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Research article

Measuring sound velocity based on acoustic resonance using multiple narrow band transducers

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ABSTRACT

The sound velocity in a medium is closely related to its material properties, including its composition, structure, density, pressure, and temperature. Various methods have been developed to determine the sound velocity through materials. Among them, a strategy based on ultrasound resonance frequency has been most widely used due to the simplicity. However, it requires a transducer with a wide bandwidth to cover enough resonance frequencies to perform the consequent calculations. In this paper, we develop a resonance method for measuring sound velocity, using multi-frequency narrow-band transducers breaking through the limitation of transducer bandwidth on the utilization of the resonance method. We use different transducers at different center frequencies and with different bandwidth to measure the sound velocity in 100-μm and 400-μm thick steel pieces. The measurement results of different combinations are in good agreement, verifying that the use of multi-frequency narrow-band transducer combinations. Given that most therapeutic transducers have a narrow bandwidth, this method can be used during intracranial ultrasound stimulation to optimize targeting by non-invasively measuring the sound velocity in the skull, especially at thinner locations.

1. Introduction

The sound velocity through a medium is closely related to its composition, structure, density, pressure, and temperature [1]. Material sound velocities are important for many applications. For example, the sound velocity in construction materials such as concrete or train parts measured using ultrasonic testing (UT) technology can be used to evaluate the strength of the materials for

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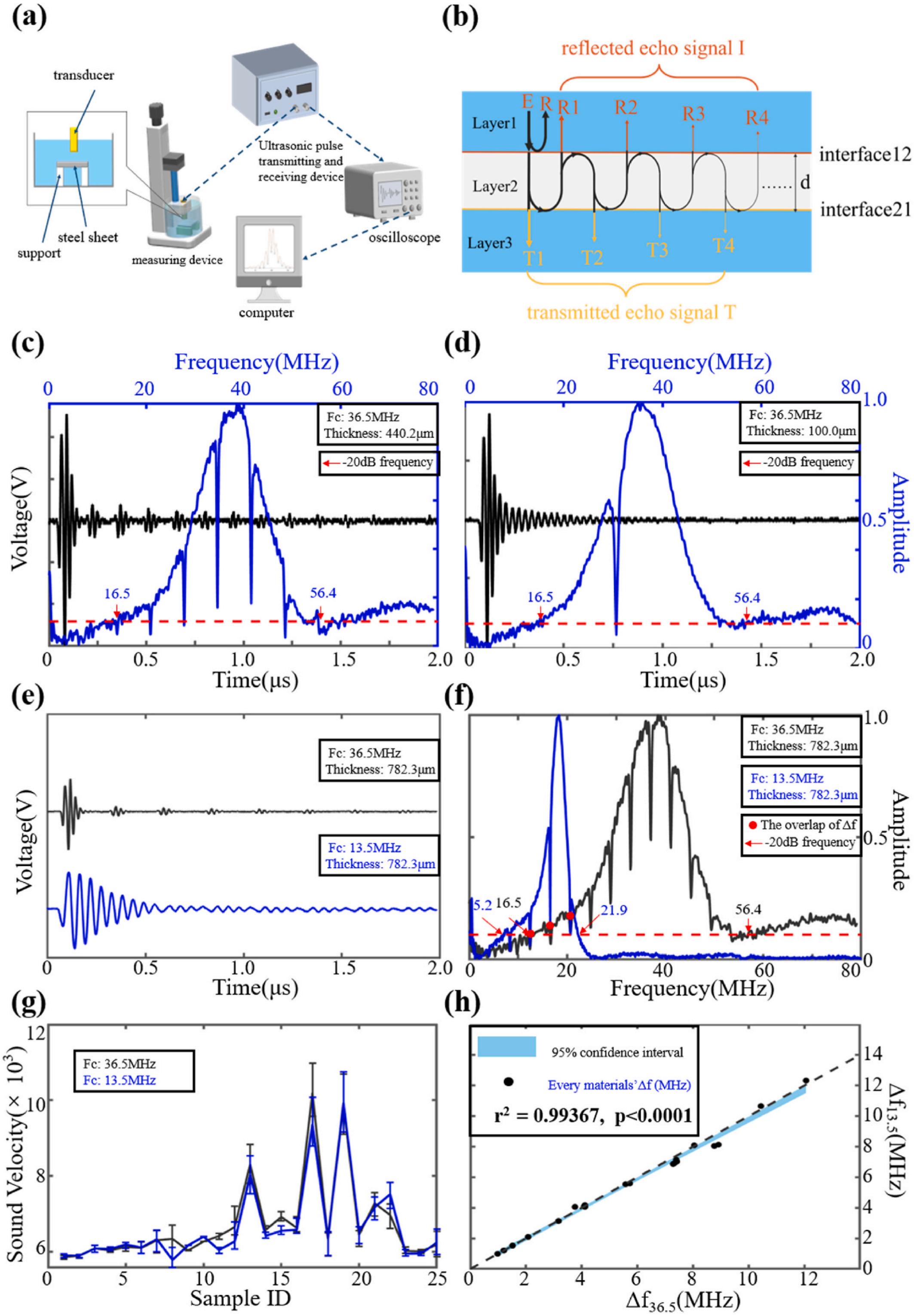

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Fig. 1. Resonance frequencies measured using a single transducer. (a) A sketch of the experimental setup for resonance frequency measurement. (b) Ultrasound resonance phenomenon from multiple reflections and transmissions in a three-layered system. (c–d) Echoes in layer1 reflected from the top and bottom surfaces of the steel piece detected using a transducer with a center frequency of 36.5 MHz and a −20 dB frequency band (16.5 MHz, 56.4 MHz) (black: time-domain echoes, blue: frequency-domain echoes). The x-axis shows the sampling points. The sampling rate was 4 GHz. The steel piece thicknesses used are 440.2 μm and 100.0 μm for (c) and (d), respectively. (e) Echoes in the time-domain and (f) The frequency-domain analysis from a 782.3 μm-thick steel piece detected using transducers with center frequencies at 9.2 MHz (blue) and 20.5 MHz (black). (g) Sound velocities of 25 steel pieces with various thicknesses from 100.0 μm to 3020.0 μm as function of the sample ID measured using two transducers with center frequencies at 13.5 MHz (blue) and 36.5 MHz (black). Bars Represents mean ± SEM. (h) Sound velocities measured by a transducer with center frequency at 13.5 MHz as a function of sound velocities measured by the transducer with center frequency at 36.5 MHz. The blue region notes the 95% confidence interval.

safety [2]. Another example is using sound velocities through the skull, estimated based on computed tomography (CT) images, to simulate the location of the ultrasound focus within the brain for therapeutic ultrasound treatments [3]. Errors in sound velocity estimations may affect the accuracy of phase correction of ultrasound transducer elements and transcranial ultrasound focusing [4]. Therefore, to improve the success rate of ultrasonic treatments, it is crucial that the sound velocities get accurately measured instead of estimated [5].

The sound velocity can be measured using the time of flight of an ultrasound pulse between the two boundaries of the sample of a known thickness. However, this method fails when the thickness of the sample is too small or the sound velocity is too high. Moreover, it is unfit to be used for this method in dispersive materials, because the shape of echoes gets changed as the sound waves propagate through the material [6]. This is the case with non-metallic materials, such as human skulls [4].

Guyott (1988) proposed the resonance method to measure the sound velocity in materials [6]. This resonance method has advantages: 1) it can be used to measure the sound velocity in dispersive materials, and 2) it effectively solves the situation where the ultrasonic echoes from the upper and lower boundaries of a thin sample in the time domain are indistinguishable [7]. Therefore, the resonance frequency method is suitable for real-time phase correction of transcranial focused ultrasound (tcFUS) [8], which solves the problem of uncertain changes in sound velocity due to increase in cranial temperature during ultrasound treatment [8,9]. However, for a given material, as its thickness decreases, the requirement for transducer bandwidth increases. The resonance method is not widely used for this reason, because it is difficult and costly to make a wide bandwidth transducer.

In this paper, we summarize the resonance-based method, which allows the prediction of the sound velocity using an ultrasound transducer with a frequency bandwidth of −20 dB; then, we present a multi-frequency narrow-band measurement method for measuring sound velocity. Finally, an easy-to-use tool is shared to help predict the range of sound velocity that can guide the selection of transducers.

2. Materials and methods

2.1. The experimental setup

The ultrasonic emission angle adjustment device (Fig. 1(a)) consists of a fixed support composed of steel and a two-dimensional micrometer adjustment moving disk. The transducer is fixed to the underside of the moving disk. Panametrics Olympus 5072 PR was used as the ultrasonic signal generator to excite the transducer to emit ultrasound vertically to the surface of the steel piece; all echoes received by the transducers and through Panametrics Olympus 5072 PR recorded on oscilloscope whose sampling rate is 4 GHz.

2.2. The manufacture of transducers

1) Upper surface echo from a very thick marble is used to characterize the ultrasonic transducer, it is a kind of general method in ultrasonic transducer device fabrication laboratory. The effective band width is the part of above 10% of the maximum amplitude, as known as −20 dB band width. The center frequency is average of the lower and upper band limits.
2) The transducers at center frequency of 36.5 MHz and 13.5 MHz are made by the following steps: PiezoCAD was used to simulate the thickness of piezoelectric (lithium niobate) and matching layer (silver epoxy) of needed transducers. Sand the lithium niobate to the desired thickness. A side of lithium niobate is connected to the silver epoxy by gold plating and then the silver epoxy is sanded to the desired thickness. Another side of lithium niobate is connected to the E-solder by gold plating. Connect lead wire and put on Housing (copper ring).
3) The transducers at center frequency of 9.2 MHz and 20.5 MHz are made by the following steps: piezoCAD was used to simulate the thickness of piezoelectric (lithium niobate) of needed transducers without matching layer. Sand the lithium niobate to the desired thickness. A side of lithium niobate is connected to the lead wire by gold plating. Using epoxy to encapsulate Housing (copper ring).

2.3. The alignment of transducers

The size of all used transducers is basically consistent. Some circle marks whose size is as the same as the size of transducers are made on the samples. When the transducer is perpendicular to the samples, the peak amplitude of the echo is maximum. Based on this method, we adjust the setup angle of the transducer through the optical leveler. Unfortunately, our spatial resolution is limited by the size of transducer.

3. Materials

The experimental materials are 304 steel pieces with a thickness range of 10 μm–3020 μm purchased from chenyan factory. The area to be measured was delineated with a marker for the center of each steel piece. The thickness of the area was measured 10 times by thickness gauge and averaged.

3.1. Signal process

For time-dimension, each experimental data was compensated zero in the end to make all data the same length which determinate the resolution of frequency-dimension. Then each data was processed by Fourier transform (FT) through MATLAB. In frequency-domain, through the data whose intense goes beyond −20 dB, the resource frequencies were obtained by the local minimum. The tool code can be downloaded from https://github.com/Alex-czh/Resonance_frequency_GUI.

4. Result

4.1. Resonance frequencies measurement is limited by transducer frequency band

The sound velocity of a 440.2 μm-thick steel piece is measured based on the resonance frequency using the experimental setup (Fig. 1(a)) by a transducer center frequency at 36.5 MHz with −20 dB frequency band of (16.5 MHz, 56.4 MHz). Driven by electrical signals from the ultrasonic signal generator, the transducer transmits ultrasonic waves vertically into the steel piece (Fig. 1(a)). The incident pulses underwent multiple reflections and transmission in the top and bottom interfaces (Fig. 1(b)). The echoes in time-domain (Fig. 1(c)) in the layer1 were detected by the transducer and the corresponding analysis in frequency-domain (Fig. 1(c)) was performed by Fourier transform of the time-domain signals. The sound velocity can be calculated based on six resonance frequencies in frequency-domain [6,8,10,11]. This calculation can be derived using the angular spectrum method as documented in the Supplementary.

The Δf measured by a transducer using the resonance method needs to satisfy the following condition:

$$f_L < n\Delta f < (n+1)\Delta f < f_H \tag{1}$$

f_L and f_H are the upper and lower frequency limits respectively of the frequency band. $n\Delta f$ is the *n*th resonance frequency. *n* is a positive integer.

$$\frac{f_L}{n} < \Delta f < \frac{f_H}{n+1} \tag{2}$$

The existence of the above relation must satisfy:

$$\frac{f_L}{n} < \frac{f_H}{n+1} \tag{3}$$

so:

$$n > \frac{1}{\frac{f_H}{f_L} - 1} \tag{4}$$

The range of measurable Δf given by a transducer whose −20 dB frequency band is known can be calculated by equations (1)–(4). The measurable range of sound velocity of the sample by single transducer is limited. Only one resonance frequency was obtained for a 100.0 μm-thick steel piece by using the same transducer (Fig. 1(d)). The sound velocity of the steel piece cannot be calculated based on the measured resonance frequency.

On the other hand, each transducer has different directional and frequency characteristics. Echoes in time-domain (Fig. 1(e)) and the corresponding frequency-domain analysis (Fig. 1(f)) from a 782.3 μm-thick steel piece was detected and performed by transducers with center frequencies at 36.5 MHz (transducer A1) and 13.5 MHz (transducer A2). The difference between echoes in time-domain was significant in several aspects. 1) Directional characteristics determine the acoustic energy density transmitted and the range of spatial directional angles of acoustic energy received by the transducer. 2) Frequency characteristics determines some parameters of the transducer such as the transmitting power, the efficiency and the receiving sensitivity. These will lead to different reflected signal at different frequency. Fortunately, the frequency domain amplitude corresponding to the resonance frequency is locally minimal between the adjacent resonance frequencies, so the error in the resonance frequency due to the difference in frequency characteristics is small. The average Δf almost are equal as shown in (Fig. 1(f)). The sound velocities of 25 steel pieces with various thickness from 100.0 μm to 3020.0 μm were measured by two transducers with center frequency at 13.5 MHz and 36.5 MHz (Fig. 1(g)). It confirms that the difference of Δf obtained by using different transducers for the same material is negligible. The results of sound velocity of these two transducers are in good agreement (Fig. 1(h)). These results set solid foundation for developing our novel strategy to measure sound velocity by using multiple band transducers.

4.2. Sampling resonance frequency using multiple transducers with narrow frequency band

In order to better demonstrate the feasibility of using multiple narrow band transducers to measure the resonance frequencies, the possible conditions of using two transducers for measuring resonance frequencies were simulated. When the steel piece is so thin that all resonance frequencies are greater than the maximal upper frequency limits of −20 dB frequency bands, the resonance frequency cannot be sampled (Fig. 2(a)). Secondly, when the resonance frequencies and the −20 dB frequency bands of the transducers are interleaved, the resonance frequency cannot be determined either (Fig. 2(b)). Thirdly, when there is at least one resonance frequency is in a −20 dB frequency band of the transducers (Fig. 2(c), (d)) it is possible to calculate the sound velocity directly. The above conditions can be descripted by the following equation:

$$\Delta f \in CF\{f_i\} \tag{5}$$

CF{} is to calculate common factor and f_i is the ith measurable resonance frequency. Define $\Delta f' = HCF\{f_i\}$, where HCF{} is to calculate highest common factor,

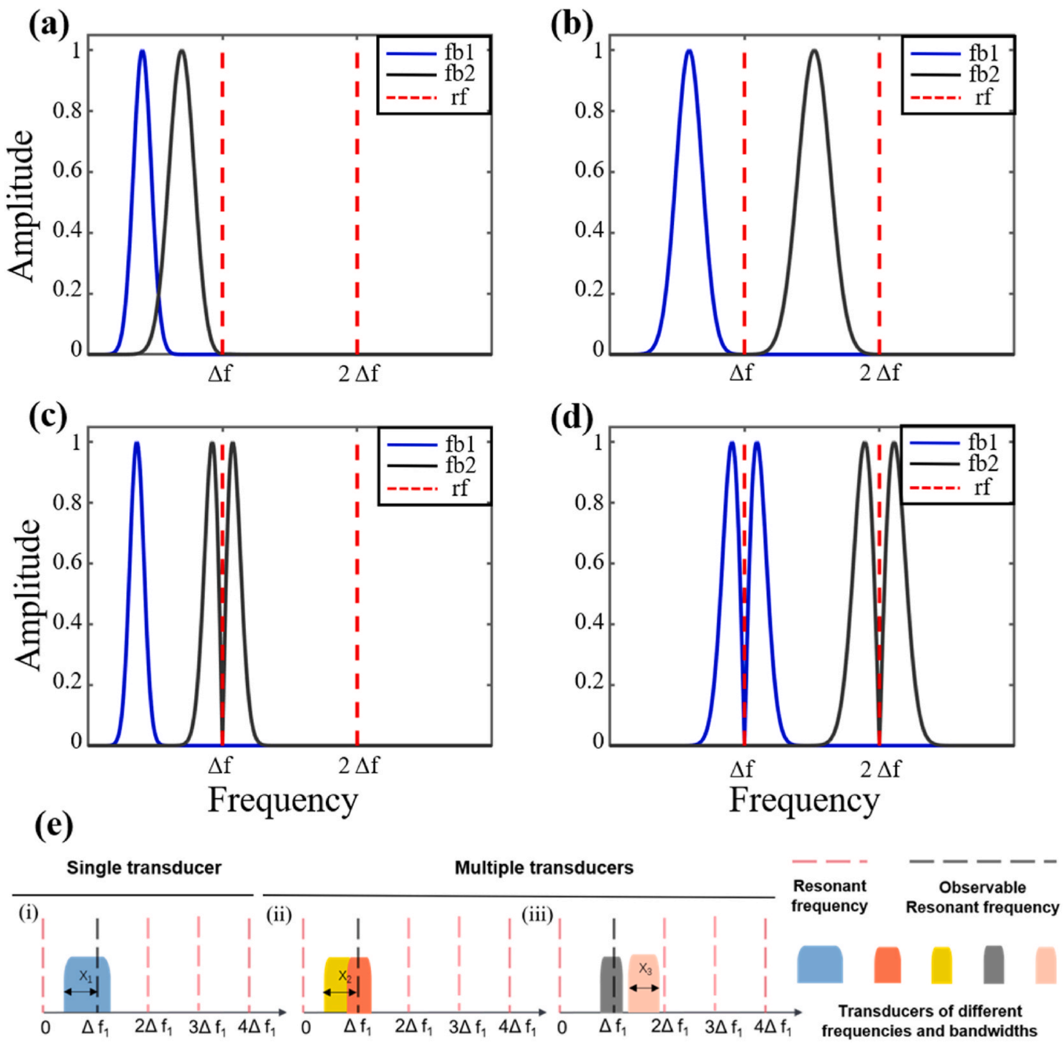

Fig. 2. Sampling the resonance frequency by two transducers. (a–b) Two possible situations which the resonance frequency of the sample is missing by the two transducers (a) All resonance frequencies are greater than the maximal upper frequency limits of −20 dB frequency bands. (b) Represents the resonance frequencies are interleaved with the −20 dB frequency bands of the two transducers. (c–d) Two possible situations that the resonance frequency of the sample is successfully sampled. (c) Represents a resonance frequency is in the range of a −20 dB frequency band. (d) Represents two resonance frequencies are in two −20 dB frequency bands. fb1: 20 dB frequency band of lower frequency transducer. fb2: 20 dB frequency band of higher frequency transducer. rf: resonance frequency (e) Illustration of how to measure Δf when (i) one resonance frequency is covered by the −20 dB frequency band of a transducer; (ii) one resonance frequency is covered by two −20 dB frequency bands of transducers where overlap; (iii) one resonance frequency is covered by a −20 dB frequency band of one of two transducers.

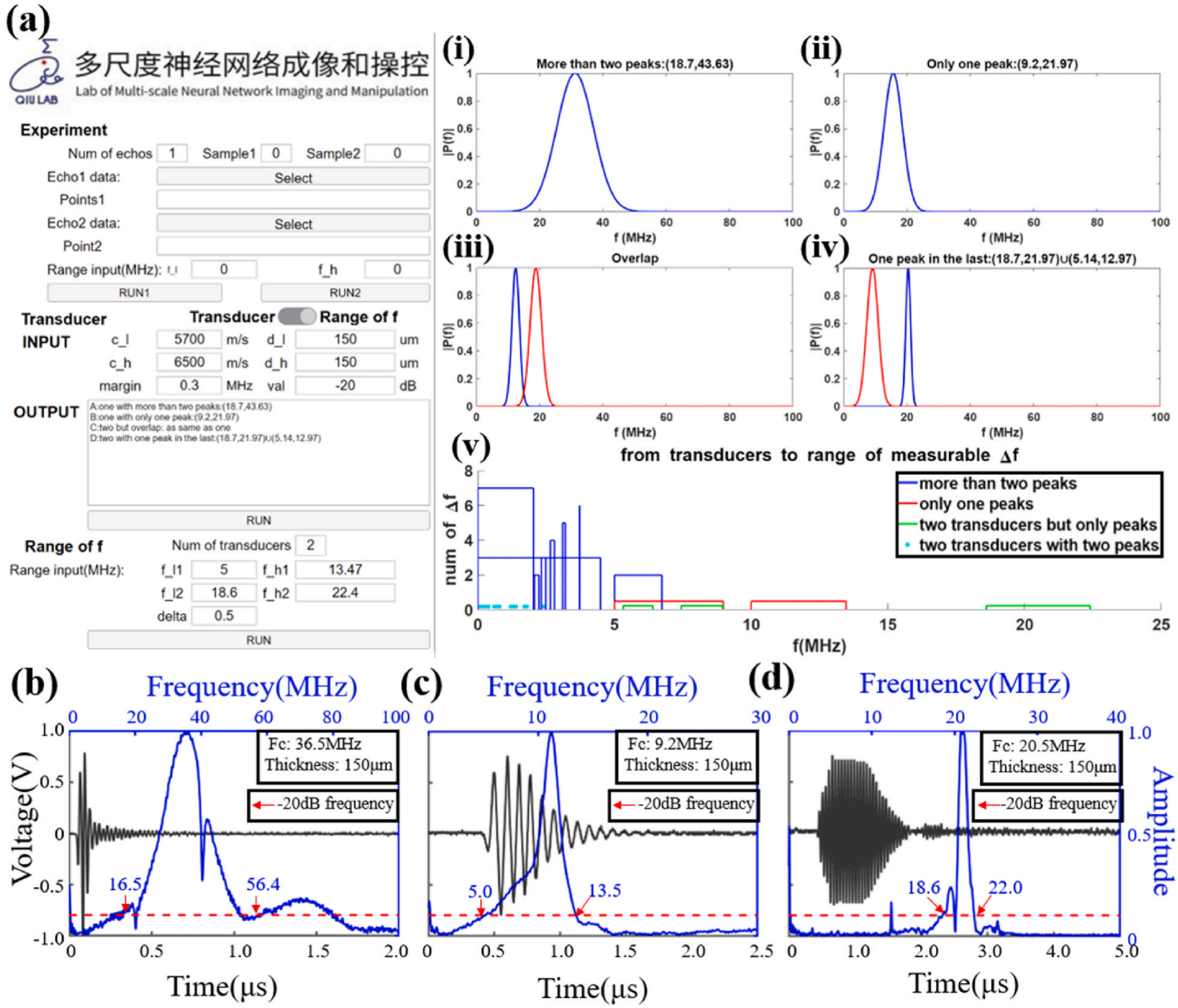

Fig. 3. Resonance frequency based method for sound velocity measurement using narrow bandwidth transducers. (a) A tool for guiding the transducer selection for ultrasound resonance measurement is developed by MATLAB. The part of experiment is used to analyze data of actual experiment. Allows us to analyze two sets of data simultaneously and offers us the spectrogram and phase change; The part of transducer is used to offer the useable groups of transducers for measurement according the rough range of thickness and sound velocity of material to be measured. (1) Input: cl: the lower sound velocity limits of the material; c_h: the higher sound velocity limits of the material; d_l: the lower thickness limits of the material; d_h: the higher thickness limits of the material; margin: the desired frequency band boundary margin for measurement; val: the desired value of dB of frequency band. (2) Output: parameters of transducers for different kinds groups are predicted when the rough ranges of sound velocity and thickness of materials are input; The part of Range of f is used to offer us the measurable of the range of Δf according to the parameters of transducers you input. Num of transducers: the number of transducers you will use; f_{l1}, f_{l2}: the lower frequency limits of the frequency band; f_{h1}, f_{h2}: the higher frequency limits of the frequency band; delta: discrete intervals due to Δf's continuity. A-D in output show that the results correspond to parameters of transducers and also are drawn as i - iv in Fig. 3(a) v shows that the range of measurable Δf is predicted when the frequency ranges of transducers are input. (b–d) Echoes in time-domain and frequency-domain, respectively, reflected from a 150.0 μm-thick steel piece with four transducers of different center frequencies (black: time-domain echoes, blue: frequency-domain echoes).

$$\Delta f \geq F \tag{6}$$

F was defined as the maximum value of all width of frequency bands unable to sample the resonance frequencies, the frequency difference between the resonance frequency and frequency limits of the frequency band.

Any value of $\frac{\Delta f'}{m}$ could be Δf because the resonance frequency is an equivariant series with Δf as an equal difference. All possibilities except Δf could be eliminate as follows:

$$\begin{cases} F > \dfrac{\Delta f'}{2} \\ f_L < \Delta f' < f_H \end{cases} \tag{7}$$

or

$$\begin{cases} F > \dfrac{\Delta f'}{m} \\ f_L < \dfrac{\Delta f'}{k} < f_H \ (k = 2, 3, \ldots, m-1) \end{cases} \tag{8}$$

m is a positive integer.

In short, a transducer can also measure large Δf when only one resonance frequency is obtained in the frequency band with the following condition hold:

$$2f_L < \Delta f < f_H \tag{9}$$

or

$$f_L < \Delta f < \frac{2f_H}{3} \tag{10}$$

Multiple transducers whose frequency bands overlap can be seen as one. The detailed derivation of equation is in the Supplement.

Based on our analysis, there are three possibilities to measure the sound velocity of a sample using narrow frequency band transducers. (1) When the x1 is greater than one half of the resonance frequency (equation (9) or (10)), the Δf can be obtained based on a resonance frequency by using single narrow frequency band transducer (i in Fig. 2(e)). (2) Two transducers whose frequency bands overlap can be treated as a wide frequency band transducer (ii in Fig. 2(e)). And the sound velocity can be measured based on consecutive resonance frequencies or a resonance frequency. (3) When the lower frequency transducer obtained the first resonance frequency and the frequency band of higher frequency transducer is greater than one half of the resonance frequency (equation (7)), the sound velocity can be obtained by these transducers without frequency bands overlap. For another situation, when the lower frequency transducer obtained the first resonance frequency, the frequency band of the higher frequency transducer is greater than one in m of resonance frequency and all other who are larger than the bandwidth of the higher frequency transducer are included in this frequency band (equation (8)), the sound velocity can be obtained by these transducers without frequency bands overlap (iii in Fig. 2 (e)).

4.2.1. *Experimental procedures*

The specific procedures for measuring sound velocity of a sample when there are estimations on sound velocity and the thickness are as follows.

1. Calculate the range of Δf based on the range of sound velocity and thickness.
2. Measure the (f_L, f_H) (−20 dB frequency band) of the existing transducers.
3. Determine whether there are transducers whose frequency bands overlap. If so, these transducers can be considered as one.
4. Measure Δf

1) Determine whether Δf, f_L and f_H satisfy equations (2) and (4). If so, the consecutive resonance frequencies of the sample can be obtained by the transducer and the sound velocity can be calculated directly.
2) Determine whether Δf, f_L and f_H satisfy equations 9 and 10. If so, a resonance frequency can be obtained by the transducer and the value of this resonance frequency is equal to the Δf.
3) If none of the above is true, add a transducer to ensure that the resonance frequency is obtained according to equations (5)–(8). The value of the only one resonance frequency is equal to the Δf. And the value of the common ratio of resonance frequencies is equal to the Δf if there are greater than or two resonance frequencies in different frequency bands.
4) Add a transducer if the Δf cannot be determined by existing two transducers. Using the same measurement method as in step 3) to determine the Δf.

5. Calculate sound velocity of the material based on the Δf.

4.3. *A user-friendly tool for guiding resonance frequencies measurement*

4.3.1. *A tool for guiding the resonance frequency measurement*

To make it easy to use, a tool was designed by using MATLAB which can guide the selection of transducers with sound velocity and thickness estimations (i-iv in Fig. 3(a)) or a measurable Δf range of given transducers (v in Fig. 3(a)). For example, the sound velocity ranges from 5700 m/s to 6500 m/s was input. The frequency band of result i, which greater than or equal to two resonance frequencies were obtained by a transducer, was (18.7 MHz, 42.3 MHz). The frequency band of result ii, which only one resonance frequency was obtained by a transducer, was (9.2 MHz, 21.3 MHz). The frequency band of result iii, which only one resonance frequency was obtained by two transducers whose frequency bands were overlap, was (9.2 MHz, 21.3 MHz). The frequency bands of result iv, which only one resonance frequency was obtained by lower frequency transducer and there was no resonance frequency in frequency band of higher frequency transducer, were (5.1 MHz, 13.0 MHz) and (18.7 MHz, 22.0 MHz).

4.3.2. *Experimental sound velocity*

The range of sound velocity of a 150.0 μm-thick steel piece was from 5700 m/s to 6500 m/s. The sound velocity of it was measured by a transducer center frequency at 36.5 MHz and −20 dB frequency band of (16.5 MHz, 56.4 MHz). Only two resonance frequencies were obtained (Fig. 3(b)) and the sound velocity of the sample was 6075 m/s. Two transducers center frequency at 9.2 MHz and 20.5 MHz, −20 dB frequency band of (5.0 MHz, 13.5 MHz) and (18.6 MHz, 22.4 MHz) measured the sound velocity of the sample. There was no resonance frequency in the frequency band of lower frequency transducer (Fig. 3(c)) and a resonance frequency in the frequency band of higher frequency transducer (Fig. 3(d)). One half of the resonance frequency was obtained in the range of lower frequency band and there was no minimum. One third of the frequency was smaller than the width of the lower frequency band. Therefore, the value of the resonance frequency was determined to be equal to the Δf and the sound velocity of the sample was 6030 m/s. These data were listed in Table 1.

The requirements of the −20 dB bandwidth of the multiple transducers method significantly decrease. t_B was to include both an odd multiple of one half of the resonance frequency in t_C and a width greater than one third of the resonance frequency to exclude all possibilities except Δf. Therefore, the −20 dB frequency band of the t_B can also be (26.5 MHz, 34.5 MHz). There is excellent agreement between the two methods and the maximum error of sound velocity between them being under 0.5%. We also measure the sound velocity of zinc and the results in supplement.

5. Discussion

Firstly, we have developed a complete and systematic theory to expand and improve resonance frequency based method for determination of sound velocities using multiple narrow band transducers. Secondly, we have developed a tool to help us to fully take advantage of our theory conveniently. Thirdly, to verify the accuracy and correctness of our theory and tool, we measured sound velocity of 304 steel pieces with thickness of 150.0 μm and 453.3 μm. From the results, it confirms our methods and the maximum error is less than 0.5%, which illustrates that our theory and tool are reliable and convenient.

Traditionally, people use the different time of reflected echoes to obtain the sound velocity. However, this method will loss effect when all echoes are overlapped as shown in Fig. 1(e) (transducer A2). In time-domain the transducer A2 has a longer signal than which obtained by the transducer A1 because of its smaller bandwidth. The echoes are overlapped leading to the failure of time-of-flight method. As shown in Fig. 1(f), in frequency-domain, the transducer A2 certainly has a narrow bandwidth. Obviously, the wider bandwidth it has, the more resonance frequency the transducer can get. Unfortunately, the wide bandwidth transducer is difficult to make especially in low frequency range in ultrasound treatment applications. The resonance method is limited by the transducer's frequency bands. There is no resonance frequency arising in a shallow frequency band and the method will also lose effect. Therefore, we developed a multi-transducers method to overcome this problem. In our experiment, we found the bandwidth requirement from 35.2% to 8.5% and 3.8% from Table 1; In addition, our tool have offered many multi-transducer combinations, all can be used for our experiment based on that we have input the rough thickness and sound velocity, and we can choose a scheme which is the most suitable for us, such as the transducers we keep.

Our method, as same as other traditional methods, is still ineffective for materials with very high ultrasonic attenuation because it is difficult to obtain the echo from the lower surface of materials.

There are several limitations for this paper, all the measurements were done in a plane steal piece, the feasibility of this method applied in other conditions need to be tested in the future. The ultrasonic signal needs to be incident vertically to ensure the accuracy of the measurement results for current application. These issues need to be cleared for applying our method in measuring sound velocities in skulls [8]. We have applied this method to ultrasonic arrays and the detailed results are in the supplement.

6. Conclusion

This paper introduces a multi-transducers theory and a tool, which have less limits for transducers and offer us more choices to determine sound velocity. It can be applied to improve the accuracy of phase correction in ultrasonic neuromodulation, transcranial focused ablation and opening of the blood-brain barrier.

Author contribution statement

Na Li: conceived and designed the experiments; performed the experiments; wrote the paper.
Zihao Chen: conceived and designed the experiments; analyzed and interpreted the data; wrote the paper.
Jiejun Zhu: analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.
Mi Hyun Choi: analyzed and interpreted the data; wrote the paper.
Jin Yang: contributed reagents, materials, analysis tools or data; wrote the paper.
Zhen Yuan: contributed reagents, materials, analysis tools or data; wrote the paper.
Lei Sun: analyzed and interpreted the data; wrote the paper.
Chunlong Fei: conceived and designed the experiments; analyzed and interpreted the data; wrote the paper.
Zhihai Qiu: conceived and designed the experiments; analyzed and interpreted the data; wrote the paper.

Table 1
Comparison of the method of using multiple narrow bandwidth transducers when the traditional methods as the benchmark.

	1		2	
	t_A (MHz)		t_C (MHz)	t_B (MHz)
(f_L, f_H) (tool)	(18.7, 42.3)		(5.1, 13.0)	(18.7, 22.0)
(f_L, f_H) (experiment)	(16.5, 56.4)		(5.0, 13.5)	(18.6, 22.4)
f_c	36.5		9.3	20.5
Bandwidth (−20 dB)	39.9		8.5	3.8
f_n	20.2	40.4	None	20.1
Δf	20.2		20.1	
c (m/s)	6060		6030	

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Data availability statement

Data associated with this study has been deposited at https://github.com/Alex-czh/Resonance_frequency_GUI.

Declaration of interest's statement

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e14227.

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Further reading

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