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Structured Ultrasonic Metasurfaces

Raj C Thiagarajan, PhD
ATOA Scientific Technologies Private Limited
194, Evoma Business Centre, Bhattrahalli, KR Puram, Bangalore 560049, India, Raj@atoastech.com

Abstract: Metamaterials are emerging as a futuristic engineered material with unusual electromagnetic properties for novel and unusual applications. Ultrasonic Metamaterial enables to design materials for unusual ultrasonic properties such as total transparency or reflection to ultrasonic acoustic waves. Ultrasonic acoustic waves usually encounter interfaces with significant impedance mismatch in practical medical or industrial imaging applications. A transparent interface can help to improve the performance of medical and industrial imaging and overall innovative applications. Similarly, a broadband total reflection interface can help to improve the architectural or transportation barrier acoustics. This paper examines the structured ultrasonic metasurfaces for improved transparency or reflection. The ultrasound wave propagation in a typical two phase material interface is modeled in COMSOL. The interface is numerically explored with designer shapes for reduction in impedance mismatch by interactive wave effects. The input and out energy is compared as a function of metasurface features. The geometry and acoustical property effects on the transmission coefficient are predicted and reported. The results and discussion section include practical implementation issues and potential applications.

Keywords: Metamaterials, acoustic metamaterials, Ultrasonic, acoustic impedance, acoustic transparency, Engineered surfaces, meta surfaces, ultrasonic imaging, medical imaging.

1. Introduction

Ultrasonic metamaterials exhibit unusual properties and that can be used to develop novel applications [1-3]. This paper leverages COMSOL multiphysics model to engineer interfaces for significant improvement in ultrasonic wave propagation. The ultrasonic wave propagation governing equation and a brief about its implementation in COMSOL are detailed. A numerical model was developed to study effect of structured interface on the ultrasonic transmission properties. The transmitted and received energy are predicted to investigate the effect of interface on the transmission efficiency.

The formulation, governing equation and modeling methodology related to the problem will also be reported. The transmission coefficient of the output will be extracted to evaluate the efficiency of the metasurfaces.

The model can also further be used to explore two way transparency. The effect of metasurfaces shape, size and frequency dependence on the performance will be reported. Relatively narrowband requirement of ultrasonic imaging application is critical for the success of metasurfaces.

The target of this investigation is to explore effect of engineered surfaces for improving the performance of industrial and medical imaging. Other industrial applications besides imaging of ultrasonic metamaterials will be reported. The transmission coefficient will be used as a metric to relate the output of this investigation to industrial applications.

2. Problem Formulation

Ultrasonic wave propagation usually encounters an interface with mismatch in acoustic properties. This mismatch in acoustic properties for propagation from low acoustics impedance to high acoustics impedance reflects most of the incident energy. This depends on the acoustics property of the material and hence is a limitation. The improvement in transmission efficiency can help to improve the performance of medical and industrial application of ultrasonic. The sound propagation efficiency will be investigated across an interface with mismatch in properties. The effect of engineered surface for improving the transmission efficiency will be a key focus. A water and polymer interface will be investigated for use in industrial and medical applications, respectively. Polymer interface is specially selected because that can implemented using cost effective continuous production technologies.

3. COMSOL Simulation

The sound propagation in the medium is handled by the wave propagation equation. The pressure acoustics interface in COMSOL [4] is used for this investigation. Sound waves in a lossless medium are governed by the following inhomogeneous Helmholtz equation for the differential pressure *p in* (N/m^2,

$$\frac{1}{\rho_0 c_s^2}\frac{\partial^2 p}{\partial t^2}+\nabla\cdot\left(-\frac{1}{\rho_0}(\nabla p-\mathbf{q})\right)=Q$$

Where, ρ_0 in kg/m^{3,} refers to the density and c_s in m/s is the speed of sound and *Q in* 1/s^2 is the source.

The sound wave propagation through acoustically mismatched interface is modeled as a 2D frequency domain problem. An incident pressure wave is applied at the top interface. The transmitted sound energy is measured. The transmission efficiency is predicted by integrating the pressure over the interface as follows.

At the inlet boundary is a combination of incoming and outgoing plane waves is defined as follows,

$$\left(-\frac{\nabla p}{\rho}\right)\cdot\mathbf{n}=\frac{i\omega}{\rho c_s}p-\frac{2i\omega}{\rho c_s}p_0$$

In this equation *p*0 denotes the applied outer pressure and *i* the imaginary unit. P_{in} is obtained by the following integration.

$$P_{\text{in}}=\int_{\partial\Omega}\frac{p_0^2}{2\rho c_s}dA$$

At the outlet boundary, an outgoing plane wave is set as follows,

$$\left(-\frac{\nabla p}{\rho}\right)\cdot\mathbf{n}=\frac{i\omega}{\rho c_s}p$$

P_{out} is calculated using the following integration,

$$P_{\text{out}}=\int_{\partial\Omega}\frac{|p_c|^2}{2\rho c_s}dA$$

The transmission loss is predicted using the following equation,

$$\text{TL}=10\log\left(\frac{P_{\text{in}}}{P_{\text{out}}}\right)$$

Where, P_{in} and P_{out} denote the acoustic effect at the inlet and outlet, respectively. The acoustic transmission coefficient is calculated using the following equations.

$$T_c=\frac{P_{out}}{P_{in}}$$

The analytical transmission coefficient which can be predicted from the acoustic impedance mismatch will also be used.

$$T_c=1-\left[\frac{Z_2-Z_1}{Z_2+Z_1}\right]^2$$

Where, Z1 and Z2 are acoustic impedance of medium 1 and medium 2, respectively. Acoustics impedance, Z = ρ * V, Where, Z, Acoustic Impedance of material, ρ, density and V, Velocity.

The figure 1 and 2 shows the CAD model of standard and engineered interface, respectively. Material 1 is water and material 2 is polymer, respectively. The interface feature considered is a periodic rectangular shape with width and height. Non rectangular shapes can also be considered.

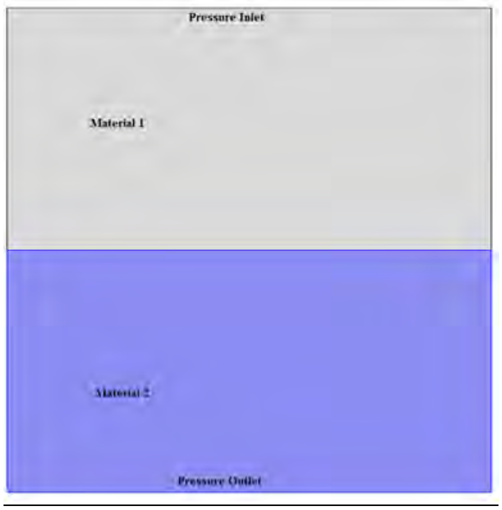


Figure 1 CAD model of standard interface.

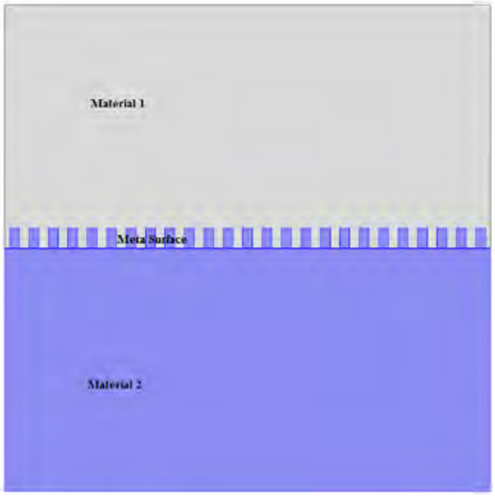
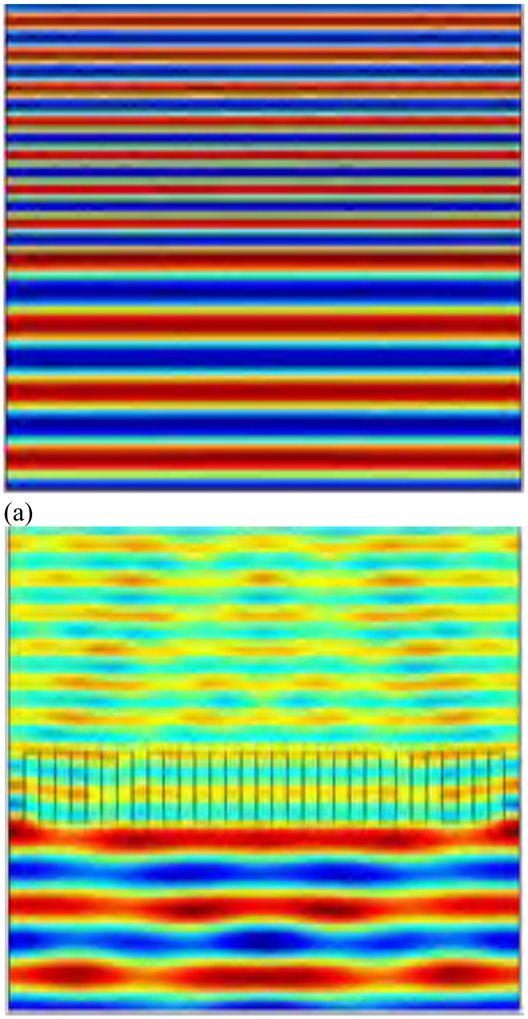


Figure 2 CAD model of engineered interface.

4. Results and Discussion

The simulation results are shown in figure 3 to 5. The ultrasonic pressure field distribution on a typical interface and an engineered interface are shown in figure 3, for a water and polymer interface. The effect of feature size (on the order of 0.1 to 1 mm) and frequency (0.1 to 10 MHz) was investigated. The transmission coefficient predicted as per the acoustic impedance mismatch for water polymer interface is 0.64. The transmission coefficient predicted for engineered interface is a maximum 0.93, which is 45% improvement in performance for a given material with engineered interface. The pressure acoustics simulation alone shows a potential transmission coefficient improvement.



(a)

(b)

Figure 3 shows the Ultrasonic wave propagation between two medium, a) with a typical non engineered interface between two medium, b) an engineered and structured metasurfaces interface.

The frequency dependence of transmission coefficient for water polymer interface is shown in figure 4. A maximum of 0.93 is observed at certain periodic frequency. Further this is observed to be a function of depth and width of the engineered interface. A resonant interaction is attributed to the increase in the transmission.

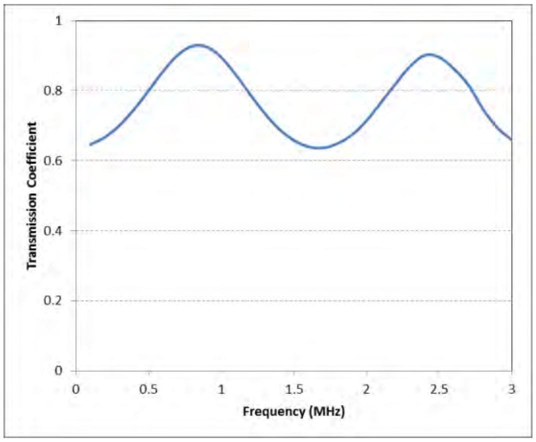


Figure 4. Transmission coefficient of water polymer interface as a function of frequency.

The effect of width and height of the engineered interface is further investigated for improvement in performance. Figure 5 shows the effects of height of the feature on the performance for given frequency and width of the feature. This shows the potential for further improvement in transmission coefficient.

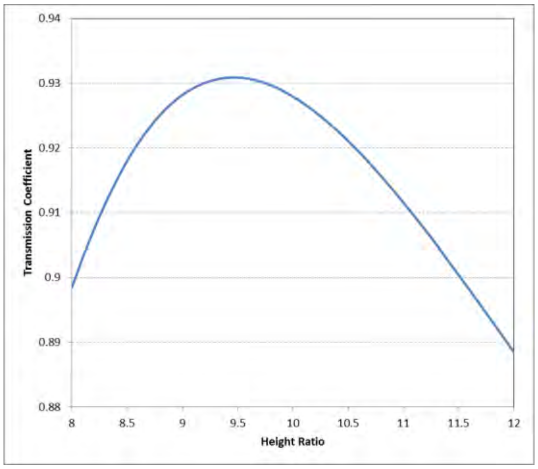


Figure 5 Transmission coefficients as function of engineered interface feature height.

The results show that the engineered interface can increase the transmission efficient. The increase in transmission coefficient is due to wave interaction effects at the interface. The performance is related to the frequency and the feature size. Further, engineering the interface can lead to 100 % efficient transmission interfaces. This can also be engineered to reflection 100% of the energy. Fabrication techniques such Replication, laser engraving, self-assembly can be used for fabrication depending on the material configuration used.

5. Conclusions

A brief review of engineered interface and its applications was given. The problem formulation and COSMOL simulation details are provided. The standard interface and engineered interface model are created to evaluate comparative transmission coefficient performance. The standard interface shows a transmission coefficient of 0.64 for water polymer interface. The engineered interface shows as high as 0.93. The increase in transmission coefficient can be exploited for improvement in ultrasonic medical and industrial imaging applications.

6. References

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