PSpice Modelling Diffraction Effects in Pulse Echo Ultrasonic System

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Abstract: The ultrasonic wave propagation is affected by absorption and diffraction. The transmission line is used to simulate the propagation media in PSpice model. To take into account diffraction effects we used the model proposed by J. Johansson [11]. A set of Gaussian beam is used to simulate the radiated field allowing us to deduce the exact diffraction loss. The diffraction loss is incorporated into the transmission line model using the attenuation parameter G. Measurements have been performed using a pulse echo system transmitting in water. The measurements show good agreement with the simulation results.

I. INTRODUCTION

Ultrasonic transducers play a key role in both generating and receiving ultrasonic waves and are widely used in many fields like as medical imaging and non-destructive evaluation systems. This success is due, essentially, to the merit of being non invasive and providing a good real-time diagnostic.

Modelling an ultrasonic pulse echo system is a real challenge because it involves electrical and mechanical properties. The transducer has been successfully modelled using equivalents circuits such as Mason’s [1], Redwood’s [2] or KLM one [3]. Many efforts have been made to implement these equivalent circuits on a computer analysis program such as PSpice [4-7]. Leach [8] proposed a model based on the controlled source technique to implement the transformer and the negative capacitance providing an elegant method to vary the transducer parameters.

The transmission line technique is used to model the propagation media in one-dimensional structure [9, 10]. This model is valid only in the case of plane wave propagation. Lossy transmission line consisting of the elements R, G, L and C per unit of length is used to take into account absorption and diffraction. Diffraction has been incorporated into PSpice model by Johansson [11] using the parameter G. However the diffraction losses are calculated in the far field zone using many approximations. The aim of this work is to include the exact diffraction losses into PSpice model. Diffraction losses are calculated for a circular source, using a superposition of Gaussian beams [12]. The results of Pspice simulation are compared to the propagation model and to the measurements results. Two transducers are studied: A disc source radiating at 2 MHz and a ring functioning at 4 MHz. The computed results show good agreement with the measurement indicating the validity of the model.

II. THEORY

A. Leach Model

The previous models (Mason, Redwood and KLM) represent some disadvantages like as the transformer primary-secondary ratio which varies according to frequency, thus difficult to implement on simulation tool and the negative capacitance which does not make sense physically. Unlike those models, Leach model propose a smart method to avoid these disadvantages by using controlled sources to ensure the transformation of energy between the electrical port and the acoustical one. The Leach model parameters are calculated from the electrical and acoustical characteristics of the transducer according to the following equations:

The piezoelectric field constant \([N/C]\)

\[ h = \frac{e}{\varepsilon_i} \]  

Where \(e\) is the piezoelectric constant \([C/m^2]\) and \(\varepsilon_i\) is the relative permittivity at constant deformation \([F]\).

The static capacitance of the transducer \([F]\)

\[ C_0 = \frac{e^2 A}{d} \]  

Where \(A\) is the cross section of the transducer and \(d\) his thickness.

The parameters of the lossy transmission line which models the acoustical port are given below:

\[ \text{length} = \frac{V_p}{2f_a} \]  

\[ L = \rho A \]  

\[ C = \frac{1}{V_p^2 \rho A} \]  

\[ R = \frac{Z_p}{(2h C_0 h)} \]  

Where \(V_p\) is the sound speed in the piezoelectric material, \(f_a\) is the anti-resonance frequency of the transducer, \(\rho\) is the transducer density and \(Z_p\) is the...
acoustical impedance of the propagating medium. Assuming that there are no losses due to diffraction in the piezoelectric material, \( G \) is taken null.

### B. Propagating medium

The propagating medium can be modelled as a lossy transmission line. The inductance \( L \) and the capacitance \( C \) control the sound speed in the medium according to the equation:

\[
V_p^2 = \frac{1}{CL}.
\]  

(7)

The resistance \( R \) can be used to model losses due to absorption:

\[
R = 2 \rho V_p A \alpha \cdot
\]  

(8)

Where \( \rho \) is the density, \( V_p \) is the sound speed and \( \alpha \) is the absorption coefficient in the propagating medium and \( A \) is the cross section of the transducer.

In our case, we are not interested to absorption losses, so we take \( R=0 \).

Diffraction losses are modelled by the parameter of conductance \( G \). Its value is calculated from the diffraction losses according to the equation below [11]:

\[
G = -\frac{2}{Z_0 z} \log(A_{\text{diff}}).
\]  

(9)

Where:
- \( Z_0 \): the mechanic impedance of the propagating medium.
- \( z \): the distance between the transmitter and the receiver.
- \( A_{\text{diff}} \): losses due to diffraction.

### C. Diffraction losses

We studied two different sources: A plane circular disc with radius \( a=5\text{mm} \) and it radiates ultrasound waves at 2MHz and a ring with internal radius \( b=7\text{mm} \) and external radius \( c=8.6\text{mm} \) functioning at 4MHz.

The sources radiate in the \( z \) direction at fundamental frequency \( f_0 \). The pressure sound wave generated by the source must satisfy the well known wave equation [13]. In the case of axisymmetric transducer, the solution can be written in terms of integrals over the Green’s function [14]:

\[
p(r,z) = \int_0^\infty p(r,0) g(r, \frac{z}{r}, 0) r' dr'.
\]  

(10)

The source function is expressed as a superposition of Gaussian beams [12]:

\[
p(r,0) = P_0 \sum_{n=1}^{10} A_n e^{-\frac{r^2}{B_n^2}}.
\]  

(11)

Where, \( P_0 \) is the source pressure level and \( A_n \) and \( B_n \) are Gaussian coefficients derived by Wen and Breazale [12].

The Green’s function, for the axisymmetric source, is written:

\[
g(r, \frac{z}{r}, z') = \frac{k_0}{i(z - z')} f_0 \left( \frac{k_0 r'}{z - z'} \right) e^{-\alpha r'} e^{i k_0 r'} e^{-\frac{\alpha (z-z')}{2}}.
\]  

(12)

Where, \( \alpha \) is the thermoviscous absorption at \( f_0 \), \( k_0=2 \pi f_0/c_0 \) is the wave number, \( c_0 \) is the local sound speed and \( J_0 \) is the zeroth-order Bessel function for the first kind.

The radiated pressure field is then expressed as:

\[
p(r,z) = P_0 e^{-\alpha z} \sum_{n=1}^{10} A_n F_n(z) e^{-\frac{B_n F_n(z)}{z}}.
\]  

(13)

\[
F_n(z) = \frac{1}{1 + \frac{z}{z_{\text{inw}}} \frac{k_0 a^2}{2 B_n}}.
\]  

(14)

The Fig. 1 shows the axial distributions for the disc and the ring. From this figure we can deduce that he focal point is located at \( z_0=6.6\text{cm} \) for the disc and at \( z_0=12.5\text{cm} \) for the ring. The last minimum delimiting the near field zone is situated at \( z_{\text{min}}=3.5\text{cm} \) for the disc and \( z_{\text{min}}=6\text{cm} \).

![Fig. 1: Axial distributions.](image)

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The radial distributions are given in Fig. 2 for the disc and Fig. 3 for the ring. The curves are plotted for \( z=z_0 \) and \( z=2 z_0 \). From these figures we can see that the beam width is larger for the disc that for the ring because the ring is more focalizing source. For the disc, the beam width is equal to 6mm at \( z_0 \) and almost 1cm at \( z=2z_0 \). For the ring we have 2.5 mm at \( z_0 \) and 5mm at \( 2z_0 \).

![Fig. 2: Beam pattern for the disc](image)

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The voltage measured by the transducer represents the average pressure over its surface and is expressed by the following equation:

\[ q(z) = \langle p(r, z) \rangle = S P_0 e^{-\alpha z} \sum_{m=1}^{10} \frac{A_m}{B_m} \left( 1 - e^{-R_m z} \right). \]  

(15)

Where, \( S \) is the active surface of the transducer.

Comparing the average pressure at point \( z \) on propagation axis to the average pressure at the source gives the diffraction losses:

\[ A_{\text{eff}} = \frac{q(z)}{q(0)}. \]  

(16)

**III. EXPERIMENTS**

The experimental setup is shown below (Fig. 4). The transducer is plunged in a tank containing the medium (liquid) to be studied and excited by the broad card TB 1000 of “Matec instruments” which permit to generate burst waves amplitudes which can reach 300V on a 50\( \Omega \) load and a frequency varying between 50KHz and 20MHz. In reception, the broad card TB 1000 offers the possibility to amplify the received echo until 70dB and proposes many combinations of high-pass and low-pass filters to improve the signal to noise ratio.

**IV. PSPICE SIMULATION**

SPICE (Simulation Program with Integrated Circuits Emphasis) is simulation tool of electric and electronic circuits developed by the University of California in 1975. P-SPICE, of SPICE family, is a very interesting tool for simulation since it makes it possible to conceive electronic circuits and to carry out various simulations (frequency analysis, transient analysis …). It makes it possible to simulate analogous and numerical circuits using discrete components and integrated circuits. The convivial interfaces which it offers make the simulation easy.

The ultrasonic experimental setup shown in the previous paragraph can be modelled, on PSpice, using the Leach model and a lossy transmission line to model the propagating medium. The result is shown in Fig. 5.

**V. RESULTS**

In this paragraph, we make a comparison between results obtained by analytical method and simulation on one hand and measurements on the other hand.

The ultrasonic waves generated by the transducer propagate through the medium (distilled water) and the reflected sound, from the interface water-air, is reconverted by the same transducer to electrical signal. Using this setup, we have measured the amplitude of the reflected signal for different distances between the transducer and the reflector.

![Fig. 4: Experimental setup](image)

![Fig. 5: PSpice Model](image)

![Fig. 3: Beam pattern for the ring](image)
VI. CONCLUSION

Our aim in this study is to show the validity of using PSpice to model the diffraction losses. Diffraction losses are calculated by the analytical expression derived using the superposition of Gaussian beams and are incorporated into PSpice model tanks to the parameter $G$ of the transmission line. This technique was used by Johansson [11] to take into account diffraction loss in the far field zone. In this study we showed that this method could be used, even in the near field zone, provided to compute diffraction loss.

PSpice simulation results fit perfectly with the analytical model showing the validity of this technique. The results are also compared to the measurement of the average pressure versus the axial propagation distance $z$ showing some discrepancies which can be explained by the measurement errors, reflection phenomenon and the effect of electrodes and cabling that we did not account for in the PSpice model. These discrepancies are also due to the current distribution in the source which is considered to be uniform in the simulation while it has a cosine shape which takes into account the edge effect in reality.

In the next steps one need to take into account absorption and to model the interface reflection exactly. Measurements in other media should allow completing the PSpice model in order to incorporate the entire physical phenomena occurring during the propagation.

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REFERENCES