Technique to compensate for unknown laminate transmission loss in phantom attenuation measurements

Karthik Nagabhushana
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, IL, USA
kjn3@illinois.edu

William D. O'Brien, Jr.
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, IL, USA
wdo@uiuc.edu

Aiguo Han
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, IL, USA
han51@illinois.edu

***Abstract*—It is important to accurately calibrate the acoustic parameters of reference phantoms used in quantitative ultrasound (QUS) applications. However, laminate membranes used on the exterior of the phantoms complicate the attenuation coefficient (AC) measurements by introducing transmission loss. The existing through-transmission method addresses this issue by characterizing additional and separate membrane and phantom material specimens to estimate the membrane transmission loss. An alternative and simpler method is proposed, that uses a single phantom to simultaneously measure the membrane transmission loss and phantom AC. This is achieved using a single-element transducer in a broadband pulse-echo setup in three steps. Firstly, signal loss due to phantom insertion (insertion loss), composed of phantom attenuation and membrane transmission loss, is measured. Secondly, the membrane reflection coefficient is measured by comparing the echo from membrane surface to the echo from of a well-studied surface such as Plexiglas. Furthermore, the measured membrane reflection coefficient is compared with the theoretical membrane reflection coefficient to estimate the unknown acoustic parameters of the membrane and phantom material. Finally, these parameters are used in estimating the membrane transmission loss, which, in turn, is used to estimate the phantom AC from the insertion loss obtained in the first step.**

Two phantoms were used to validate the proposed method. AC of both phantoms were measured using the existing method, yielding a range of 0.5-1.2 dB/cm-MHz over 1.6-6.4 MHz. The AC estimates acquired using the proposed method showed good agreement with the existing method. Between the two methods, a root mean square AC difference of 0.006 dB/cm-MHz for the first phantom and 0.014 dB/cm-MHz for the second phantom was observed.

Keywords—quantitative ultrasound, reference phantom, attenuation measurement, transmission coefficient

I. Introduction

Phantoms with tissue mimicking material (TMM) are widely used to test and validate general ultrasound (US) imaging systems. They have added significance in quantitative ultrasound (QUS) applications, where they are used as references in removing the diffraction effects of the transducer array [1]. This reference phantom technique demands accurate calibration of phantom acoustic properties such as attenuation coefficient (AC), backscatter coefficient (BSC) and sound speed. Typically, the phantoms are lined with protective thin membranes on their external surface that complicate this calibration. Specifically, the transmission loss due to the membrane is nonnegligible and can introduce errors in the through-transmission phantom AC measurement if the transmission loss is not properly compensated for. The existing through-transmission methods [2][3] compensate the membrane transmission loss by characterizing acoustic parameters of separate membrane and phantom material samples. However, this additional step complicates the calibration process since separate membrane and phantom material samples are not always freely available. Therefore, a new and simpler method is proposed that simultaneously estimates membrane transmission coefficient and phantom AC using a single phantom. Additionally, the paper validates the proposed method with respect to the existing method through phantom experiments.

II. Membrane Pressure Reflection and Transmission

The pressure reflection and transmission coefficients for a thin membrane sandwiched between two media, as shown in Figure 1, is well studied [4].

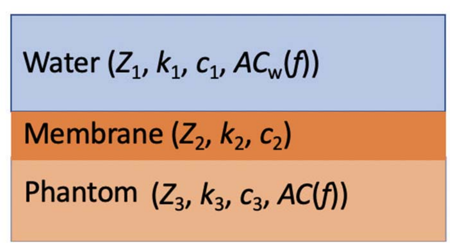

Fig. 1. A thin phantom membrane sandwiched between water and phantom material. For a given medium, Z_i indicates the acoustic impedance, k_i indicates the wavenumber, c_i represents the sound speed, and $AC_w(f)$ and $AC(f)$ represent the AC (dB/cm-MHz) of water and the phantom material, respectively. L is the membrane thickness which is typically much smaller than the phantom thickness.

For a planar pressure wave traveling through the water-membrane-phantom interface, reflection coefficient (R_1) and transmission coefficient (T_1) are given by (1) and (2), respectively.

NIH Support: R01CA226528, R01DK106419, R01HD089935.

$$R_1(f) = \frac{(Z_3-Z_1)Z_2\cos(k_2L)+j(Z_2^2-Z_3Z_1)\sin(k_2L)}{(Z_3+Z_1)Z_2\cos(k_2L)+j(Z_2^2+Z_3Z_1)\sin(k_2L)} \quad (1)$$

$$T_1(f) = \frac{2\,Z_3Z_2}{(Z_3+Z_1)Z_2\cos(k_2L)+j(Z_2^2+Z_3Z_1)\sin(k_2L)} \quad (2)$$

Similarly, for a planar pressure wave traveling through the phantom-membrane-water interface, reflection coefficient (R_2) and transmission coefficient (T_2) are given by (3) and (4), respectively.

$$R_2(f) = \frac{(Z_1-Z_3)Z_2\cos(k_2L)+j(Z_2^2-Z_1Z_3)\sin(k_2L)}{(Z_1+Z_3)Z_2\cos(k_2L)+j(Z_2^2+Z_1Z_3)\sin(k_2L)} \quad (3)$$

$$T_2(f) = \frac{2\,Z_1Z_2}{(Z_1+Z_3)Z_2\cos(k_2L)+j(Z_2^2+Z_1Z_3)\sin(k_2L)} \quad (4)$$

The acoustic impedance of water (Z_1) is calculated as a function of water temperature [5]. However, the other variables in (1)-(4) are unknown. Further, the argument in the trigonometric functions, k_2L, is given by

$$k_2L = \frac{2\pi f}{c_2}L \quad (5)$$

wherein c_2 is the sound speed in the membrane. Usually, the membrane is attenuative, which would be mathematically modeled by k_2L being a complex number. However, the attenuation provided by membrane is much smaller compared to the membrane transmission coefficient. Hence, the membrane is modeled as non-attenuative.

III. Methodology

A. Experimental setup

The phantom, whose attenuation coefficient needs to be estimated, consists of a cylindrical enclosure filled with tissue mimicking material lined with a membrane on the top and bottom surfaces. Measurements for estimating AC are performed with a single-element transducer in a broadband pulse-echo setup. A planar Plexiglas surface, immersed in degassed water, is placed at the planar focus of the transducer as shown in Setup 1 of Figure 2. The transducer is connected to a pulser-receiver system (UT340, UTEX Scientific Instruments Inc.). A digitizer (PDA14-200 A/D converter, Signatec Inc.) is used to digitize the received echoes. The planar focus of the transducer is determined iteratively by placing the Plexiglas at various distances and maximizing the echo amplitude from Plexiglas.

B. Phantom insertion loss measurement

The first step in estimating phantom attenuation is the phantom insertion loss measurement as shown in Figure 2. It involves capturing two individual echoes of the Plexiglas from Setup 1 and Setup 2. In Setup 1, the Plexiglas is placed at the planar focus of the transducer. The resulting echo (E_r), called reference echo, captures the transducer diffraction and frequency response [6].

Next, the phantom specimen is inserted between the transducer and the Plexiglas as shown in Setup 2. Although the phantom insertion can shift the planar focus, this shift is small due to the minor difference in sound speed of water and phantom material, and hence ignored. The received echo from Plexiglas (E_3), called attenuation echo, captures the round-trip insertion loss, consisting of phantom attenuation and membrane transmission loss, in addition to transducer diffraction and frequency response. The diffraction and frequency response of transducer are removed by dividing the two echo spectra, $E_3(f)$ and $E_r(f)$, leading to

$$\mathit{Insertion\ loss} = 20\log_{10}\left(\frac{|E_r(f)|}{|E_3(f)|}\right) \quad (6)$$
$$= 2\cdot f\cdot h\cdot[AC(f) - AC_w(f)] - 20log_{10}(|T_1T_2|^2)$$

where $AC(f)$ is the frequency-dependent phantom AC (dB/cm-MHz), f is the frequency in MHz and h is the phantom thickness in centimeter. The frequency-dependent AC of water, $AC_w(f)$, is determined by water temperature [7].

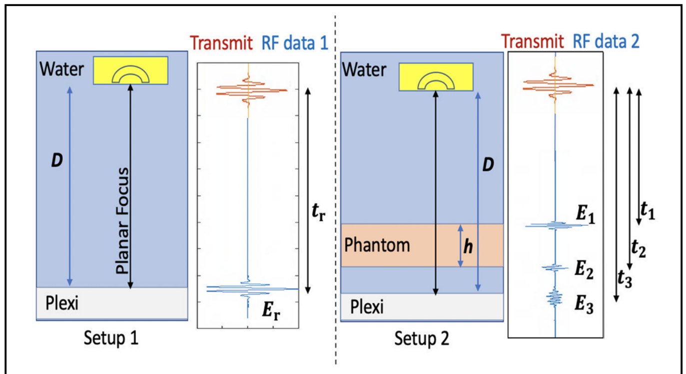

Fig. 2. Measuring phantom insertion loss

The goal is to obtain $AC(f)$ from (6), where h, T_1 and T_2 are unknown. These unknown parameters are estimated in subsequent steps (III-C & III-D) prior to the $AC(f)$ estimation (III-E).

C. Estimating membrane transmission coefficient

The existing method [2] estimates the membrane transmission coefficients by using (2) and (4), where the unknown parameters, phantom material impedance, membrane thickness, sound speed and impedance, are measured using additional independent specimens of the membrane and phantom material. Specifically, the phantom material impedance is determined by measuring its sound speed and density, the membrane thickness is measured by using a micrometer, the membrane sound speed is characterized using a narrowband through-transmission method, which, combined with a measurement of membrane density calculates the membrane impedance. Since all the acoustic parameters of water, membrane and phantom material have been determined, T_1 and T_2 can be estimated using (2) and (4).

On the contrary, the method proposed herein takes a simpler approach. The key idea is to fit (1) to the measured reflection coefficient, R_1, to estimate the unknown parameters Z_2, Z_3, L and c_2. Afterward, these estimated parameters are substituted in (2) and (4) to estimate T_1 and T_2 respectively.

1) Measuring membrane reflection coefficient: Two setups are involved in measuring the membrane reflection coefficient as shown in Figure 3. Setup 1 has a Plexiglas at the planar focus that generates the reference echo, E_r. Setup 3 has a membrane at the same planar focus that generates the membrane echo, E_m. Because the Plexiglas has a well-studied [8] reflection coefficient of 0.375, the membrane reflection coefficient, R_1, is derived by taking a ratio of the two echo spectra, $E_r(f)$ and $E_m(f)$, that is,

$$|R_1(f)| = 0.375 \cdot \frac{|E_m(f)|}{|E_r(f)|} \quad (7)$$

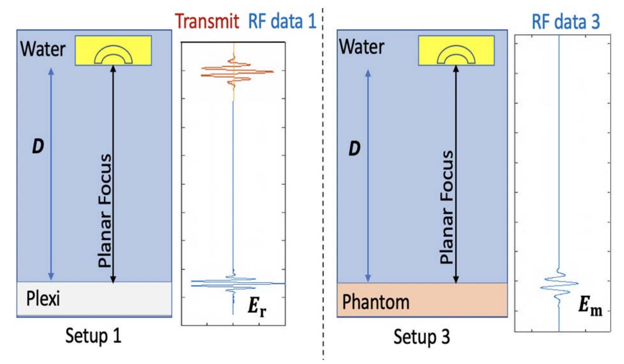

Fig. 3. Measuring membrane reflection coefficient

D. *Measuring phantom thickness*

The RF data from Setup 1 and 2 (Figure 2) is reused to measure the phantom thickness (h). RF data 1 from Setup 1 generates the reference echo (E_r) from the Plexiglas. RF data 2 in Setup 2, with phantom insertion, yields echoes from phantom surfaces (E_1 and E_2) in addition to echo from Plexi surface (E_3). The relative delays, $(t_r - t_1)$, $(t_r - t_2)$, and $(t_r - t_3)$, are determined by applying cross correlation and envelope detection to RF data 1 and 2.

Finally, the phantom thickness, h, is determined by,

$$h = \frac{c_1}{2} \cdot [(t_r - t_3) - (t_r - t_2) + (t_r - t_1)] \quad (8)$$

E. *Processing phantom attenuation coefficient*

By modifying (1), the phantom AC is expressed as

$$AC(f) = AC_w(f) + \cdots \quad (9)$$

$$\ldots + \frac{1}{2 \cdot h \cdot f}[Insertion\ Loss + 20\ log_{10}(|T_1 T_2|^2)]$$

where the insertion loss, membrane transmission coefficients, and membrane thickness are determined using the methods described in III-B, III-C, and III-D, respectively.

The phantom AC is calculated using (9) within a bandwidth determined by the intersection of the -10 dB bandwidth of the reference echo and the -10 dB bandwidth of the attenuation echo.

IV. Results and Discussion

Two phantoms (CIRS, Inc.), denoted as Phantom 1 and Phantom 2, were measured for attenuation coefficient using the proposed method and the existing through-transmission method. Table I summarizes the properties of transducers that were used to characterize the phantoms.

TABLE I. MEASURED PARAMETERS OF THE TRANSDUCERS USED

Part number	*Transmit center frequency (MHz)*	*Diameter (cm)*	*F#*
V382 (Panametrics Inc.)	4.3	1.27	3.63
V321 (Panametrics Inc.)	7.7	1.91	3.82

Comparison of the results from the proposed method and the existing method are outlined in Figure 4 and Table II. With a rms AC difference of less than 0.02 dB/cm-MHz over 1.6-6.4 MHz, a good agreement is observed between both the methods.

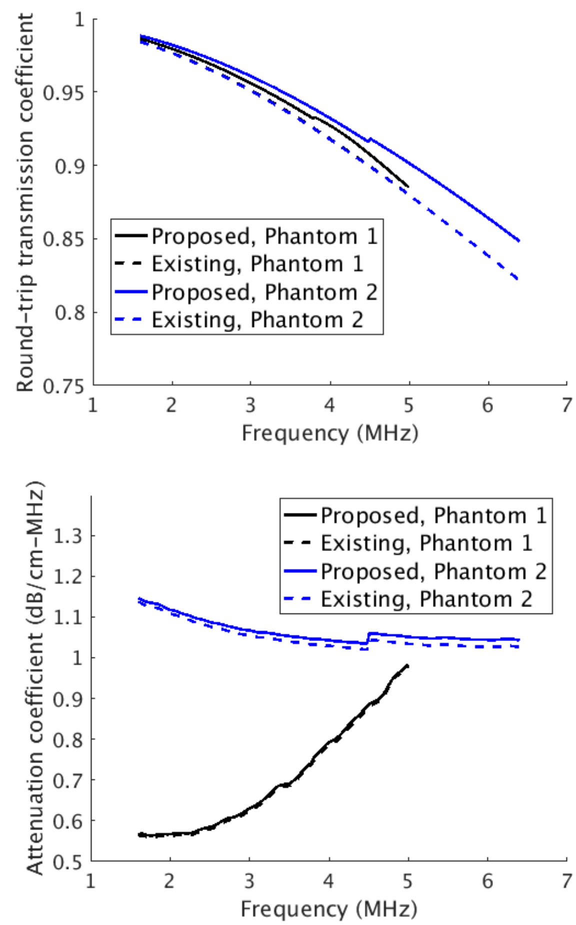

Fig. 4. (a) Round-trip transmission coefficient and (b) attenuation coefficient for the proposed method and the existing method plotted within each phantom's analysis bandwidth. The round-trip transmission coefficient captures the variation in received echo amplitude due to the membrane.

TABLE II. SUMMARY OF PHANTOM ATTENUATION COEFFICIENT ESTIMATION FOR THE PROPOSED METHOD. THE RMS DIFFERENCE IS CALCULATED WITH RESPECT TO THE EXISTING METHOD

Phantom	***h (cm)***	***Analysis bandwidth (MHz)***	***Attenuation coefficient range (dB/cm-MHz)***	***RMS difference (dB/cm-MHz)***
1	2.6	1.6 – 5.0	0.56 – 0.98	0.006
2	2.5	1.6 – 6.4	1.02 – 1.15	0.014

V. CONCLUSION

The proposed method to simultaneously measure phantom AC and membrane transmission loss is experimentally validated. Moreover, the proposed method requires a single phantom specimen without additional membrane samples and hence simplifies the reference phantom calibration methodology for QUS applications.

REFERENCES

[1] L. X. Yao, J. A. Zagzebski, and E. L. Madsen, "Backscatter coefficient measurements using a reference phantom to extract depth-dependent instrumentation factors," *Ultrasonic Imaging*, vol. 12, no. 1, pp. 58–70, 1990.

[2] K. A. Wear, T. A. Stiles, G. R. Frank, E. L. Madsen, F. Cheng, E. J. Feleppa, C. S. Hall, B. S. Kim, P. Lee, W. D. O. Brien, M. L. Oelze, B. I. Raju, K. K. Shung, T. A. Wilson, and J. R. Yuan, "Interlaboratory comparison of ultrasonic backscatter coefficient measurements from 2 to 9 MHz," *Journal of Ultrasound in Medicine*, vol. 24, no. 9, pp. 1235-1250, 2005.

[3] A. Han, M. P. Andre, J. W. Erdman, R. Loomba, C. B. Sirlin, and W. D. O'brien, "Repeatability and reproducibility of a clinically based QUS phantom study and methodologies," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 64, no. 1, pp. 218–231, 2017.

[4] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics*. New York: Wiley, 2000.

[5] J. Lubbers and R. Graaff, "A simple and accurate formula for the sound velocity in water," *Ultrasound in Medicine & Biology*, vol. 24, no. 7, pp. 1065–1068, 1998.

[6] X. Chen, D. Phillips, K. Q. Schwarz, J. G. Mottley, and K. J. Parker, "The measurement of backscatter coefficient from a broadband pulse-echo system: a new formulation," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, vol. 44, no. 2, pp. 515–525, 1997.

[7] F. H. Fisher and V. P. Simmons, "Sound absorption in sea water," *The Journal of the Acoustical Society of America*, vol. 62, no. 3, pp. 558–564, 1977.

[8] I. Y. Kuo, B. Hete, and K. K. Shung, "A novel method for the measurement of acoustic speed," *The Journal of the Acoustical Society of America*, vol. 88, no. 4, pp. 1679–1682, 1990.