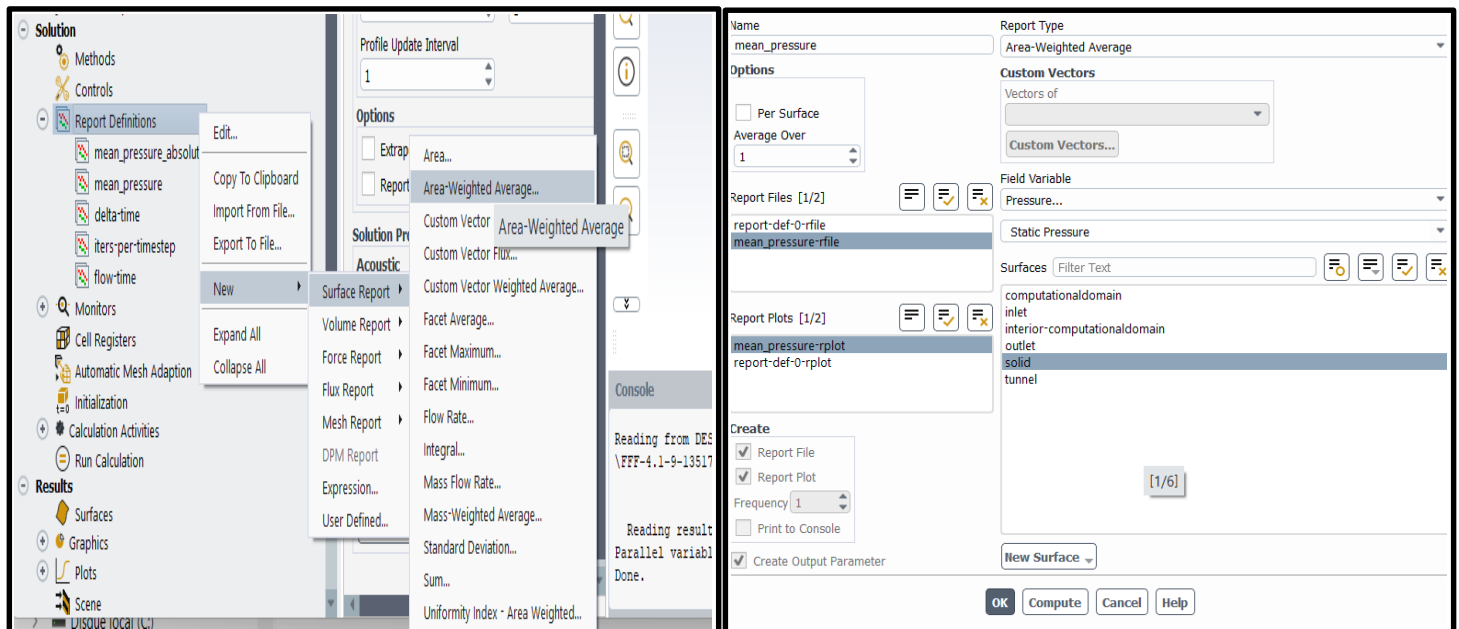


Figure 5. 14: How to draw a chart mean pressure

Chapter 6: RESULTS AND DISCUSSIONS.

6.**6.1. Introduction to results**

This chapter shows and discusses the numerical result of a series of CFD simulations performed using ANSYS Fluent.

The simulations were intended to study the generation and propagation of acoustic waves caused by the impingement of a compressible flow onto a stationary solid object inserted in a duct.

The study is mostly interested in examining the acoustic pressure distribution under different physical conditions, with three important parameters:

- As a basis for understanding how the radius of an obstacle affects wave intensity and reflection, use the rigid body's radius.
- The wavelength (λ) of the imposed inlet wave under consideration of its effect on the wave propagation and space behavior of the acoustic field;
- The phase shift (φ) of the inlet velocity waveform, in order to assess the effect of timing on wave-body interactions.

Results for each case are given in the following sections, with physical interpretations provided by the pressure fields, waveforms, and acoustic trends present. Comparing examples allows us to determine dominant effects and acoustic behavior.

6.2. Part -1-: Effect of wavelength

Two simulations were run with varying λ values to investigate the influence of wavelength (λ) on acoustic behavior.

Table 6. 1: Wavelength–Frequency–Time Step Relationship in Acoustic Simulation

$\lambda(m)$	$\omega(\frac{rad}{s})$	$\Delta t(s)$
1	$2\pi \times 340.3$	5.6×10^{-4}
0.1	$2\pi \times 3403$	5.6×10^{-5}

In both cases, the same field and rigid body geometry were employed, but the velocity equation and time step were changed to achieve the required wavelength.

6.2.1. Results:**6.2.1.1. SPL Spectrum – Comparison:**

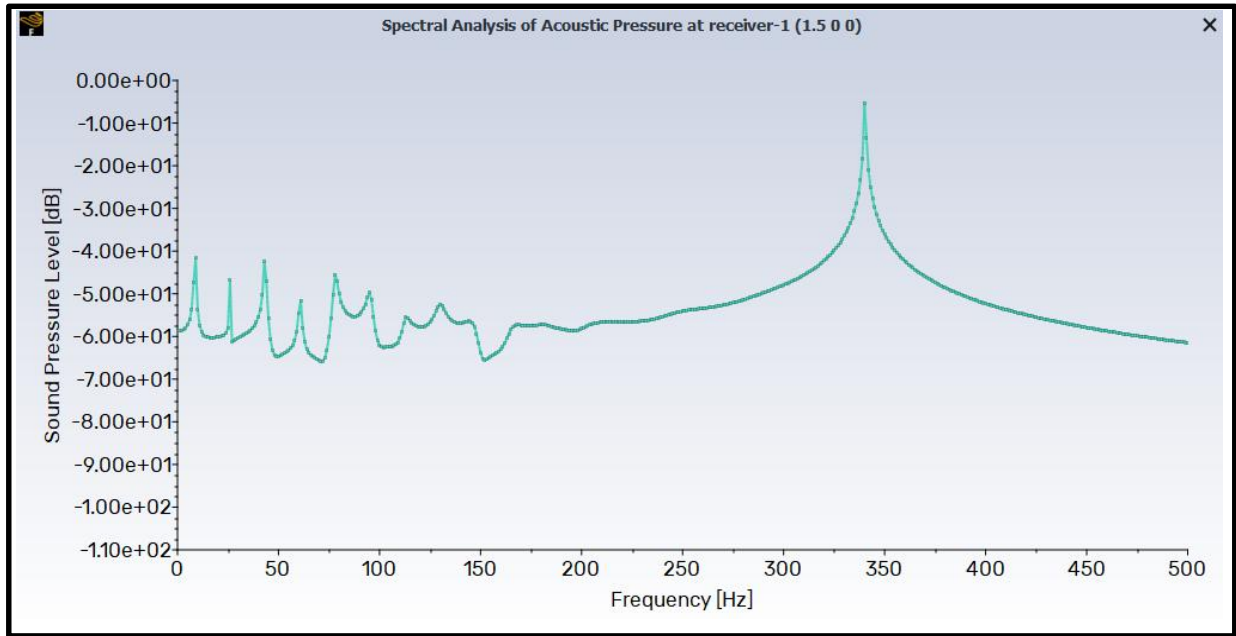


Figure 6. 1: Chart of spectral analysis of acoustic pressure for $\lambda(m)=1$

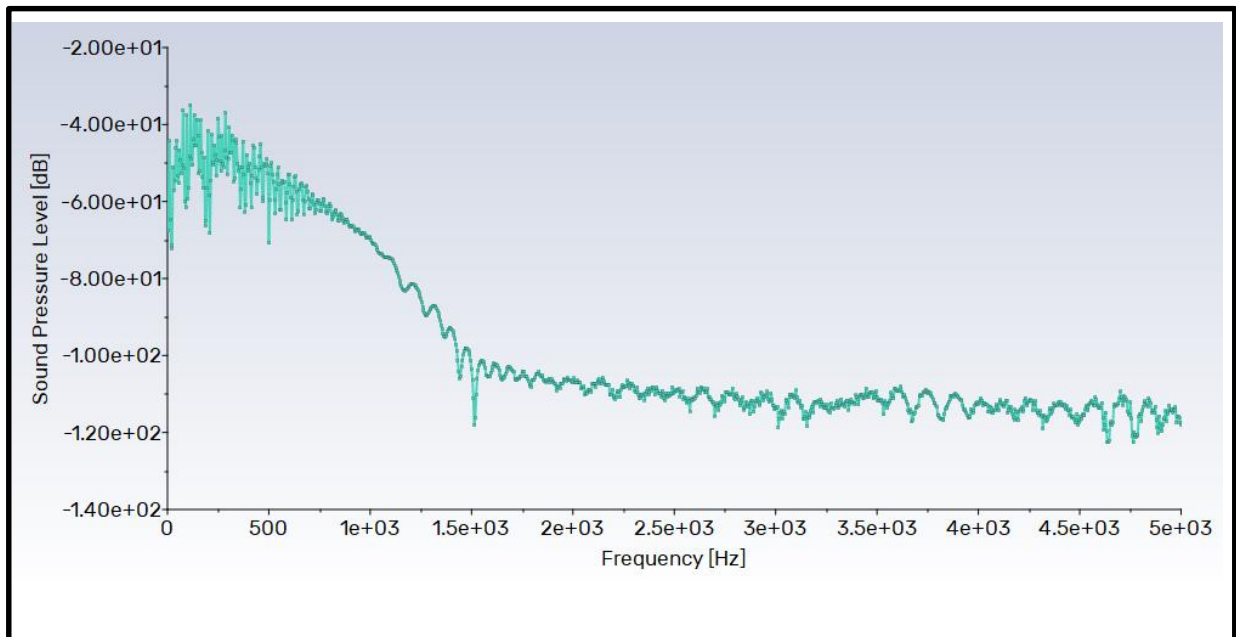


Figure 6. 2: Chart of spectral analysis of acoustic pressure for $\lambda(m)=0.1$

- Notes and comments:
 - The SPL at a stationary receiver point was plotted versus time in both test cases ($\lambda = 1\text{ m}$ and $\lambda = 0.1\text{ m}$). The SPL spectrum clearly has a peak at approximately 300 Hz in the case $\lambda = 1\text{ m}$, the same as that of the applied sinusoidal input velocity. The signal is stable after the initial transient stage and is of decent amplitude. This implies a

smooth and continuous wave propagation with little high-frequency content and reflection or interference near the body.

- The greater frequency range and higher SPL peak value of the SPL spectrum when $\lambda = 0.1$ m indicate a higher degree of acoustic interactions, likely due to:
 - Short wavelengths generate more wave-body interaction.
 - Increased reflection and constructive interference between incident and reflected waves.
- As a result, the pressure fluctuations observed near the body become increasingly stronger and stronger, and the system may be getting close to resonance conditions at some frequencies.
- Interpretation:
 - With decreasing wavelength (increasing frequency), the acoustic field becomes more intense and spatially inhomogeneous.
 - The solid body begins to behave as an even better scatterer, increasing local pressure peaks.
 - They agree with acoustic theory that states reducing wavelength increases resolution and sensitivity to geometry.

6.2.1.2. Time-Domain Acoustic Pressure Signal:

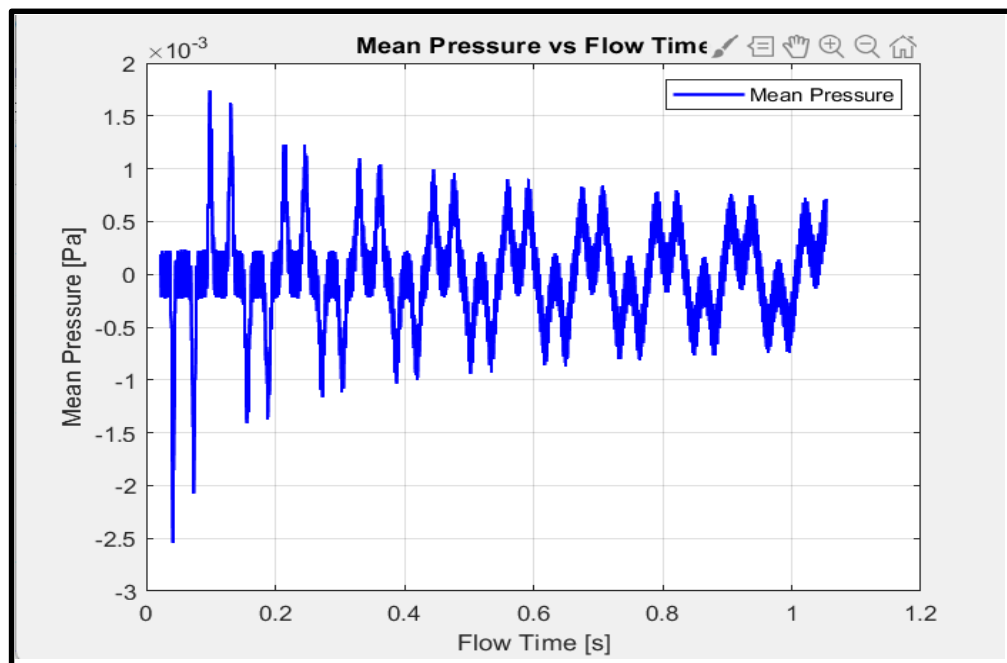


Figure 6. 3: Chart of mean pressure vs flow-time for $\lambda = 1$ m

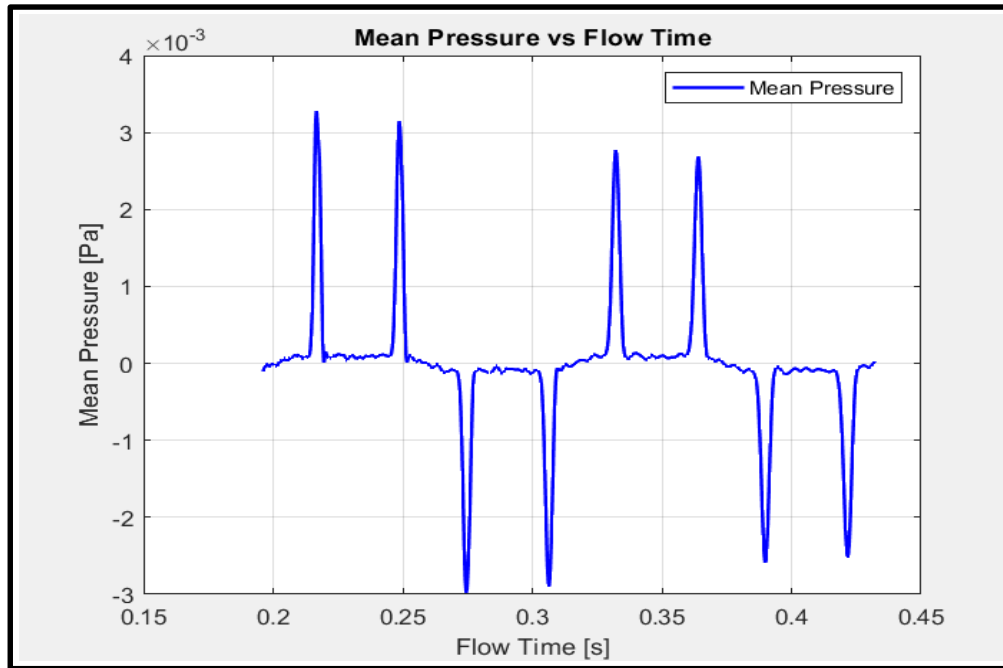


Figure 6. 4: Chart of mean pressure vs flow-time for $\lambda = 0.1$ m

- Notes and comments:
 - When $\lambda = 1$ m the pressure signal starts off as a random transient pattern and, as it settles, gradually becomes a smooth, quasi-periodic waveform. This is characteristic of the wave settling into a regime of steady oscillation from an initial transient period. The waveform amplitude is very small, as it corresponds to the moderate SPL of the frequency-domain plot. The system appears to be operating well, with little distortion and reflections.
 - The pressure signal in case $\lambda = 0.1$ m exhibits more intense oscillations and greater changes in amplitude. Although periodicity is evident, the waveform is more energetic and shows signs of nonlinear characteristics such as sharper peaks and more frequent oscillations. This supports the role of short wavelengths in contributing to greater acoustic interactions and perhaps exciting higher-order modes in the duct.
- Interpretation:
 - Decreased λ yields more dynamic and interactive wave behavior, which increases localized pressure fluctuations.
 - As λ decreases, the effect of the body on the wave becomes stronger.

6.3. Part –2-: Effect of Cylinder Radius (R):

In this series of simulations, the influence of cylinder radius (R) on acoustic wave behavior was assessed with all other parameters maintained constant. We took $\lambda = 0.1$ m We aimed to see how sound pressure levels, wave scattering, and acoustic field distribution were affected with the increase in the size of the obstacle.

Table 6. 2: Radius Variations

$R(m)$
1
2
5

6.3.1. Results:

6.3.1.1. SPL Spectrum – Comparison:

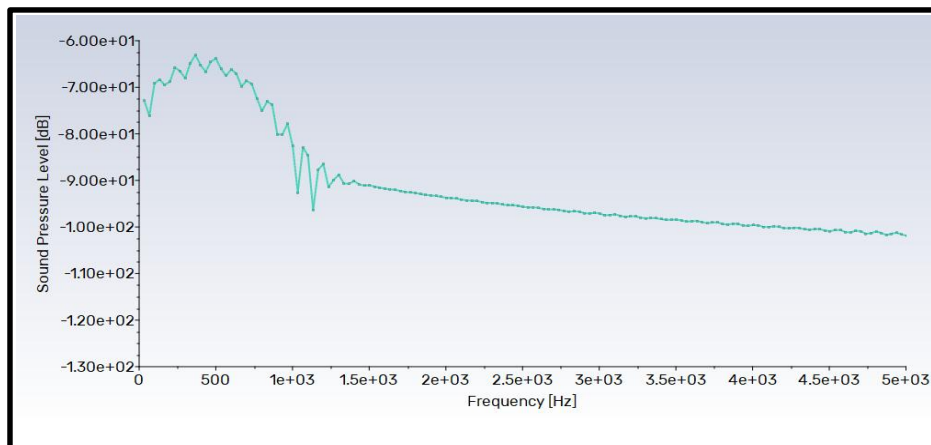


Figure 6. 5: Chart of spectral analysis of acoustic pressure for $R=1$

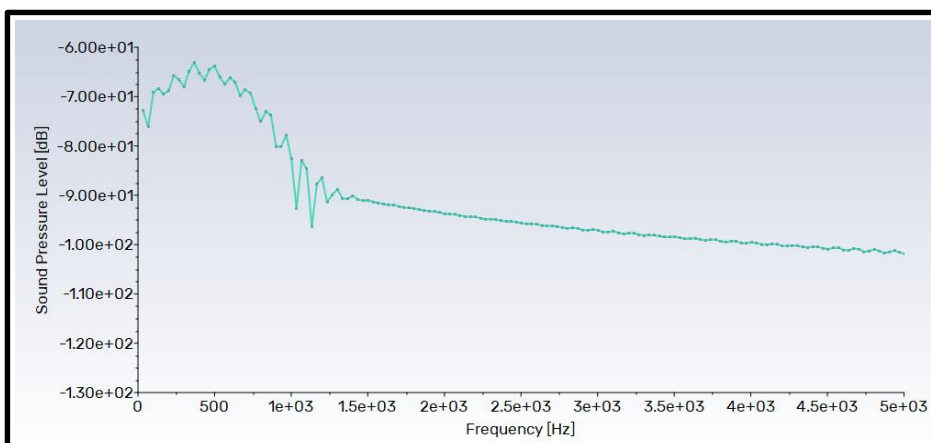


Figure 6. 6: Chart of spectral analysis of acoustic pressure for $R =2$

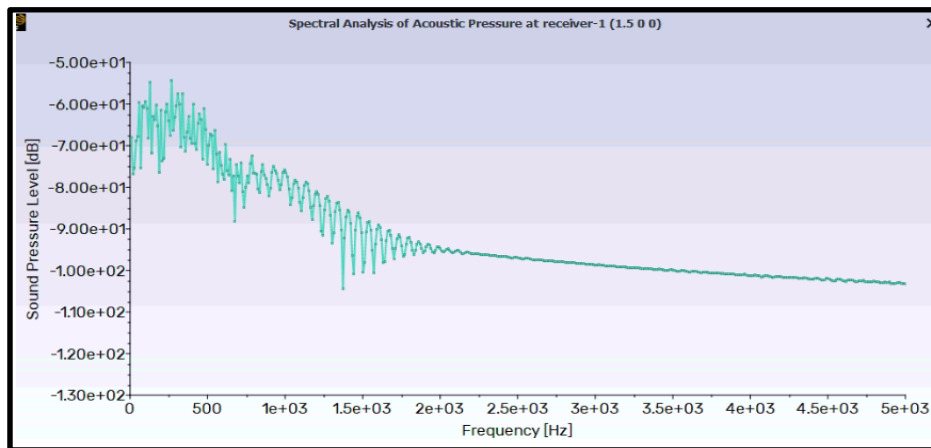


Figure 6. 7: Chart of spectral analysis of acoustic pressure for R=5

- Notes and comments:
 - R = 1: The SPL spectrum clearly reveals the frequency with the highest dominance as the inlet wave. The amplitude is moderate, showing low blockage of the wave and fairly smooth transmission.
 - R = 2: As the radius is increased, the SPL peak becomes stronger. This demonstrates a greater wave-body surface interaction, producing higher reflection and localized pressure enhancement.
 - R = 5: An increased radius provides a larger frequency range and higher pressure levels. With the additional surface area available to interact with the wavefront, the solid body now functions as an important acoustic scatterer, resulting in multifaceted patterns of the waves and possibly the creation of secondary harmonics.
- Interpretation:
 - Small cylinders allow more wave energy through unobstructed.
 - Large cylinders reflect the most wave energy, altering the field and boosting SPL around the body.
 - As R grows, the influence of the body changes from passive to dictating acoustic control.

6.3.1.2. Time-Domain Acoustic Pressure Signal:

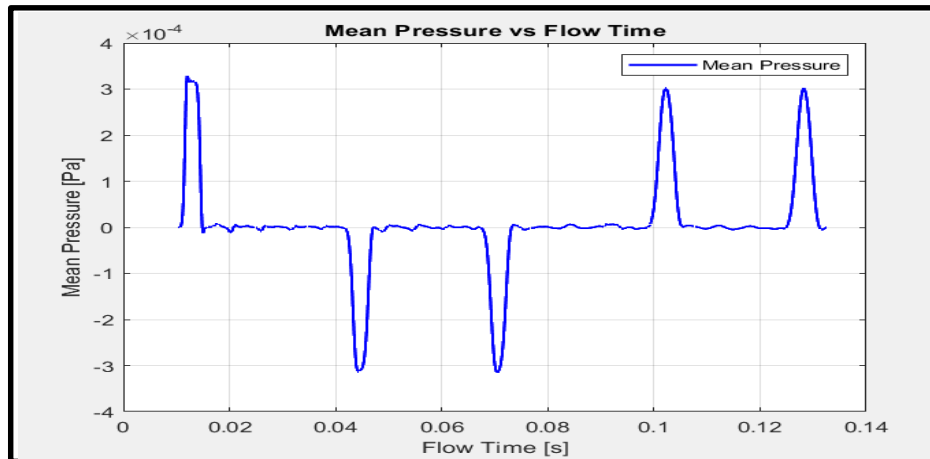


Figure 6. 8: Chart of mean pressure vs flow-time for R=1

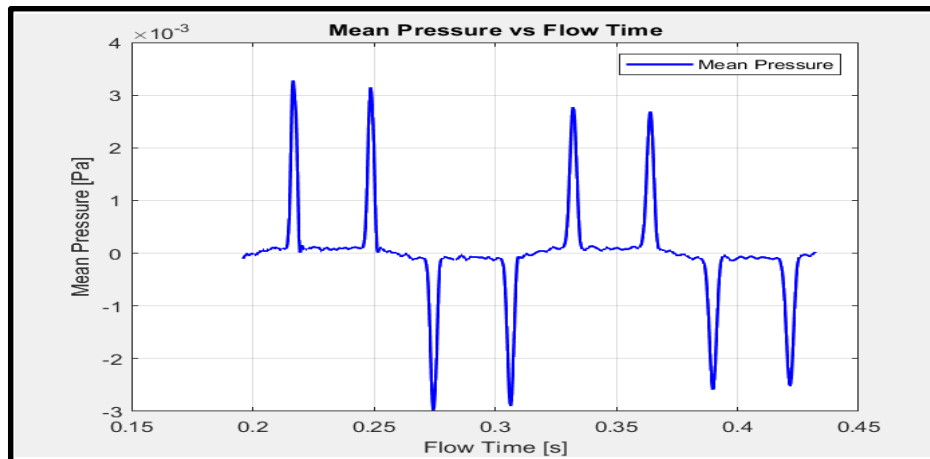


Figure 6. 9: Chart of mean pressure vs flow-time for R=2

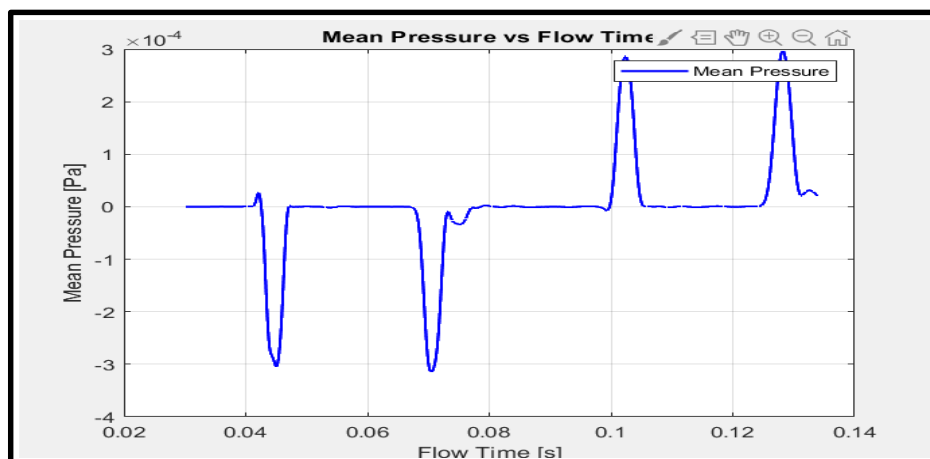


Figure 6. 10: Chart of mean pressure vs flow-time for R=5

- Notes and comments:
 - $R = 1$ m: The pressure signal is a uniform, low-amplitude waveform, that is, the propagating acoustic wave is not greatly perturbed. The body is very tiny so that most of the wave can travel through with very little reflection. The signal damps rapidly and is periodic.
 - $R = 2$ m: When the cylinder radius is increased, the waveform has larger amplitude oscillations with clearer peaks. This shows that the wavefront and larger body surface are reflecting and interacting more strongly. The signal is constant, but fluctuates more around the mean value.
 - $R = 5$ m: The pressure signal is more dynamic, with steeper peaks and less repetitive oscillations. The body is now a significant acoustic barrier, producing intense wave reflections and probable interference effects. The waveform takes longer to stabilize and the pattern is more dynamic.
- Interpretation:
 - A growth in the radius R leads to a stronger interaction of the wave with the body.
 - This provokes greater amplitudes of the acoustic pressure, more gradual stabilization, and more complex pressure signals.
 - The experiments reveal that larger obstacles reflect not only larger amounts of wave energy, but also modify the temporal structure of the pressure field around them.

6.4. Part –3-: Effect of Phase (φ)

This set of simulations examines the effect of the phase angle (φ) of the inlet velocity waveform on acoustic wave generation and propagation. All parameters other than wavelength, geometry, domain, amplitude were kept constant and varied only the phase offset in the sinusoidal function.

Table 6. 3: Phases Variations

φ	$v(t)$
0	$v(t) = 4.8 \times 10^{-5} \times \sin(2\pi \times 3403t)$
$\frac{\pi}{2}$	$v(t) = 4.8 \times 10^{-5} \times \sin(2\pi \times 3403t + \frac{\pi}{2})$
π	$v(t) = 4.8 \times 10^{-5} \times \sin(2\pi \times 3403t + \pi)$

6.4.1. Results:

6.4.1.1. SPL Spectrum – Comparison:

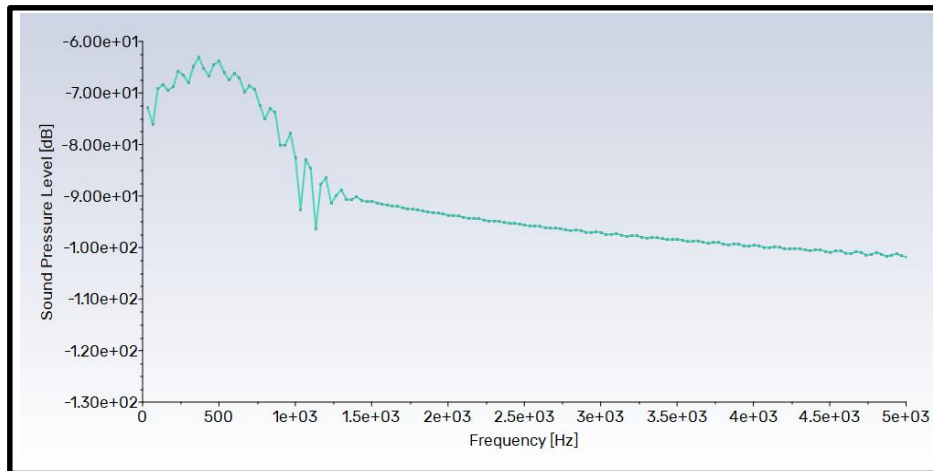


Figure 6. 11: Chart of spectral analysis of acoustic pressure for $\phi = 0$

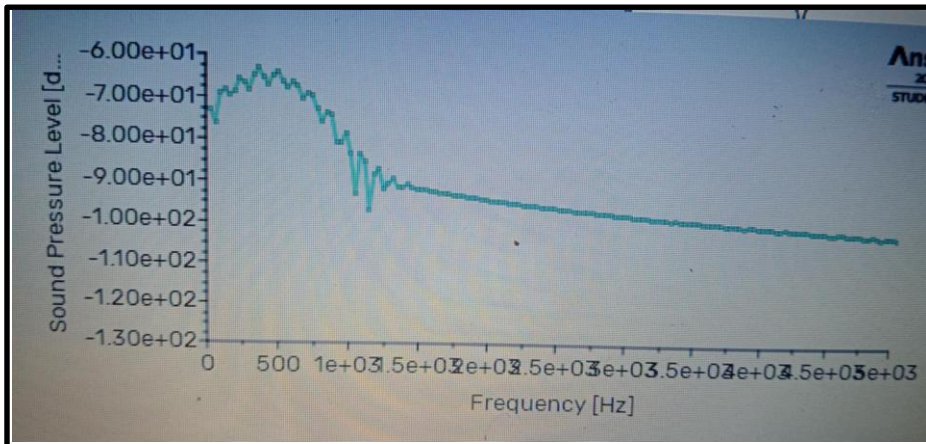


Figure 6. 12: : Chart of spectral analysis of acoustic pressure for $\phi = \pi/2$

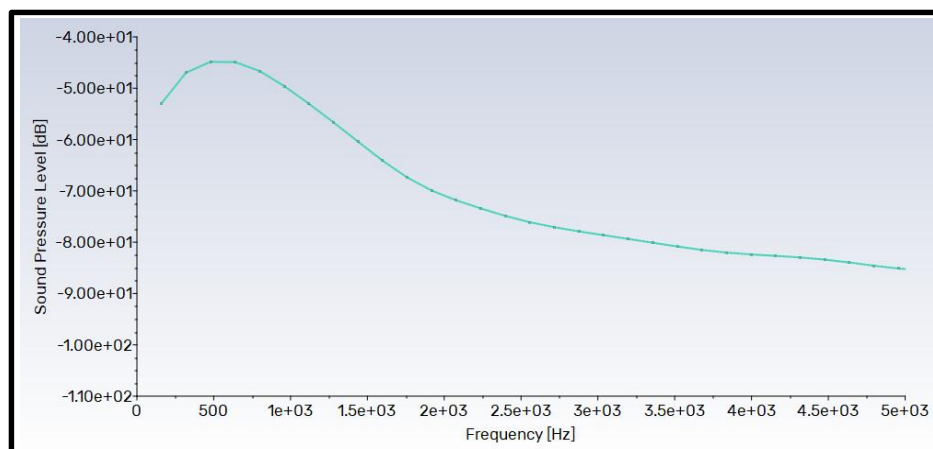


Figure 6. 13: Chart of spectral analysis of acoustic pressure for $\phi = \pi$

- Notes and comments:
 - For $\varphi = 0$. The SPL spectrum has an evident and sharp peak near the dominant frequency. The signal is stable and the waveform appears clean, i.e., there is a good synchronization of the pressure oscillation with the simulation domain.
 - At $\varphi = \pi/2$, the SPL as well as time signal has a slight shift in their waveform. The amplitude is as in the $\phi = 0$ case, but the wave settles after a little more time and secondary peaks are more prominent, possibly due to incomplete destructive interference at the beginning.
 - $\varphi = \pi$: The waveform begins in the opposite phase as $\phi = 0$, and the SPL spectrum exhibits tiny changes in secondary frequencies. While the dominant frequency remains constant, the signal may exhibit phase-shifted reflections, which could change local pressure distribution around the solid.
- Interpretation:
 - Changing the phase will change the initial state of the wave, but not its frequency content.
 - The first interaction between the fixed structure and the wave, though, is phase-dependent, particularly in short simulations.
 - In the long run, all cases become the same acoustically, but differences may still be noted in early reflections, wave buildup, and pressure stability.

6.4.1.2. Time-Domain Acoustic Pressure Signal:

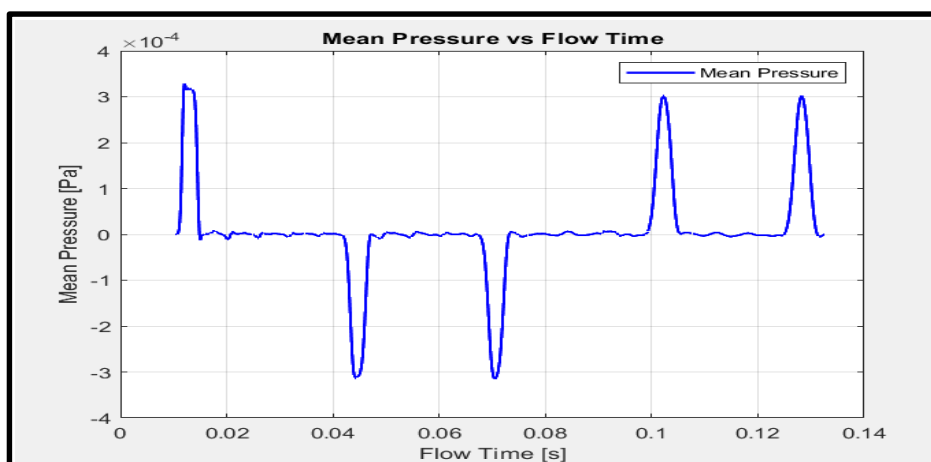


Figure 6. 14: Chart of mean pressure vs flow-time for $\varphi = 0$

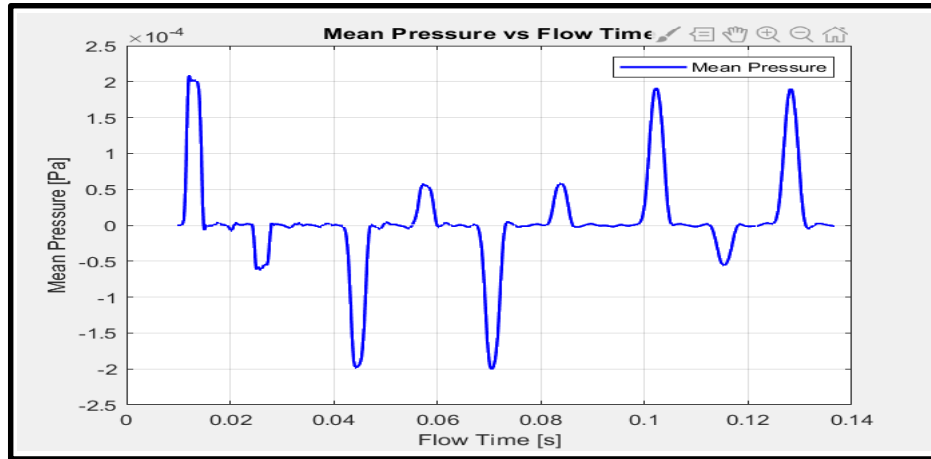


Figure 6.15: Chart of mean pressure vs flow-time for $\phi = \pi/2$.

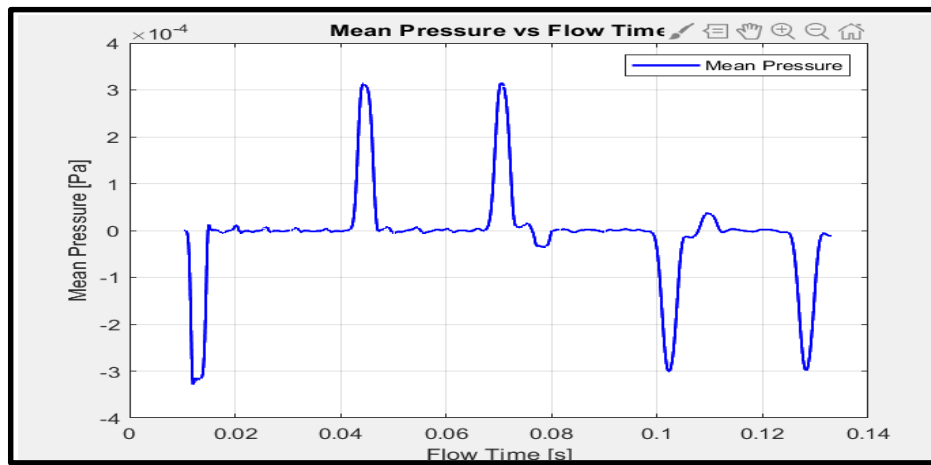


Figure 6.16: Chart of mean pressure vs flow-time for $\phi = \pi$

- Notes and comments:
 - $\phi = 0$: The pressure signal starts smoothly and immediately stabilize into a consistent, periodic waveform. This indicates that the production of the wave is in good sync with the body and the domain and results in stable interactions and consistent pressure levels.
 - $\phi = \pi/2$: The waveform is advanced to grow due to a quarter-period phase shift. The initial signal settles later and has additional oscillations in the transition, probably due to partial destructive interference in the early time steps. The waveform acquires a periodic shape soon thereafter.
 - $\phi = \pi$: This is the most severe phase inversion. The pressure waveform starts with a negative sign with respect to $\phi = 0$, and with reversed initial behavior. Global periodicity is not destroyed, but the initial contact with the solid is out of phase and would influence early reflection or resonance characteristics.

- Interpretation:
 - All three examples eventually settle into periodic waveforms.
 - Phase has its major influence on the transient phase of wave generation.
 - The selection of phase can influence early-time acoustic responses, which is significant in applications where start-up or synchronization of waves is depended on.

GENERAL CONCLUSION

GENERAL CONCLUSION

In the present thesis, we have examined the generation and propagation of acoustic waves as a result of the motion of a rigid body inside a compressible fluid. The problem was performed under three different acoustic configurations each with a unique set of inlet wave characteristics. The simulations confirmed that the obstacle radius, imposed wavelength, and inlet velocity phase shift all had a dominant influence on the spatial pattern and magnitude of the acoustic field. Amongst the three configurations, the small wavelength case ($\lambda = 0.1m$), non-zero phase shift ($\varphi = \frac{\pi}{2}$ ou $\frac{3\pi}{2}$), or small obstacle radius ($R = 2m$) created the most intense sound effects. This configuration offered:

More intense reflected waves

- Increased mean pressure on the obstacle surface.
- A more intense and focused SPL spectrum.

Hence, it can be said that the incorporation of a small wavelength along with a suitable phase shift and a small obstacle radius increases wave-body interaction to maximize acoustic wave production within the given simulated environment.

This result emphasizes the necessity of wave parameter optimization and also provides a solid foundation for possible future experimental verification and use in applications such as aeroacoustics, ultrasonic imaging, and noise control.

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