Investigating the Effects of Physical Parameters on First and Second Reflected Waves in Air-Saturated Porous Media under Low-Frequency Ultrasound Excitation

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Abstract

This simulation study investigates the impact of a 20% variation in physical parameters, including porosity, tortuosity, viscous and thermal characteristic lengths, and two newly introduced viscous and thermal shape factor parameters, on the reflected waves at the first and second interfaces in air-saturated porous media in the low-frequency domain of ultrasound. The acoustic behavior of air-saturated porous media is modeled using the equivalent fluid theory and the Johnson-Allard model refined by Mustapha Sadouki. This study enhances our understanding of the underlying mechanisms governing acoustic wave propagation in porous media, providing valuable insights for optimizing ultrasound-based techniques in a range of applications, such as nondestructive testing, medical imaging, and noise pollution control.
2 II. Model

Acoustic propagation in porous materials is a complex phenomenon that involves the interaction of sound waves with fluid and solid components of the porous medium. When considering air-saturated porous materials with immobile solid skeletons, wave propagation is confined to the fluid, and this behavior is typically modeled using the equivalent fluid model [5,6], which is a particular case of Biot theory [7-13,14]. The two frequency response factors, the dynamic tortuosity of the medium (\(\tau\)) and the dynamic compressibility of air in the porous material (\(\beta\)), are used to account for structure-fluid interactions. The dynamic tortuosity is provided by Johnson et al [5,6], while the dynamic compressibility is given by Allard [7]. In the frequency domain, these factors are multiplied by the density and compressibility of the fluid.

At extremely low and high frequencies, the equations governing the acoustic behavior of the fluid simplify and the parameters involved are different. In the high-frequency range [7], this simplification occurs when the viscous and thermal skin thicknesses \(\tau(\delta/\delta'' \delta')' = \tau = \tau\) and \(\sigma(\delta/\delta'' \delta')' = \sigma = \sigma\) and \(\tau(\delta/\delta'' \delta')' = \tau = \tau\) and \(\sigma(\delta/\delta'' \delta')' = \sigma = \sigma\), respectively. Conversely, the impact of tortuosity is more pronounced on the 1st reflected signal than on the 2nd. Additionally, the sensitivity of tortuosity to the reflected waves by -40.98\% and -27.47\%, respectively. Notably, the impact of tortuosity is more significant as the tortuosity value is increased by +20\%, the amplitude of the 1st and 2nd reflected waves increases by +33.16\% and +10.82\%, respectively. Conversely, a decrease of -20\% in tortuosity results in a decrease in the amplitude of the 1st and 2nd reflected waves by -66.84\% and -65.06\%, respectively. Conversely, when the porosity decreases by -20\%, the amplitude of the 1st and 2nd reflected signals decreases by -66.84\% and -65.06\%, respectively.

Tortuosity and porosity are parameters that influence the behavior of waves in a porous medium. The tortuosity value is related to the length and complexity of paths that waves must follow, while porosity refers to the fraction of the medium that is empty space. Both parameters affect the reflection and transmission of waves, with tortuosity impacting the first reflection and porosity affecting both the first and second reflections.

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In the time domain, the reflected signal \(\psi(\delta/\delta'' \delta')' = \psi = \psi\) is obtained by taking the inverse Fourier transform of Eq. (5): \(\psi(\delta/\delta'' \delta')' = \psi = \psi\) and \(\psi(\delta/\delta'' \delta')' = \psi = \psi\). Figure 5 illustrates the sensitivity of tortuosity \(\tau\) on the 1st and 2nd reflected waves, for an excitation pulse of frequency 50 kHz. The initial tortuosity value is increased by +20\%, the amplitude of the 1st and 2nd reflected waves increases by +33.16\% and 10.82\%, respectively. Conversely, a decrease of -20\% in tortuosity results in a decrease in the amplitude of the 1st and 2nd reflected waves by -40.98\% and -27.47\%, respectively. Notably, the impact of tortuosity is more pronounced on the 1st reflected signal than on the 2nd. Additionally, the sensitivity of tortuosity to the reflected signal increases with frequency, as detailed in Table 1.
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7 c) Effect of Viscous Characteristic Length $\eta$ on the

8 Reflected Waves

The impact of varying the viscous characteristic length on the 1st and 2nd reflected waves at high frequency is shown in Figure 5. With an excitation frequency of 50 kHz, a +20% change in $\eta$ results in a -1.07% decrease in the amplitude of the first reflected wave and a 42.76% increase in the amplitude of the second reflected wave. Furthermore, as the frequency increases, the sensitivity of the viscous characteristic length decreases for the 1st reflected wave and increases for the 2nd reflected wave. Therefore, we can conclude that the viscous characteristic length has a relatively small influence on the 1st reflected wave at high frequency but a high sensitivity on the 2nd reflected wave. The sensitivity of the thermal characteristic length $\eta'$ on the two reflected waves at low ultrasonic frequency is shown in Figure 5 for a variation from +20% to -20% of its initial value. From Figure 6, we can see that for a frequency of 50 kHz, there is very little influence of the thermal characteristic length on the 1st reflected signal. An increase of +20% in $\eta'$ results in a 0.17% increase in the modulus of the 1st reflected signal, while a variation of -20% results in a -0.26% decrease in the amplitude of the 1st reflected signal. However, the second reflected wave is more sensitive than the first. For a variation of +20% of $\eta'$, the amplitude of the 2nd reflected wave increases by 3.29%. Moreover, according to Table 1, we observe that the sensitivity of the thermal characteristic length slightly decreases with frequency for the first reflection, while it increases for the second reflected wave. The sensitivity of the shape factor $\alpha$ on the 1st and 2nd reflected waves in the Low-Frequency Ultrasound regime is presented in Figure 7. According to this figure, a -20% variation of $\alpha$ results in a regression of -0.26% and -4.89% in the amplitude of the 1st and 2nd reflected waves, respectively. For a variation of +20% of $\alpha$, we observe a growth of +0.17% and 3.29% in the amplitude of the 1st and 2nd reflected waves. It can be concluded that the shape factor $\alpha$ has a weak influence on the first reflected wave but a strong sensitivity on the second wave in the low-frequency range of ultrasound. Moreover, the variation decreases for the first reflected wave and increases for the second wave as the frequency increases.

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10 Signal

To investigate the impact of varying the thermal shape factor $\alpha'$ on the 1st and 2nd high-frequency reflected waves, Figure 8 is presented. At an excitation frequency of 50 kHz, a +20% variation in $\alpha'/\alpha$ results in a +0.10% increase and a -1.91% attenuation in the amplitude of the 1st and 2nd reflected waves, respectively. This parameter exhibits a weak influence on the 1st reflected wave but a more significant effect on the 2nd reflected wave in the low-frequency ultrasound regime. Table 3 summarizes the effects of porosity, tortuosity, viscous and thermal characteristic lengths, as well as the two shape factors on the 1st and 2nd reflected waves in the low-frequency regime of ultrasound (50-120 kHz). Based on the results presented in Table 3 and Figures ??, we can classify the sensitivity of each parameter on the reflected signal in the order of decreasing influence as presented in Table 2.

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12 IV. Conclusion

In conclusion, this study investigated the influence of physical parameters on the reflected wave at the 1st and 2nd interface of rigid porous media in the low-frequency ultrasound regime. The results show that porosity and tortuosity are the most influential parameters affecting the two reflected signals. This influence varies proportionally with the frequency and inversely with the porosity for both the 1st and 2nd reflected waves. For the 1st reflected wave, the influence varies proportionally with the tortuosity and frequency, while for the 2nd reflected wave, it varies proportionally with the tortuosity and inversely with the frequency. However, the impact of porosity and tortuosity on the 1st reflected wave is greater than on the 2nd reflected wave. Moreover, the viscous characteristic length has a small effect on the 1st reflected wave but a substantial influence on the 2nd reflected wave, exceeding the impact of tortuosity. On the other hand, the shape factor has a minor impact on the 1st reflected wave and a significant sensitivity on the 2nd reflection. Concerning the thermal parameters, the thermal characteristic length and the thermal shape factor have a negligible impact on the 1st reflected wave, while the sensitivity of the thermal characteristic length on the 2nd reflected wave is considerable. The study’s strength is that it analyzed the two reflected waves separately and independently, which allows us to treat each wave individually. These results could have important implications for the design and optimization of ultrasound-based techniques in various applications such as medical imaging, non-destructive testing, and materials characterization. However, further research may be necessary to investigate the effect of these parameters in other frequency ranges and porous medium structures.
IV. CONCLUSION

Figure 1: P © 2023

Figure 2: Figure 1 :
Figure 3:

Figure 4: I
Figure 5: Figure 3 : Figure 4 : I

Figure 6: Figure 5 :
Figure 7: I

Figure 8: Figure 6:

\[ \text{R R} \% \text{ corresponding to a variation of } \pm 20\% \text{ of each physical parameter} \]

Figure 9: Table 1:
### IV. CONCLUSION

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Variations</th>
<th>50 kHz</th>
<th>120 kHz</th>
<th>50 kHz</th>
<th>120 kHz</th>
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<tr>
<td>Porosity ?</td>
<td>+20%</td>
<td>-66.84</td>
<td>80.26</td>
<td>-68.88</td>
<td>82.30</td>
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<tr>
<td></td>
<td>-20%</td>
<td>82.30</td>
<td>-68.88</td>
<td>80.26</td>
<td>-66.84</td>
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<tr>
<td>Tortuosity ? ?</td>
<td>+20%</td>
<td>33.16</td>
<td>-40.98</td>
<td>34.02</td>
<td>10.82</td>
</tr>
<tr>
<td></td>
<td>-20%</td>
<td>-42.10</td>
<td>34.02</td>
<td>10.82</td>
<td>-40.98</td>
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<td>Viscous characteristic length</td>
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<td>-1.07</td>
<td>-0.61</td>
<td>42.76</td>
<td>58.54</td>
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<td>(? (??m))</td>
<td>-20%</td>
<td>1.77</td>
<td>0.93</td>
<td>-44.86</td>
<td>-52.95</td>
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<tr>
<td>Ratio thermal-viscous</td>
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<td>0.17</td>
<td>0.11</td>
<td>3.29</td>
<td>4.63</td>
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<tr>
<td>characteristic lengths</td>
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<td>-0.26</td>
<td>-0.16</td>
<td>-4.89</td>
<td>-6.57</td>
</tr>
<tr>
<td>(?/?)</td>
<td>+20%</td>
<td>0.10</td>
<td>0.19</td>
<td>-11.91</td>
<td>-12.16</td>
</tr>
<tr>
<td>Viscous shape factor ?</td>
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<td>-0.97</td>
<td>-0.18</td>
<td>13.56</td>
<td>13.88</td>
</tr>
<tr>
<td>Ratio viscous-thermal</td>
<td>+20%</td>
<td>0.16</td>
<td>0.25</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>shape factors ?/?’</td>
<td>-20%</td>
<td>-0.25</td>
<td>-0.38</td>
<td>-0.52</td>
<td>-0.51</td>
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</table>

Figure 10: I

Figure 11: I

### Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Influence on the 1st reflected signal</th>
<th>Influence on the 2nd reflected signal</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>++++ +  ~~~~~~?</td>
<td>++++ +++  ~~~+</td>
</tr>
</tbody>
</table>

: Considerable
~: Weak

transmitted I

Figure 12: Table 2
Acknowledgment

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