Investigation of the Effect of Receiver Bandwidth on Nonlinearity Measurements in Biological Samples

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Abstract

Investigation of measurement of nonlinearity parameter of biological media has been done in many papers. Among the introduced methods for the measurement of B/A as the nonlinearity parameter in materials, there are two primary approaches, finite amplitude methods (FAM) and thermodynamic Methods (TM). These two fundamental procedures have been used in several references for determination of B/A. The nonlinearity parameter gives us useful information about the materials and their microstructure. Since finite amplitude methods use absolute amplitude of the second harmonic, the measurement depends on receiver transducer. The objective of this study was investigation of the transducer effect on measurement the nonlinearity parameter (B/A) in finite amplitude distortion method. We used several different transducers with different bandwidth. The results showed that the bandwidth of receiver transducer has significant effect on the accuracy of measurements. We introduced a solution to compensate transducer effect and improved the measurement repeatability and accuracy.

Keywords: Ultrasound, Nonlinearity, Harmonic, Bandwidth, Biological

1- Introduction

Non-destructive testing (NDT) is a testing and analysis method used by various industries to evaluate the properties of a material, structure, or system for identification of welding defects and discontinuities without destroying the original sample. There are various nondestructive testing methods like UT, RT, MT, ET, and ultrasonic testing is a powerful technique in identification of surface, subsurface and internal defects [1-6]. Pulsed echo ultrasonic techniques are widely used in the automotive, aerospace and railroad industries, where they are used to detect the presence of welding or manufacturing defects in steel and other homogeneous metallic alloys. Basically, this NDT method consists in transmitting an ultrasonic wave inside the material under test, and then acquiring the reflected echoes by the discontinuities or acoustic impedance mismatches that the beam encounters along its path. Through the measurement of the echo delay the depth of the defect is easily identified, as the sound velocity in the medium is constant and known. An infinitesimal amplitude sound wave loses energy at a rate proportional to distance from source and its amplitude. A large finite amplitude wave loses additional energy due to the nonlinearity properties of the material in which it propagates [7]. Nonlinearity has several effects on wave propagation including wave distortion, harmonic generation, subharmonic generation, acoustic streaming, and cavitation [8]. These phenomenon lead to increase the energy loss from the wave. It can be said that nonlinearity is a kind of attenuation in general or the attenuation that depends on the amplitude of the excitation voltage [9].

2- Theory

The instantaneous pressure within a sound field P can be represented by a Taylor series expansion in terms of the density change of the medium [10]:

\[ P = P_0 + A\left(\frac{\rho - \rho_0}{\rho_0}\right) + B\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \ldots \] (1)

Where:

A is a constant which may be weakly temperature dependent and is equal to: \[ A = \rho_0 \frac{\partial P}{\partial \rho} \rho_0 \]
B is a constant which may be weakly temperature dependent and is equal to: \( B = \rho_0^2 \frac{\partial^2 P}{\partial \rho^2} \rho_0 \)

\( P \) is the instantaneous pressure at \( x \),

\( P_0 \) is the equilibrium pressure at \( x \),

\( \rho \) is the instantaneous density of material and

\( \rho_0 \) is the average density of material.

The nonlinearity parameter is defined as the \( B/A \), the ratio of the second and first coefficient in equation (1). The harmonic generation is the dominant phenomenon during wave propagation and the wave distortion result from high harmonic generation in material. Investigation on measurement of nonlinearity parameter has been done in many papers. Among the introduced methods for the measurement of \( B/A \) as the nonlinearity parameter in materials, there are two primary approaches, finite amplitude methods (FAM) and thermodynamic Methods (TM). These two fundamental procedures have been used in several references for determination of \( B/A \) [11-15]. The nonlinearity parameter gives us useful information about the biological media properties and microstructure of solid materials [16].

In many papers it has been mentioned that for finite amplitude sound wave in a lossless medium (low acoustic attenuation) the second harmonic is generated during propagation in material and its amplitude at distance \( x \) from the source is given by [17]:

\[
P_2 = \frac{\omega x P_0^2}{4 \rho_0 C_0^3} \frac{B}{A} (1 + 2)
\]

Where:

\( \omega \) is the angular frequency of the wave

\( x \) is the distance from the source

\( P_2 \) is the amplitude of the second harmonic

\( P_0 \) is the amplitude of the wave at the source,

\( C_0 \) is the instantaneous density of material and

\( \frac{B}{A} \) is the nonlinearity parameter.

The main assumption in equation (2) is that the medium is lossless. In the other words, attenuation has been ignored. It can be seen that the amplitude of the second harmonic increases by increasing the source pressure or increasing the distance.

3- Finite Amplitude Insert-Substitution Method

For measurement of nonlinearity parameter in FAM, the absolute amplitude of the second harmonic and absolute amplitude of the generated wave by transmitter are required. The comparative methods like insert-substitution methods are suitable solution for eliminating the constant parameters like \( P_0 \). In this method we use a reference sample with known \( B/A \) as the reference (for example distilled water with \( B/A=5.2 \)) and another material sample which we want to measure its nonlinearity parameter. We measure the amplitude of the second harmonic of the reference and the amplitude of the second harmonic of the sample whose \( B/A \) is unknown. Generally, material sample and reference sample were formed in test cylinders with 25 \( \mu \)m thick Saran Wrap on each end. They have a diameter of 13 cm and the thickness of the test cylinders along the direction of wave propagation is 6 cm. They were filled with desired material and degassed distilled water, respectively. Each sample was placed between the receiver and the transmitter and it should be kept as close to the receiver as possible. But we should make sure that there is not any reverberation between sample and receiver in the acquired signal. By locating the test cylinders close to the receiver, then simplified equation can be represented as [14]:

\[
\frac{\left( \frac{B}{A} + 2 \right)_s}{\left( \frac{B}{A} + 2 \right)_r} = \left( \frac{P_{2s} L}{P_{2r} d T^2} - \frac{L}{d} + 1 \right) \left( \frac{\rho C^3}{\rho C^3} \right)_s
\]

(3)
\[ T'' = \frac{2\rho c_w}{(\rho c)_w + (\rho c)_s} \]  

(4)

\[ T'' = \frac{2\rho c_x}{(\rho c)_w + (\rho c)_s} \]  

(5)

Where:

- \( s \) represents the sample,
- \( r \) represents the reference,
- \( d \) is the thickness of the sample,
- \( l \) is the distance between the source and receiver,
- \( T'' \) is the transmission coefficient from water to sample and
- \( T' \) is the transmission coefficient from sample to the water

So, if we have the amplitude of the second harmonic corresponds to the reference and sample, then the nonlinearity parameter \((B/A)\) of the sample can be calculated by the mention equation. If medium has high attenuation, we can use corrected equation by considering the attenuation and diffraction effects.

### 4- Method

In order to investigate the effect of the receiver transducer bandwidth on second harmonic, we performed seven tests with different transmitter and receiver with distinct bandwidths. All tests have been done as through transmission and immersion mode and the main setup has been shown in Figure 1.

![Figure 1: Experimental setup](image)

The experimental setup consists of a water tank, a Tektronix model AFG 3251 function generator, an Agilent model DSO5012A oscilloscope and several pairs of unfocused transducers with various center frequencies. The function generator created a low amplitude sinusoidal voltage signal of 30 and 50 cycles at a specific frequency which was sent to a transmitting transducer (according to the Table 1). The receiver was located along the beam axis and 60 cm from the transmitter and, therefore, it was in the far field and gave us a good approximation of plane wave. Figure 2 shows the test cylinders. The received signal through the receiving transducer was displayed on the oscilloscope and a total of 1024 consecutive signals were averaged in the main memory of the scope and then sent to a PC via a GPIB interface for offline processing.
Table 1: Specifications of the transducers and excitation voltage

<table>
<thead>
<tr>
<th>Test</th>
<th>Transmitter</th>
<th>Receiver - Bandwidth</th>
<th>Distance L</th>
<th>Excitation Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>2.25 MHz</td>
<td>2.25 MHz, 1.2 – 3.4 MHz</td>
<td>60 cm</td>
<td>Burst, 2.25 MHz, 30 Cycles, Amplitude 5 V</td>
</tr>
<tr>
<td>Test 2</td>
<td>2.25 MHz</td>
<td>3.5 MHz, 1.8 – 5.2 MHz</td>
<td>60 cm</td>
<td>Burst, 2.25 MHz, 30 Cycles, Amplitude 5 V</td>
</tr>
<tr>
<td>Test 3</td>
<td>2.25 MHz</td>
<td>5 MHz, 2.5 – 7.5 MHz</td>
<td>60 cm</td>
<td>Burst, 2.25 MHz, 30 Cycles, Amplitude 5 V</td>
</tr>
<tr>
<td>Test 4</td>
<td>2.5 MHz</td>
<td>3.5 MHz, 1.8 – 5.2 MHz</td>
<td>60 cm</td>
<td>Burst, 2.5 MHz, 30 Cycles, Amplitude 5 V</td>
</tr>
<tr>
<td>Test 5</td>
<td>2.5 MHz</td>
<td>5 MHz, 2.5 – 7.5 MHz</td>
<td>60 cm</td>
<td>Burst, 2.5 MHz, 30 Cycles, Amplitude 5 V</td>
</tr>
<tr>
<td>Test 6</td>
<td>3 MHz</td>
<td>3.5 MHz, 1.8 – 5.2 MHz</td>
<td>60 cm</td>
<td>Burst, 3 MHz, 30 Cycles, Amplitude 5 V</td>
</tr>
<tr>
<td>Test 7</td>
<td>3 MHz</td>
<td>5 MHz, 2.5 – 7.5 MHz</td>
<td>60 cm</td>
<td>Burst, 3 MHz, 30 Cycles, Amplitude 5 V</td>
</tr>
<tr>
<td>Test 8</td>
<td>10 MHz</td>
<td>2.5 MHz, 1.3 – 3.7 MHz</td>
<td>60 cm</td>
<td>Burst, 10 MHz, 50 Cycles, Amplitude 5 V</td>
</tr>
</tbody>
</table>

Figure 3 Shows the received signal and its power spectrums for seven tests.
The fundamental frequency in all tests was in the range of receiver bandwidth. For investigation of the receiver response to excitation signal, which is out of its bandwidth, we did test 8. In this test a 10 MHz transducer and 2.25 MHz transducer were used as the transmitter and receiver, respectively. Error! Reference source not found. shows the power spectrum of the received signal in test 8.
5- Results and Discussion

FAM method has been highly recommended for measurement of nonlinearity. As it was mentioned, absolute amplitude of the fundamental wave at the source place and amplitude of the second harmonic at the receiver place is needed to calculate the nonlinearity parameter and measuring the absolute amplitude of the fundamental wave is very difficult and needs special calibration. The amplitude of the second harmonic in frequency spectrum is considered as the absolute amplitude of the second harmonic. The results of the tests 1-7 show that the amplitude of the second harmonic is not only medium dependent, and it depends on the receiver bandwidth. Furthermore, results show that the difference between fundamental and second harmonic are in range 14 – 19 dB.

The result of test 8 reveals that some part of the received signal is always converted to a wave with a frequency within the receiver bandwidth. In this test, some part of the generated wave by transmitter with frequency 10 MHz is converted to a wave with frequency 2.25 MHz and its amplitude is around -20 dB. That is, if both fundamental and second harmonics are not within the receiver bandwidth, the amplitude of the second harmonic in frequency spectrum is not suitable estimation of absolute amount and it is not reliable.

In order to compensate this effect, we proposed a special calibration method. In new proposed method, we use a reference signal in addition to the reference sample. By subtracting reference signal from obtained signal from the reference and sample, we can compensate the transducer effect.

We made another test to verify the performance of the proposed method. In last test, we made two test samples, one filled with Ethanol and other filled with distilled water as the reference. Phantom is an artificial sample which has structure, properties, and quantitative parameter like biological tissue. Since using real sample of biological tissue is not so easy, so, phantom is used instead. The base of the most phantoms that we use are made of Ethanol. I some papers the nonlinearity of the Ethanol has been reported 9.8. We measured the nonlinearity of the Ethanol based on (3) with various transducers. Moreover, we calculated the nonlinearity of Ethanol using calibration method. The obtained datum are represented in Table 2.

<table>
<thead>
<tr>
<th>Transmitter, Receiver</th>
<th>B/A without calibration method</th>
<th>B/A with calibration method</th>
<th>Reported B/A [14]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25 – 3.5 MHz</td>
<td>7.7</td>
<td>9.3</td>
<td></td>
</tr>
<tr>
<td>2.25 – 5 MHz</td>
<td>8.2</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>2.5 – 3.5 MHz</td>
<td>7.9</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>2.5 – 5 MHz</td>
<td>8.3</td>
<td>9.6</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 shows that calculated B/A using calibration method has better accuracy and repeatability.

6- Conclusions

The results showed that the receiver transducer and its bandwidth have a significant effect on the amplitude of the second harmonic. Thus, the amplitude of the second harmonic in frequency domain is not a reliable parameter to measure the absolute magnitude of the second harmonic due to medium’s nonlinearity effect. We used a reference signal to compensate this effect. This new proposed method can improve the accuracy and repeatability of the nonlinearity measurement.

Reference


