# Modeling the Impedance of Sound Waves Passing through a Roughness Pipe using COMSOL Multiphysics

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*Abstract:* - This work examines, both theoretically and statistically, the acoustic impedance behavior of sound waves traveling through cylindrical pipes having smooth or rough interior surfaces. The study's main goal is to ascertain how pipe design, frequency, and medium characteristics affect impedance and to examine these effects using simulation in the COMSOL Multiphysics framework. The classical wave equation was used to discuss the propagation of acoustic waves, and the ideas of input impedance and characteristic impedance were developed. Specifically, when the wavelength was large in relation to the pipe diameter, the model was simplified using the plane wave approximation. In the simulations, a 4 m long, 2.5 cm diameter closed-end pipe was used to study the propagation of sound waves at a frequency of 171.5 Hz. The findings unequivocally show how standing waves form and how pressure is distributed inside the pipe. Impedance achieves its greatest values at locations where particle velocity approaches zero, according to an analysis of the impedance distribution. Energy losses were found to be minimal in pipes with smooth surfaces; nevertheless, impedance is impacted by increased viscous and thermal losses as roughness increases. For the modeling and experimental investigations of in-pipe acoustic systems, this work offers a solid theoretical and numerical basis.

*Key-Words:* - Sound Waves, Classical Wave Equation, Sound Pressure, Roughness Pipe, Mathematical Modeling, Impedance, COMSOL Multiphysics.

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## 1 Introduction

An acoustic wave is a mechanical wave caused by the vibration of particles in a medium around their equilibrium positions. The particles oscillating in an acoustic wave do not undergo a net translational motion. Particles in the medium create a mechanical wave that propagates by transferring energy through gaseous, liquid, and solid media. Acoustic waves are longitudinal waves, meaning that the compression of particles creates high pressure and their rarefaction creates low pressure [1]. Through this back-and-forth vibration, sound energy propagates, and sound waves cause the eardrum and inner ear structures to vibrate, making phenomena such as hearing possible. This also forms the basis of how a microphone works. The speed of sound varies depending on the temperature and density of the medium [2].

The motion of acoustic waves is described by the classical wave equation. This equation is a second-order partial differential equation in which the sound pressure $p(\mathrm{x},\mathrm{t})$ or the particle velocity $v(\mathrm{x},\mathrm{t})$ is a function [3], [4].

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0 \qquad (1)$$

Here, p represents the sound pressure, and c represents the speed of sound in the medium.

In the field of acoustics, the concept of impedance is used in two different contexts: specific (characteristic) acoustic impedance and input impedance [5]. Characteristic impedance is used for a plane wave propagating without reflection.

The resistance of a medium exhibit to the propagation of sound waves is defined as the specific acoustic impedance and is expressed as the

ratio of acoustic pressure to particle velocity at a given point, as follows [6].

$$Z_0 = \frac{p}{v} \quad (2)$$

Here, $p$ represents the acoustic pressure (Pa), and $v$ represents the particle velocity (m/s).

For plane waves propagating in a homogeneous and lossless medium, the specific acoustic impedance is generally expressed in terms of the medium's properties and is assumed to be frequency independent.

$$Z_0 = \rho . c \quad (3)$$

Here, ρ is the density of the medium and c is the speed of sound (m/s).

According to these expressions, the parameters affecting the specific acoustic impedance are the speed of sound, the velocity of the vibrating particles in the medium, and the density of the medium.

The input impedance, on the other hand, is the acoustic impedance measured at the inlet cross-section of an acoustic system (such as a pipe) and is expressed in a similar manner [7].

$$Z_{in} = \frac{p(0)}{v(0)} \quad (4)$$

Here, $Z_{in}$ is the impedance input. For an acoustic wave propagating through a pipe, the following relationship holds between the input impedance, the output impedance, and the specific impedance.

$$Z_{in} = Z_0 \frac{Z_L + iZ_0 \tan(kL)}{Z_0 + iZ_0 \tan(kL)} \quad (5)$$

Here, $Z_{in}$ is the output impedance, L is the length of the line, and k is the wave number. As can be seen from this equation, the input impedance depends on the length of the line and is a complex quantity. The input impedance can generally be expressed as follows:

$$Z_{in} = R + iX \quad (6)$$

Here, R represents the resistance associated with energy loss, while X represents the reactance associated with energy storage. For an acoustic wave traveling through a smooth pipe, energy loss due to friction and shear stress is minimal, so R is small.

Specific acoustic impedance determines a medium's ability to transmit, reflect, or absorb sound energy [8]. When a wave passes from one medium to another, and the wave propagation and energy transfer are being studied, the specific acoustic impedances of the media are considered. When a wave reaches the boundary between two media, if there is no energy absorption—that is, no energy loss—part of the wave is reflected, and part is transmitted. If the specific acoustic impedances of the two different media are different, the sound wave is partially reflected and partially transmitted at the boundary surface. This situation forms the basis of wave transmission problems. The reflection coefficient is given by [9];

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \quad (7)$$

When impedance matching is achieved—that is, when the specific impedances are equal ($Z_1$=$Z_2$), energy transmission reaches its maximum level, while reflection is minimized. Impedance matching is of critical importance, particularly in certain engineering applications.

When the amount of sound energy reflected is high or when sound insulation is high, the impedance difference is also high. Conversely, when sound transmission is high, that is, when insulation is low, the impedance difference is low. When the surfaces covering the medium through which sound waves propagate are rough or porous, impedance varies depending on frequency, and this forms the basis of sound absorption mechanisms [10]. The mode shapes and resonance frequencies of sound systems such as waveguides, Helmholtz resonators, and pipe acoustics can be determined by acoustic impedance [11], [12]. In everyday life, the impedance of wall materials for sound insulation in homes or workplaces, impedance matching between the air and the driver to improve sound quality in speakers and headphones, and impedance control in acoustic design for large halls are all considered. In industry and manufacturing, acoustic impedance is important for determining physical properties such as the density or elastic characteristics of materials [13], [14]. In ultrasonic testing and non-destructive inspection, impedance optimization is employed when designing acoustic panels to isolate the environment from noise [15]. As in this study, impedance plays a central role in both experimental and numerical modeling of sound transmission in pipes with rough interiors.

### 1.1 The Transmission of Sound Waves through a Smooth, Hollow, and Rigid Tube

Sound waves propagate as longitudinal waves inside a hollow, smooth tube with inelastic walls, just as they do in air [16], [17]. When propagating inside

the tube, the waves travel in the form of tube modes due to reflections off the tube walls [18]. The air molecules inside the tube create regions of compression and rarefaction, transmitting the vibrational energy along the tube's axis by reflecting off the tube walls. If the pipe walls are smooth and rigid, the air molecules collide with the pipe walls, causing the waves to lose very little energy; they primarily travel by reflecting off the pipe walls, thereby minimizing friction losses [19]. The propagation of sound waves within a pipe can also be modeled using the wave equation, which describes sound pressure as a function of position and time [20].

$$p(z,t) = Acos(kz - \omega t) \quad (8)$$

Here, $k = \frac{2\pi f}{c}$ is the wave number.

The fundamental mode frequency in an open-ended tube [21], [22];

$$f_{open} = \frac{c}{2L} f_1 = \frac{c}{2L} \quad (9)$$

In a closed-end pipe, however This can be expressed as follows.

$$f_{closed} = \frac{c}{4L} f_1 = \frac{c}{4L} \quad (10)$$

These mode frequencies give rise to standing waves. A pipe with a smooth inner surface can be considered hydrodynamically homogeneous [23]. The primary causes of energy losses during the propagation of acoustic waves within a pipe are related to viscous and thermal boundary layer effects. If the pipe's inner surface is smooth, the shear stress—that is, the amount of force per unit area acting parallel to the surface—is very low in regions near the pipe walls. In this case, viscous losses occur at a minimum level, and acoustic waves propagate with minimal energy loss—that is, with minimal attenuation. In this scenario, the resistance component—the real part of the acoustic impedance—decreases but does not become zero [24]. This is because the air medium is a viscous medium, and thermal losses are always present. Despite these losses, waves that are quite distinct within the pipe are obtained, and resonance modes are observed more sharply. This is characterized by the Q factor. If viscous losses, shear stress, and energy loss are small, the Q factor is high. The Q factor can be defined as follows [25];

$$Q = \frac{Energy\ stored}{Energy\ lost\ in\ one\ period} \quad (11)$$

High-frequency sound waves, or upper harmonics, experience greater viscous or thermal losses. Therefore, high-frequency waves are more attenuated on rough surfaces.

## 1.2 Sound Waves have an Acoustic Impedance Inside a Smooth Tube

Acoustic impedance studies in pipes with an assumed smooth inner surface began with fundamental theoretical studies and analytical modeling. Theoretical studies involved the planar wave approach, waveguide, and impedance frequency and boundary condition studies. In the planar wave approach, the frequency condition is [26], [27];

$$f < \frac{c}{d} \quad (12)$$

Here, 'd' is the inner diameter of the tube through which the sound is transmitted. Accordingly, for a plane wave approximation, the inner diameter of the tube must be small compared to the wavelength. If the diameter of the tube is much smaller than the wavelength ($d \ll \lambda$), only plane waves are propagated. When the diameter of the tube and the wavelength of the sound are close to each other ($d \approx \lambda$), higher modes begin. If the diameter of the tube is larger than the wavelength ($d > \lambda$), multimodal propagation occurs. In this case, the waves are not only in a plane mode but also undergo spatial changes within the tube cross-section, and the wave motion needs to be described in a more complex way. In the case of multimodal propagation, the velocity of the particles in the medium and the acoustic pressure vary not only along the tube axis but also in radial and angular directions. When the diameter of the tube is much smaller than the wavelength, the acoustic impedance can be considered frequency-independent. If this condition is not met, the acoustic impedance is considered frequency-dependent, and mode structures must be taken into account.

Experimental methods used to support theoretical and analytical models and verify the studies are based on measurements obtained using impedance tubes, the transfer function method, and standing waves. In addition to theoretical and experimental studies, numerical modeling has been performed using methods such as wavenumber analysis, mode matching, and the finite element method (FEM) [28].

One of the first systematic experimental methods for studying standing waves in a pipe is the Kundt tube, developed by August Kundt. Standing waves can be obtained using a Kundt tube, and by

measuring the wavelength of these waves, the speed and frequency of sound can be calculated, and the impedance of the medium can be indirectly determined. Calculating impedance with the transfer function using the two-microphone method is a study in accordance with the ISO 10534 standard [29]. In the two-microphone method, the pipe used in sound transmission is modeled as a one-dimensional waveguide [30]. Impedance is calculated thanks to the reflection coefficient of the medium. In addition, the characterization of a material placed in the medium can also be done in this system. In a study conducted in 2007, they investigated the effects of vibrations in the cylindrical pipe walls on the input impedance and showed that the impedance remains almost constant in a smooth pipe and that the impedance is only affected by the inner surface of the pipe and the vibration modes of this surface [31]. In another study in 2018, the acoustic wave propagation inside the pipe was modeled with FEM, and it was shown that impedance changes depend on the geometry of the pipe, the frequency of the sound, and the boundary conditions [32]. In a study in 2018 on acoustic wave damping in a turbulent flow environment in a smooth pipe, it was shown that the viscous boundary layer and the acoustic layer thickness affect the impedance [33]. In a study 2021, acoustic wave propagation was investigated in coaxial pipes, and it was shown that wave propagation, mode structures, and acoustic impedance can be solved analytically by examining the mode matching method [34]. In a study in 2019, it was shown that the impedance of the inner surface coating of the pipe through which the sound is transmitted affects the wave propagation [35].

## 2 Modeling and Simulation

Many scientific studies have been conducted on the mathematical modeling and numerical simulation of acoustic waves. These studies have spread to different fields such as architectural acoustics, optimizing sound insulation in enclosed spaces, underwater acoustics and oceanography, the propagation of ultrasonic sound waves in biomedical engineering, aeroacoustics in the aviation and automotive sectors, and, as in this study, materials science and noise control. In software such as COMSOL Multiphysics, acoustic impedance is used as a boundary condition. Acoustic impedance also plays a critical role in solving wave equations. Acoustic impedance provides information about the transmission, reflection, and absorption of sound waves and helps explain these mechanisms. It defines how a medium responds to sound waves. By identifying these mechanisms, it is also possible to control the transfer of sound energy.

Many academic and scientific studies have been conducted using COMSOL regarding the propagation of acoustic waves in a smooth tube. These studies generally utilize COMSOL's Pressure Acoustics, Thermoviscous Acoustics, Pipe Acoustics, and Boundary Mode Analysis interfaces. These tools are used to examine properties such as the attenuation amount, impedance, and mode structures of the acoustic wave within the tube, and to investigate waveform structures.

## 3 Result and Discussion

In this study, an impedance analysis was performed using COMSOL Multiphysics for a situation where the sound wavelength is much larger than the pipe's diameter in a closed-ended pipe. When the pipe's diameter is significantly smaller than the sound wavelength, it can be assumed that the wave behaves like a plane wave. It can also be assumed that higher-order modes do not emerge or can be neglected. In this study, sound waves with a frequency of 171.5 Hz propagating inside a 4-meter-long pipe with a 2.5 cm diameter and a rigid surface were investigated. Since this study will also form part of an experimental investigation, numerical values have been carefully calculated and selected to ensure they are realistic and easily reproducible in a laboratory setting. To this end, it was planned that the operating frequency would remain below the cutoff frequency generated by the first higher-order mode, and it was assumed that the resulting waves would propagate as plane waves. Since a plane wave is obtained, the formation of three-dimensional wave patterns, such as helical and radial modes, is prevented. Since the sound wavelength is larger than the pipe diameter, it can be assumed that no phase difference occurs at all points on the pipe cross-section, or that it can be neglected. With this optimal geometry and sound frequency, the Navier-Stokes equations can be simplified, and the Euler equations in their 1D form can be used in analyses.

Generally, even if the inner surface of a pipe is hard, viscous friction and thermal conduction losses occur between the air molecules carrying the sound waves as they propagate through the pipe. By selecting the pipe diameter as small as possible relative to the wavelength, the wave retains its plane-wave characteristic. There is a limit to how small the pipe diameter can be selected. If the pipe

diameter is selected to be too small, a narrow region forms, and the wave loses its plane-wave form. By selecting these optimal numerical values, the system's acoustic compactness is preserved, ensuring that the measured impedance data is free from parasitic noise caused by cross-modes and that the results exhibit high correlation with the theoretical plane wave equations.

Since the system used in this study has cylindrical symmetry, a 1D approach was chosen to simplify the problem. For this purpose, a simulation was performed in COMSOL Multiphysics (V6.3) under the Pressure Acoustics, Frequency Domain module. First, the formation of standing waves was simulated. Since the length of the 2.5 cm diameter pipe through which sound is transmitted is 4 m and the sound frequency is 171.5 Hz, this indicates that the system is in a resonance state at integer multiples of this frequency. The standing wave obtained using the COMSOL program is shown in Figure 1.

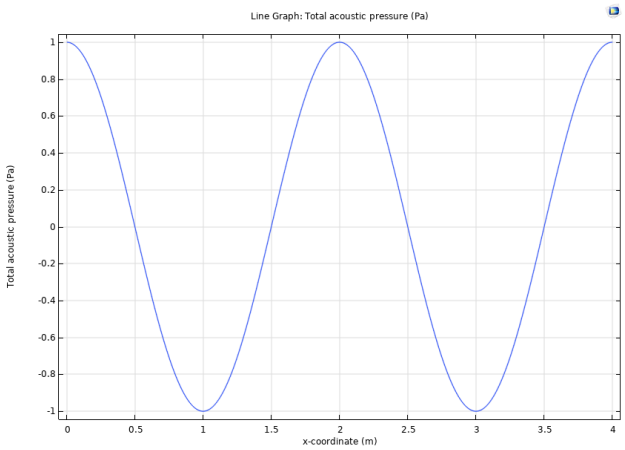



Fig. 1: Line Graph of total acoustic pressure
*Source: created by the authors*

As shown in Figure 1, the pressure starts at the maximum value, decreases along the x-axis to zero, and then increases in the opposite (negative) direction. The pressure value varies between the positive maximum and the negative maximum. This is consistent with the pressure distribution (pressure propagation) in longitudinal waves. Additionally, the figure shows that two sound waves at 171.5 Hz fit within a 4-meter-long pipe. The points where the curve intersects the x-axis—at 0.2, 1.5, 2.5, and 3.5 meters—are the silent points where the sound pressure is zero. The points where the pressure is highest are the maximum points in the negative and positive directions.

This waveform has been converted into an impedance plot using the COMSOL software, as shown in Figure 2.

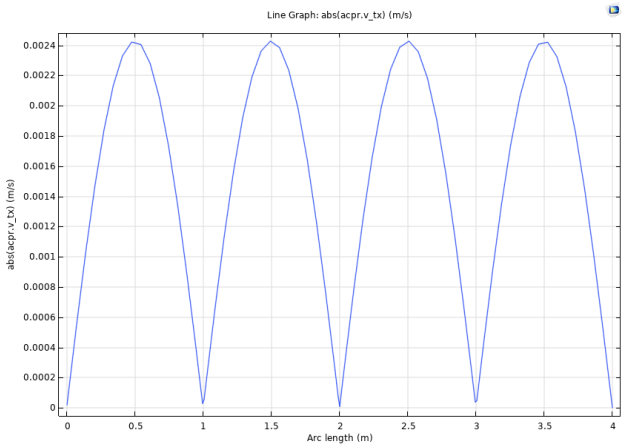



Fig. 2: Line graph of the absolute value of velocity $v_x$ with respect to distance x
*Source: created by the authors*

The peaks in the impedance graph indicate the acoustic response of the pipe. Since impedance is the ratio of pressure to particle velocity according to Equation 2, the impedance variation graph resembles the pressure variation graph but exhibits a significantly different characteristic. At points where the particles are at rest—that is, where the velocity is zero—the impedance approaches infinity. Since the inner surface of the pipe used in the simulation is smooth and the pipe walls are rigid, these maximum values remain constant along the entire length of the pipe without decreasing. If the inner surface of the pipe were rough or if the pipe walls were elastic enough to be affected by sound pressure, the values at these maximum points would decrease along the length of the pipe.

# 4 Conclusion

The acoustic impedance behavior of sound waves traveling through a cylindrical pipe has been thoroughly examined in this paper, both theoretically and numerically, using the finite element approach. The study's main goal is to clarify how the internal surface features of the pipe—roughness and geometric factors in particular—affect energy loss mechanisms, impedance characteristics, and sound wave propagation. In this case, frequency-domain calculations were carried out in the COMSOL Multiphysics environment after a physical model of the system was created using the classical acoustic wave equation and impedance definitions.

The results show that when the pipe diameter is selected to be much smaller than the wavelength, the plane wave approximation is valid, and that this method enables the system to be represented with

great accuracy in one dimension. The analyses were made simpler by the suppression of higher-order mode production under these circumstances, and it was found that the results were very consistent with theoretical predictions. According to simulation results, unique standing wave structures formed inside the pipe, with the acoustic pressure nearing zero at the nodes and the pressure distribution fluctuating between maximum and minimum values on a periodic basis.

It was shown that impedance achieves its maximum values at locations where particle velocity is zero when evaluated in terms of impedance analysis, which is in line with the theoretically predicted p/v ratio. It was shown that viscous and heat losses are reduced in pipes with smooth, stiff inner surfaces; as a result, impedance is mainly preserved throughout the pipe's length. However, it is expected that when internal surface roughness rises, boundary layer effects will become more pronounced, energy losses from heat conduction and viscous friction will increase, and both the amplitude and phase components of the impedance will shift significantly. Specifically, the system shows a frequency-dependent attenuation of high-frequency vibrations over rough surfaces. Specifically, the system displays a frequency-dependent impedance characteristic due to the increased attenuation of high-frequency waves on rough surfaces.

The study's numerical model was chosen to be consistent with an experimentally implementable system, and the outcomes were judged verifiable in a lab environment. In this sense, the study offers a framework for experimental acoustic research in addition to a theoretical analysis. Specifically, parameters that may be directly compared with experimental methods, such as standing wave analysis, the two-microphone method, and impedance tubes, have been produced.

In conclusion, this study offers a thorough explanation of how interior surface characteristics impact sound transmission, reflection, and absorption mechanisms and amply illustrates the critical function that acoustic impedance plays in wave propagation within pipes. The results offer valuable information for a range of technical applications, such as material characterization, vibration and sound analysis in pipe systems, acoustic insulation design, and noise control. Incorporating parametric modeling of rough and porous surfaces, including turbulent flow conditions, and examining three-dimensional mode effects would enable the development of more realistic and thorough acoustic models in subsequent research.

**Declaration of Generative AI and AI-assisted Technologies in the Writing Process**

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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**Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)**

- Timur Canel was responsible for the Investigation.
- Evrim Guven, Timur Canel were responsible for the Methodology.
- Evrim Guven was responsible for Data Curation.
- Timur Canel created the Visualizations for the manuscript
- Evrim Guven handled the writing - review & editing for the paper.

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**Conflict of Interest**

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