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MODELING IMPERMEABLE MEMBRANES AS ACOUSTIC FILTERS FOR BIOMEDICAL APLICATIONS

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Abstract— The main purpose of this research project was to explore a mathematical expression that could be used by medical device designers to appropriately select impermeable membranes to isolate acoustic transducers from water, dust, earwax or other foreign material. The sound transmission properties of various types of impermeable membranes were analytically evaluated and compared to experimental measurements. Computer simulations were also performed to estimate the effects of three key membrane parameters: thickness (h), density (ρ) and sound speed (c), on the membrane's overall acoustic response. Results indicated that membrane thickness and density affect sound transmission the most. Membrane sound speed had minimal effect on sound transmission.

Keywords— **Transmission coefficient, membrane, impermeable, sound propagation.**

I. INTRODUCTION

Medical devices that employ high-fidelity acoustic transducers, such as hearing aids, acoustic airway imaging systems and acoustical breathing tube monitors [1- 6], often require the use of impermeable or semi permeable membranes that prevent the entrance of foreign materials, such as earwax, water or dust, into the transducers. Blockages caused by the accumulation of such foreign materials may lead to sound distortion and attenuation, thus decreasing the performance of the device.

The main purpose of this project was to explore a mathematical expression that could be used by medical device designers to appropriately select impermeable membranes to be placed between an acoustic transducer and the propagating media, to avoid the entrance of water, dust and other foreign materials without affecting the transducer's acoustic response. The sound transmission properties of various types of impermeable membranes were evaluated analytically and compared to bench top measurements. Computer simulations were also performed to estimate the effects of three key membrane parameters: thickness (h), density (ρ) and sound speed (c), on the membrane's overall acoustic response.

II. ACOUSTIC PRINCIPLES

An acoustic wave undergoes a reflection every time it encounters a change in acoustic impedance. At any interface (x_0) between two different acoustic impedances the reflection and transmission coefficients at the boundary are given by [7]

$$R_{x_0} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{1}$$

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$$T_{x_0} = \frac{2Z_2}{Z_2 + Z_1} \tag{2}$$

where Z_1 and Z_2 are the acoustic impedances preceding and following the interface, respectively. If sound waves are traveling inside a rigid, lossless tube, the acoustic impedance is

$$Z = \frac{\rho c}{S} \tag{3}$$

where ρ and c are the density and sound speed of the medium, respectively, and S is the cross sectional area of the tube's lumen.

In the case when there is a section of different acoustic impedance that separates two acoustic media (see Figure 1), the reflection and transmission coefficients at the first boundary ($x=0$) are

$$R_{x_0} = \frac{(1 - Z_1/Z_3)\cos k_2 h + j(Z_2/Z_3 - Z_1/Z_2)\sin k_2 h}{(1 + Z_1/Z_3)\cos k_2 h + j(Z_2/Z_3 + Z_1/Z_2)\sin k_2 h} \tag{4}$$

$$T_{x_0} = \frac{2}{(1 + Z_1/Z_3)\cos k_2 h + j(Z_2/Z_3 + Z_1/Z_2)\sin k_2 h} \tag{5}$$

where Z_1, Z_2, and Z_3 are the acoustic impedances of media 1, 2, and 3, respectively, h is the thickness of medium 2, and k_2 is the wave number (ω/c) of the second medium [7-8]. Equation (5) was utilized to model the sound transmission properties of a uniform membrane of thickness h that was placed in an air-filled cylindrical tube. Assuming that sound signals that propagate through the membrane are complex and that the cross sectional areas are equal, equation (5) can be expressed as a function of radian frequency (ω), density (ρ_m), membrane thickness (h) and sound speed (c_m):

$$T_{x_0}(\omega, h, \rho_m, c_m) = \frac{2}{2\cos\frac{\omega h}{c_m} + j\left(\frac{\rho_m c_m}{\rho_0 c_0} + \frac{\rho_0 c_0}{\rho_m c_m}\right)\sin\frac{\omega h}{c_m}} \tag{6}$$

where ρ_0 and c_0 are the density and the sound speed of the air

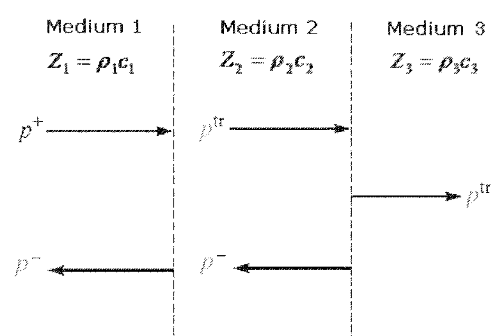


Fig. 1 Reflection and transmission of sound at normal incidence, when a section of different acoustic impedance lies between two media.

at both sides of the membrane, respectively. For the studies presented in this paper, equation 6 was used to model the membrane as an acoustic filter whose response depends on frequency and on the physical properties of the membrane and the surrounding air.

III. SYSTEM EVALUATION

A. Experimental setups.

Figure 2 depicts a schematic representation of the setup used to perform the acoustical measurements. The experimental setup consisted of one loudspeaker (Knowles ED-9457) and two microphones (Knowles EM-3046) mounted on a 0.5 in diameter plastic tube. A specialized fixture was created so that an elastic membrane could be placed across the tube's lumen. A more detailed representation of the location of acoustic transducers and of the membrane is shown in Figure 3. A computer was utilized for signal generation and analysis. Electrical signals generated at the computer were used to drive the loudspeaker. Signals recorded at the microphones were amplified (AC-coupled, 40 dB gain) and recorded using a data acquisition board (National Instruments PCI-MIO-16E-1). Custom LabView and MATLAB programs were employed for signal acquisition, analysis and display.

B. Methods.

Several types of membranes were tested using the experimental setup presented before. The physical properties and dimensions of the membranes are presented in Table 1.

Table 1. Physical properties and dimensions of the different membranes used for the experiments.

	Material	Thickness (mm)	Density (Kg/m^3)	Sound velocity (m/s)
1	Air	0	1.204	343
2	Latex	0.08	950	1050
3	Thick Latex	0.12	950	1050
4	Polypropylene	0.01	930	2698

Pressure pulses generated by the loudspeaker were recorded at both microphones in order to obtain the acoustic transfer characteristics $T_m(f)$ of each membrane, which was estimated using

$$T_m(f) = \frac{M_t(f)}{M_i(f)} \qquad (7)$$

where $M_t(f)$ and $M_i(f)$ are the spectra of the pressures recorded at the first and second microphones, respectively. For each membrane, the experimental acoustic transmission curves were compared to those predicted using equation (7).

IV. RESULTS

A sensitivity analysis was performed to gain insight into the effects that each of the three membrane parameters (thickness, density and sound speed) has on sound transmission across the membrane. The sensitivity analysis was carried out using equation (6) applied to the polypropylene membrane. Each parameter was varied from its nominal value by factors of 0.01, 0.1, 10 and 100.

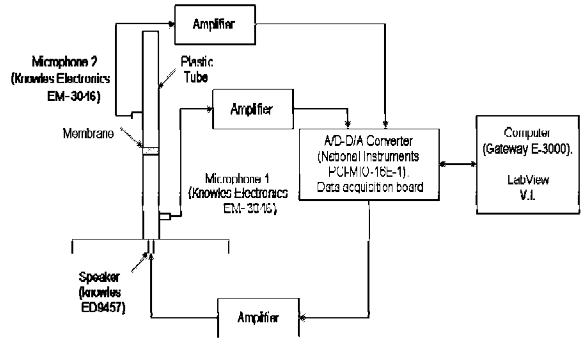


Fig.2 Schematic of the experimental setup.

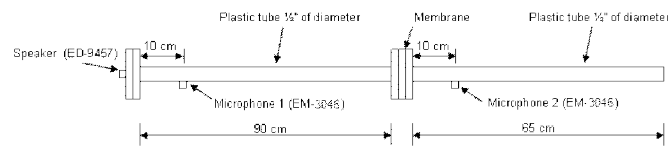


Fig. 3 Dimensions of the experimental setup.

Figures 4, 5 and 6 show frequency-dependant transmission coefficient curves for differents values of density, membrane thickness and sound speed respectively. It is important to note that when the magnitude of the transmission coefficient is unity (0dB), the membrane becomes acoustically transparent.

The theoretical and experimental frequency responses for the three membranes are shown in figures 7-a and 7-b, respectively. It can be noticed that there is a high degree of correlation between both plots. Figure 8-a shows the different incident pulses obtained in the experimental setup, as recorded by the microphone placed distally from the membrane. The shapes and relative amplitudes of these pulses correlate well to those obtained via computer simulations, and which are shown

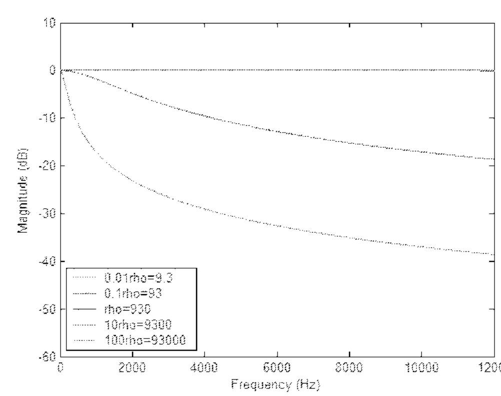


Fig.4 Theoretical transmission coefficient of a polypropylene membrane as a function of frequency, for multiple values of membrane density ρ.

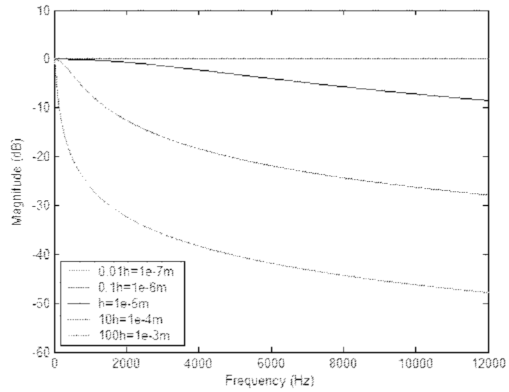


Fig. 5 Theoretical transmission coefficient of a polypropylene membrane as a function of frequency, for multiple values of membrane thickness *h*.

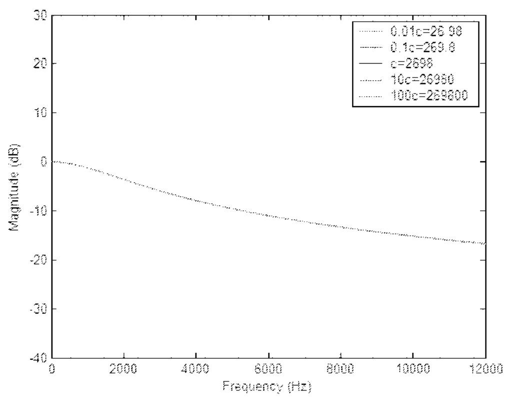


Fig. 6 Theoretical transmission coefficient of a polypropylene membrane as a function of frequency, for multiple values of membrane sound speed *c*.

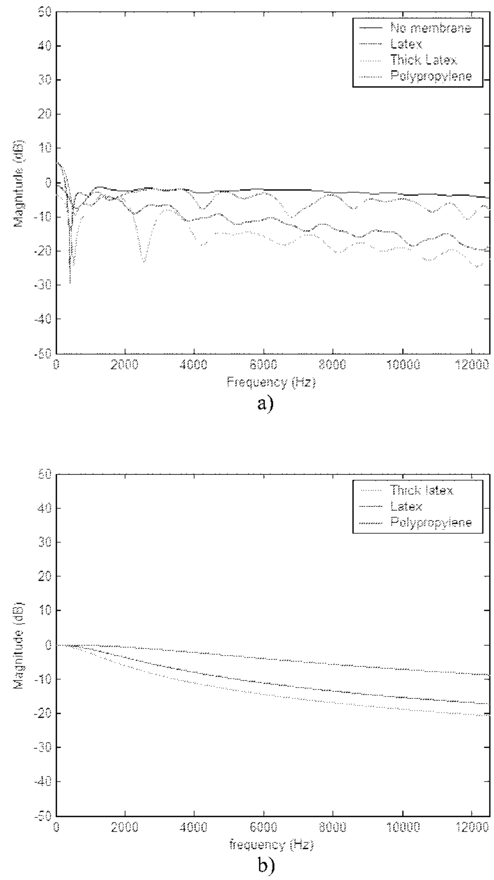


Fig. 7 Transmission coefficient filter of different membranes, a) experimental results with differents membranes and no membrane, b) simulated results.

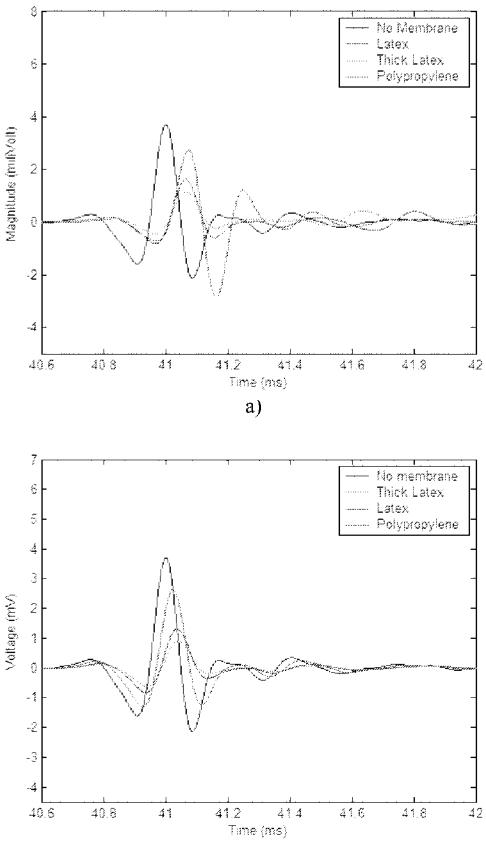
in Figure 8-b. The recorded pulses were delayed by approximately 0.12 ms, compared to the pulse received when no membrane was present in the system. This time delay is explained by the fact that the phase angle of the transmission coefficient was negative over the entire frequency range of operation (see Figure 9).

V. DISCUSSION

From the sensitivity analysis presented in this paper, we can conclude that membrane thickness and density are the parameters that affect sound transmission the most. As membrane thickness and density becomes smaller, the membrane behaves as it is acoustically transparent. Increased membrane thickness and density cause the membrane to reflect more sound, and therefore, diminishing sound transmission. Membrane sound speed had minimal effect on sound transmission.

If an impermeable membrane is considered to act as an acoustic filter, the overall membrane acoustic behavior is similar to that of a low-pass filter. This behavior is evident from the experimental and theoretical transmission coefficient curves shown in figures 7-a and 7-b. The magnitude of the transmission coefficients are close to unity (0dB) at low frequencies (f<1.5kHz), but then decrease as frequency increases. The polypropylene membrane exhibited the best acoustic response as compared to the latex membranes, since its acoustic response exhibited less dependency on sound frequency. This finding is expected since the polypropylene membrane was the thinnest of all (all had similar densities), and it has already been shown that thickness greatly affects sound propagation across the membrane.

There seemed to be a high degree of correlation between the transmission coefficients obtained experimentally and those obtained from simulations. Figures 7-a and 7-b show experimental and theoretical transmission coefficient curves for polypropylene and latex membranes. Both plots show approximately the same trends: the magnitude of the reflection coefficient decreases as frequency increases, and that the polypropylene membrane exhibits the best acoustic response, followed by the 80μm latex membrane. The 120μm thick latex membrane had the least desirable response.



a)

b)

Figure 8. This plot illustrates different acoustic pulse obtained for different membranes using the transmission coefficient filter. a) experimental results and b)simulated results.

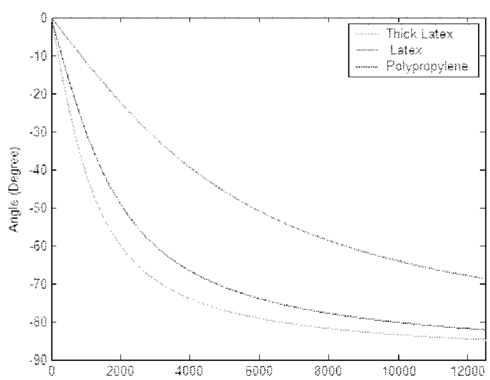


Fig. 9. Phase angles (in degrees) of different transmission coefficient filters.

VI. SUMMARY

Through this research we proved that the mathematical expression used to estimate the transmission coefficient yielded results that were similar to those obtained experimentally. Therefore, the transmission coefficient expression (6) is a good predictor of the sound transmission properties of impermeable membranes. When selecting impermeable membranes that isolate acoustic transducers but that do not adversely affect their acoustic response, the designer should opt for membranes that are thin (relative to the acoustic wavelength) and that have low density values.

VII. REFERENCES

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