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Iraqi Journal of Industrial Research (IJOIR)

Journal homepage: http://ijoir.gov.iq

Computational Analysis for Fluid-Solid Interface Using Computational Fluid Dynamics Analysis Techniques

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Article information

Article history:
Received: March, 03, 2025
Accepted: May, 28, 2025
Available online: June, 14, 2025

Keywords:
Acoustic waves,
Reflection coefficient,
Permeability

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DOI:
https://doi.org/10.53523/ijoirVol12I1ID549

Abstract

This study presents a one-dimensional steady-state computational analysis of fluid-solid interactions using Computational Fluid Dynamics Analysis (CFD) analysis techniques. The analysis is conducted through numerical simulation based on Biot's theory, implemented using COMSOL Multiphysics 6.0. Four two-layer models: air-stainless steel, air-silicon carbide, water-limestone, and water-sand are examined to investigate the influence of key parameters on acoustic wave reflection at interfaces. The models were analyzed under varying acoustic frequencies (10 Hz to 10 kHz) and oblique incidence angles (0° to 80°). The results indicate that the reflection coefficient is relatively stable at low frequencies, ranging between 0.8 and 0.9. However, with higher frequencies and larger incidence angles, the coefficient gradually decreases, reaching approximately 0.4 at 80° and 10 kHz. Silicon carbide maintained a stable reflection pattern across the frequency range with less than 5% variation, while sand showed a significant increase in reflection up to 20% at high oblique angles. Interfaces with high acoustic impedance contrast, such as air–stainless steel, exhibited the highest reflection. The study concludes that porosity, permeability, and the angle of incidence are critical parameters that influence acoustic reflection behavior. These findings support the design and optimization of porous and composite materials for insulation and noise control in engineering applications. The simulation approach can be extended in future work to validate results against experimental data and to explore more complex structures and dynamic conditions.

1. **Introduction**

Computational fluid dynamics (CFD) and solid interface is of great importance in many engineering and industrial applications. Remote sensing methods, such as acoustic sensing, can provide accurate information about these interactions without the need for direct intervention, which is why remote sensing techniques especially acoustic methods have gained widespread attention for their non-invasive and highly sensitive capabilities. This research aims to analyze the solid-fluid interface using computing techniques. Understanding this wave behavior at fluid-solid boundaries is crucial for the characterization of materials and the optimization of acoustic-based systems. It is well known that a portion of the incident energy is reflected and a portion is refracted (transmitted) when a plane elastic wave encounters a change in media as shown in Figure 1 [1]. The angle formed between the wave's direction of propagation and the normal vector of the reflecting surface is known as the angle of incidence. The transmitted and reflected waves maintain the same kind of incident wave when normal incidence occurs at the interface.

Porous materials, composed of solid frameworks and fluid-filled voids, are extensively used in industrial applications due to their ability to absorb and attenuate sound and vibrations. Many materials, both natural and man-made, can be categorized as porous materials, including soils, bones, plastic foams, fibrous materials, cements, and ceramics. To lessen noise and vibration pollution, various materials, such plastic foams and fibres, are often employed in the building trade, the automotive industry, and the aerospace industry. Thus, strong acoustic performance is a desirable characteristic in practically all building types, and it is especially crucial for residential buildings, educational institutions, and healthcare facilities. These porous materials' ability to absorb sound is primarily based on their intrinsic properties [2]. In cars and other industrial applications, porous materials—alone or in combination with viscoelastic materials are frequently utilized to reduce noise and vibration. These materials can be utilized to reduce transmission loss and damping in multilayer systems or to reduce airborne noise. They can be found on panels, in cavities, under carpets, in trim lining, and in seats, among some other.

The numerical simulation of porous materials has developed into a highly important technique in the study of systems for noise and vibration control since it is necessary to predict the behaviour of acoustical materials Numerical modelling, especially using Biot's theory, has become an essential tool in predicting the acoustic behaviour of porous media and in validating material design strategies [3]. The rate of fluid circulation through a porous media is known as permeability [4].

This study builds on previous work by providing a detailed computational simulation of fluid-solid interfaces using COMSOL Multiphysics. It aims to investigate how frequency, angle of incidence, and material properties affect the acoustic reflection behaviour, offering insights that can guide the development of more efficient sound-insulating materials.

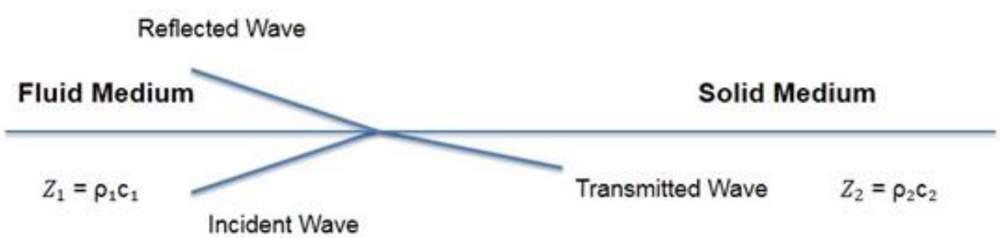

Figure (1): Transmission, Reflection, and Incidence.

Recent studies have applied hybrid numerical-experimental techniques to evaluate multilayer porous materials and their sound absorption efficiency [5]. In addition, Al-Qarishey (2021) illustrated the wide range of applications of computational techniques in engineering research by demonstrating the efficiency of modeling and simulation methodologies in studying complex fluid-structure interactions, like those seen in wind turbine systems. COMSOL Multiphysics also has been effectively used in a number of recent studies for thermal performance evaluations and modeling and simulation in renewable energy systems. For example, Abed *et al.* [2] carried out a numerical analysis to improve the performance of an integrated collector storage solar water heater, and Abood *et al.* [1] used COMSOL simulations to optimize aerodynamic parameters for wind turbines. These studies provide more evidence of COMSOL's flexibility and dependability as a modeling tool for energy-related applications.

This work's main objective is to use COMSOL Multiphysics to perform a thorough computational investigation of the fluid-solid interface with a focus on the interaction of acoustic waves at these boundaries. This study examines how important factors like frequency, angle of incidence, and material properties affect the behaviors of acoustic reflection and transmission. This study is creative because it uses a thorough simulation technique that combines advanced multiphysics modeling with Biot's theory to provide a deeper understanding of wave-material interactions. These understandings are essential for enhancing the design and optimization of materials that reduce vibration and insulate sound in a variety of applications in industry, such as automobile engineering and building acoustics.

2. Methodology

This study models the reflection of incident plane acoustic waves at fluid-solid interfaces using Biot's poroelastic theory, implemented in COMSOL Multiphysics 6.0. These interactions are simulated under different situations, such as different wave frequencies and incident angles. The effect of these factors on the reflection coefficient is the main subject of the research.

Biot's theory has been validated across a variety of porous media through time-domain simulations [6], confirming its suitability for poroacoustic modeling.

2.1. Present Model

In this study, COMSOL Multiphysics 6 was used to simulate the waves incoming through a fluid medium at an angle of incidence onto four interfaces: water-limestone, air-stainless steel, air-silicon carbide ceramic, and water-sand. A 1D geometry was used. The porous matrix domain, which involves the interaction between the fluid's elastic waves and pressure waves in the solid, is simulated using Biot's theory [3]. In order to explain the micro-structures found in multiple -structure substances (such as ceramic, limestone, etc.), the poroelastic model was used.

The reflection coefficient is a result of the interaction between these waves and the incoming homogenous pressure wave in the fluid [7]. Losses in the porous material are generated or imitated by an equivalent fluid model, which then predicts the reflection coefficient. The border between the fluid domain and the porous material was modelled as an acoustic-porous boundary. The fluid domain's uppermost point and the lower portion of the poroelastic area were modeled as perfectly matched layers [8] (ideally absorbing layer or region that is included in an acoustic model to emulate an infinite domain that is open and non-reflecting). More details about the materials and other input factors taken into account for the solid domain, and they are all combined in Table (1).

Table (1): Considered input parameters.

Name	Description	Expression	Case I	Case II	Case III	Case IV
f_0	Driving frequency	1000 [Hz]	1000 Hz	1000 Hz	1000 Hz	1000 Hz
θ_i	Incidence angle	0 [rad]	0 rad	0 rad	0 rad	0 rad
γ	Porosity	0.4	0.4	0.4	0.6	0.47
a	Parameter of pore size	4×10^{-3} [cm]	1.6×10^{-5} m	1.6×10^{-5} m	4×10^{-5} m	4×10^{-5} m
ζ	Tortuosity	1.25	2.26	2.26	5.12	1.25
k_p	Permeability	1×10^{-6} [cm^2]	1×10^{-12} m^2	1×10^{-12} m^2	1.172 m^2	1×10^{-10} m^2

This table listed the input parameters taken into account when analyzing the solid-fluid interaction with COMSOL software. The description of every parameter includes information about its range or value, and units of measurement.

2.2. Governing Equations

The wave propagation follows Snell's law:

$$\boldsymbol{k_1 \sin \theta_i = k_2 \sin \theta_t} \qquad (1)$$

Where $\theta_i$the wave's angle of incidence and k1 is is the real wave number in fluid. Alternatively, k_2 is the vector m's modulus. Finally, using COMSOL [9], the reflection coefficient was calculated utilizing the following equation:

$$R = \frac{\frac{Z_1 \cos\theta_i}{Z_0 - 1}}{\frac{Z_1 \cos\theta_i}{Z_0 + 1}} \qquad (2)$$

Where the fluid and solid's respective attenuation coefficients (Z_0 and Z_1) are determined as follows:

$$Z_0 = \rho c_c \qquad (3)$$

In a similar way, the absorption coefficient α was determined by:

$$R = \sqrt{1 - \alpha} \qquad (4)$$

COMSOL Multiphysics 6's pressure acoustics module was used to simulate the model in the frequency domain [9]. The exact value of the coefficient of surface attenuation at the point where the two domains meet calculated from the acoustic properties of the materials and was adjusted to be frequency dependent. Additionally, a thorough model according to the formulas given by Biot's theory for the interaction between the elastic porous matrix and the saturating fluid was solved using the Poroelastic Waves interface [10]. Any porous material may be modeled using this interface, which also solves for the saturated fluid's pressure as well as the displacement of the matrix that is permeable.

2.3. Mesh Study

To make sure the results are accurate, a mesh test was done. The model is 1D, so it was divided into small line sections (called elements) along the direction of the wave. A fine mesh was used with many elements to get good accuracy. To check if the results depend on the mesh size, different mesh setups tried. The results were almost the same. The final mesh gives accurate results and does not require a lot of computing time. It worked well for all four material cases.

2.4. Experimental Comparison and Future Validation

Although experimental validation is beyond the current scope of this study, the developed model was structured to match the boundary conditions and material properties used in prior experimental research, particularly the setups described by Stoll & Kan (1981) [9]and Sadouki (2018) [11]. These studies investigated the reflection of acoustic waves at fluid-porous interfaces under low-frequency conditions similar to those simulated in this work. The reflection coefficient trends observed in the simulation are in qualitative agreement with these previous experimental findings. For example, the increase in reflection with incidence angle for sandy porous media and the stable behavior of silicon carbide are both phenomena reported in experimental literature. In future work, the simulation will be extended by replicating one of these experimental conditions physically in a controlled setup, using acoustic sensors to measure the actual reflected wave amplitudes. This will allow for a direct quantitative comparison and model refinement.

3. Results and Discussion

In order to describe the impact of the substance's properties on the reflection of plane fluid waves, this section presents of computational testing and results. The impact on the coefficient of reflection minima is of special interest. Table (1) provides an overview of different input parameters that are applied in the case studies that follow. Selecting the parameters for permeability, porosity, and driving frequency is particularly delicate when precisely evaluate the acoustic response using the reflection coefficient curves. Furthermore, because to thermal and viscous losses were taken into account when modelling the solid domain for this study, high attenuating and high damping materials were chosen for the subsequent cases, while also capturing a variety of distinct permeabilities and porosities that are presently used in the manufacturing industry (as well as related fields) like composites, metals, and ceramics). As a result, the materials used in the present work are limestone, stainless steel, silicon carbide ceramic, and sand. A solid poroelastic simulated with a variety of permeability and porosity values that capture the attenuating and damping features of materials. The effects of propagation medium and the properties of solid materials are investigated in the sections that follow. Considered are the cases of fluid-solid interaction listed below.

(I) Water-Limestone Interface
(II) Air-Stainless steel Interface
(III) Air-Silicon carbide ceramic Interface
(IV) Water-Sand Interface

(I) Water-Limestone Interface
The solid domain was modelled using the properties of limestone from previous studies, while the domain that was fluid was modelled utilizing the properties of water [12], [13], [4]. Limestone is widely used in the industry. Table (1) lists the different input parameters that were taken into account under case I.

The frequencies selected for this study are 1 kHz, 10 kHz, 100 Hz, and 10 Hz in magnitude, which belong to the low frequency region for the purpose of enable a similar discussion with the validation study (given under case A) and further later examples in this section. Figure (2) shows the fluctuation of the oblique incidence's reflection coefficient onto the interface.

The reflection coefficient showed stability at lower frequencies (such as 100 Hz), indicating a uniform interaction between limestone and water. Because of the materials' different impedances, the reflection coefficient changed as the frequency increased. This indicates that limestone, which is frequently used in construction, remains to have high reflection properties, particularly at oblique angles.

(II) Air-Stainless Steel Interface
The properties of stainless steel were used to simulate the solid domain, whereas the properties of air were used to model the fluid domain. In addition to its widely using in the industry, stainless steel was chosen for this section of the study because, according to previous studies, it exhibited the highest levels of attenuation [14]. Table (1) lists the variation input parameters that were taken into account for Case II. In order to provide an accurate comparison with the plots of the frequency-dependent reflection coefficients obtained in case I, the analysis was carried out in a low-frequency range, with magnitudes ranging from 10 Hz to 100 Hz to 1 kHz to 10 kHz. Figure (3) shows the change in the reflection coefficient at the interface for oblique incidence. Considering a frequency values range 10-100 Hz, coefficient of reflection magnitude is 0.99 for all incidence angles that were taken into consideration. The fact that the maxima in this case are significantly larger than those under case I indicates that when waves travel through a gas medium—such as air—as opposed to water, the reflected energy's effective magnitude ratio will be higher. The reflection coefficients magnitude drops with each magnitude increase of 10 in the driving frequency. Higher frequencies have a faster decreasing pattern, with the minima reaching a magnitude of 0.32 at 10 KHz. This indicates the air dampens the reflection at higher frequencies.

(III) Air-Silicon Carbide Ceramic Interface
The solid domain was modelled using Silicon Carbide (SiC) parameters from previous research [15] [16] [17], while the domain that was fluid was modelled using air's properties. Due to their interesting mix of properties, which include lower thermal expansion, melting at high temperatures, increased thermal conductivity, lower density, higher specific strength, higher permeability, higher resistance to oxidation, and enhanced chemical inertness, porous silicon carbides have been used previously to determine the gaps in phonic bands of low-frequency acoustic waves [18]. Table (1) lists the different input parameters that were taken into account for case III. In order to enable an effective comparison with the reflection coefficient that varies with frequency graphs obtained in case II, the study itself was carried out in the low-frequency region. Plotted in Figure 4 is the fluctuation of the oblique incidence reflection coefficient on the interface.

Figure (4) illustrates how it's clear that the incident wave's driving frequency is irrelevant. The high permeability is the reason for this. The fluctuation for the reflection coefficient is shown in the figure as it lowers with rising incidence angle values, reaching as low as 0.15 magnitude for an incidence angle of 80 degrees. Silicon carbide is a reflective material that is stable, as demonstrated by this result. This may account for its widespread use in materials engineering applications.

(IV) Water-Sand Interface

Solid domain was modelled using sand's properties and reflected the parameter choices made by Stoll & Kan [9], whereas the domain that was fluid was modelled using water's properties. Table (1) lists the variation input parameters that were taken into account for Case IV. In order to provide an accurate comparative analysis of the reflection coefficient plots that are depending on frequency seen in case I, the analysis was carried out in a low-frequency range. Plotted in Figure (5) is the fluctuation of the reflection coefficient for oblique incidence onto the interface. The reflection coefficient's minimum values become non-zero and it increased with incidence angles values. The reflection coefficient was stable at low frequencies. However, the reflection coefficient became extremely sensitive to changes in frequency when the incidence angle increased to 80 degrees. This pattern indicates that there may be a significant amount of acoustic variation at oblique angles when using sand in industrial applications.

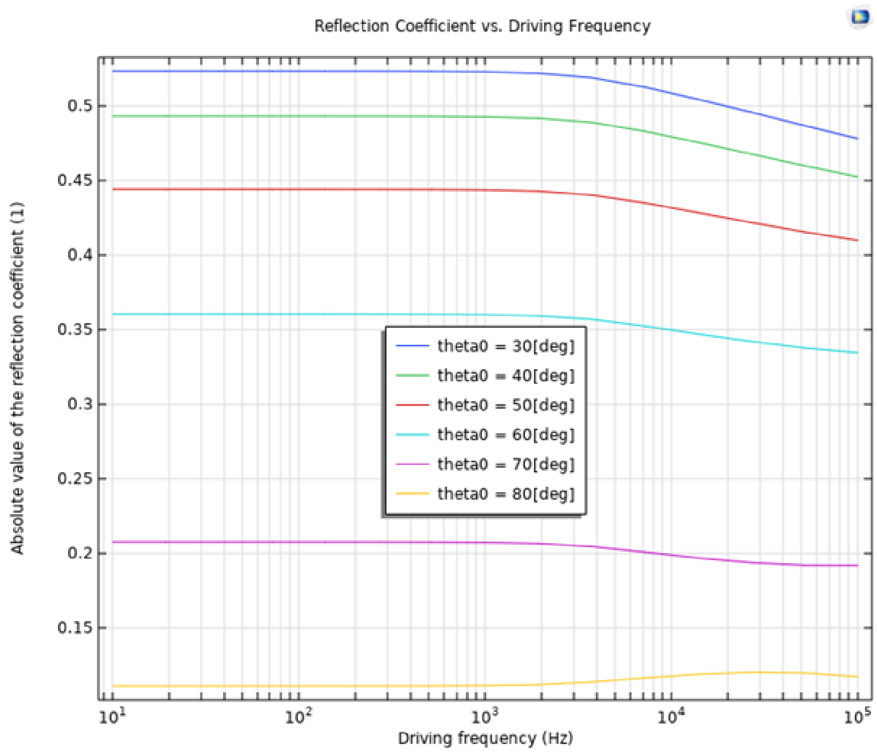

Figure (2): COMSOL simulation of |R| vs. f0 for Water-Limestone Interface.

The variation of the reflection coefficient for oblique incidence into the water-limestone interaction is shown in Figure (2). At lower frequencies, the reflection coefficient is shown to remain generally stable, indicating a steady interaction between the interface and the acoustic waves. On the other hand, the reflection coefficient varies with increasing frequency. The acoustic impedance mismatch between the limestone and water, which affects the reflection characteristics, is the cause of these variations.

The figure shows how, at an air-stainless steel interaction, the reflection coefficient's magnitude changes with frequency. Because of the significant impedance difference between stainless steel and air at lower frequencies, the reflection coefficient exhibits a significantly high and stable value, indicating strong reflection. The material's frequency-dependent acoustic characteristics and any surface imperfections may be the cause of the variations in the reflection coefficient that are seen as the frequency rises.

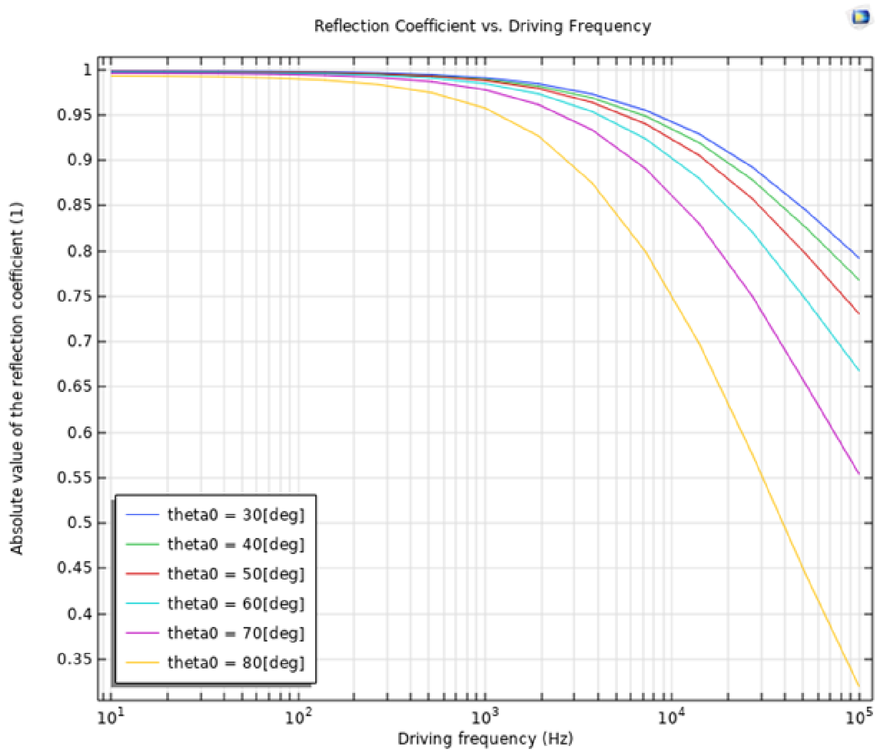

Figure (3): COMSOL simulation of |R| vs. f0 for Air- Stainless steel Interface.

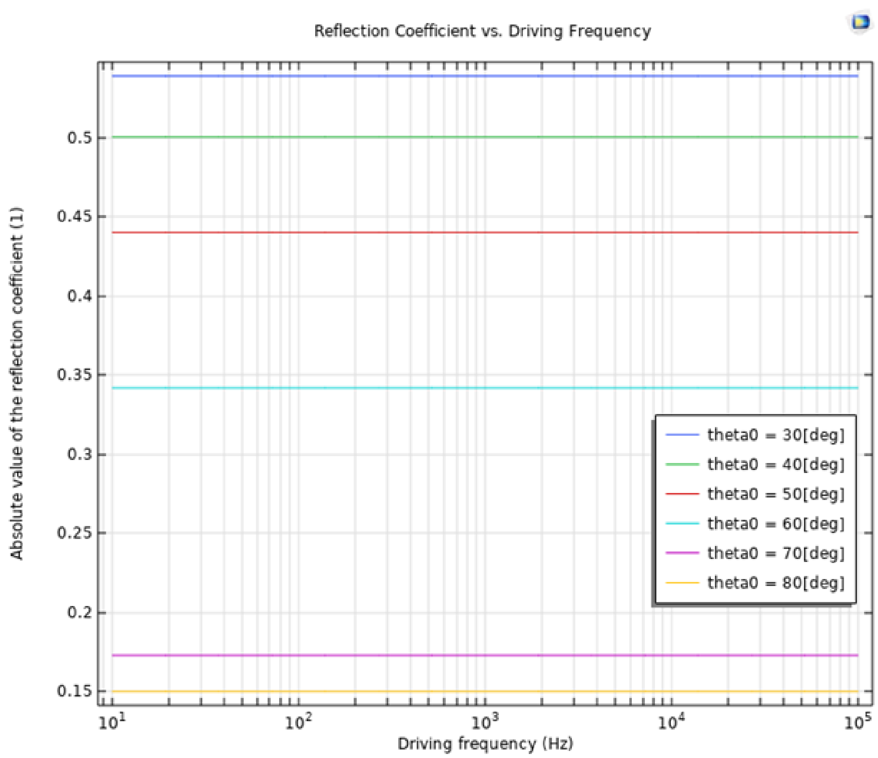

Figure (4): COMSOL simulation of |R| vs. f0 for Air- Silicon carbide ceramic interface.

The figure illustrates how the air-silicon carbide ceramic interface's reflection coefficient remains stable at various frequencies. According to the simulation results, the air-silicon carbide ceramic interface's reflection characteristics are not considerably affected by changes in frequency, since the reflection coefficient appears to be rather stable throughout a range of frequencies.

However, the reflection coefficient falls with increasing angle of incidence. This occurrence demonstrates how crucially the incidence angle affects the characteristics of the reflection. The dynamics of the interaction between the acoustic waves and the interface vary with rising incidence angles, leading to less reflection and more transmission at higher angles, which is why the reflection coefficient decreases.

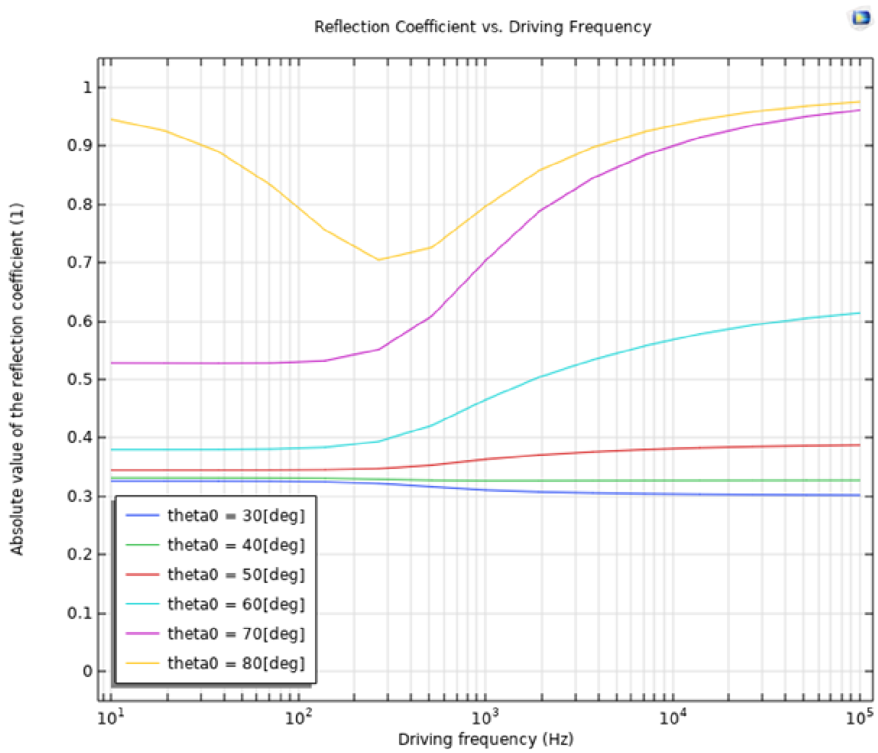

Figure (5): COMSOL simulation of |R| vs. f0 for Water-Sand Interface.

The figure illustrates how the water-sand interface's reflection coefficient is relatively stable at various frequencies. But as incidence angles increase, the reflection coefficient rises as well, indicating that the incidence angle has an important effect on the reflection properties. However, the reflection coefficient exhibits a significant sensitivity to changes in frequency at an incidence angle of 80 degrees. The increased interaction time and path length are responsible for this phenomenon. The acoustic wave's journey length via the interface increases at higher incidence angles, extending the material's interaction duration. The effects of the materials' frequency-dependent characteristics are enhanced by this prolonged interaction.

The simulation's findings demonstrate how important the properties of the material, frequency, and angle of incidence are in determining the behavior of acoustic reflection at fluid-solid interfaces. For instance: Designing efficient sound insulation systems to lower noise levels in homes, schools, and medical institutions is made easier by an understanding of wave reflection on interfaces such as sand and limestone, reflection properties at surfaces like silicon carbide ceramic and stainless steel are essential for creating lightweight components with improved vibration damping and noise reduction capabilities in the automotive and aerospace industries, understanding how water interacts with materials like sand or limestone enhances sonar technology and seabed characterization in underwater sensing and marine sediment research, which benefits resource development and environmental monitoring. These results highlight the importance that advanced computational modeling is to understand and enhance material and interface performance in a variety of engineering and industrial applications.

The study's simulation results were found to be consistent with data that had already been published. For example, the patterns outlined by Stoll and Kan [12] are consistent with the reflection behavior for the water-sediment interaction at oblique angles. The accuracy and dependability of the suggested numerical model based on Biot's theory and implemented in COMSOL Multiphysics are supported by this consistency.

4. New Ideas

Finding the critical angle of incidence beyond which the reflection coefficient decreases off drastically is one of the new insights gained from our research. This phenomenon raises the possibility of a new research area as it was not before documented in investigations. Furthermore, our analysis emphasizes how important porosity is in relation to other material properties, which can help guide future testing and material design processes.

5. Conclusions

This study presented a numerical analysis of acoustic wave reflection at various fluid-solid interfaces using Biot's theory within the COMSOL Multiphysics environment. A one-dimensional, steady-state model was developed to simulate four different material interfaces—water-limestone, air-stainless steel, air-silicon carbide, and water-sand under varying frequencies and angles of incidence. The results demonstrated that the reflection coefficient is highly sensitive to both frequency and angle of incidence. Materials with high acoustic impedance contrast, such as stainless steel and limestone, showed strong reflection across frequencies. In contrast, porous materials like sand and silicon carbide exhibited behaviour that was closely influenced by their permeability and porosity values. Notably, silicon carbide remained acoustically stable, while sand showed an increase in reflection up to 20% at oblique angles. The use of Biot's theory, combined with COMSOL's poroelastic simulation capabilities, enabled accurate modelling of pressure-acoustic interactions in porous materials. This methodology offers a reliable tool for predicting the performance of sound-insulating materials in various engineering fields such as building acoustics, automotive applications, and material design. The study enhances prior approaches by providing parametric insights across a broader range of frequencies and materials, and sets the foundation for future experimental validation and application in real-world noise control systems

Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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