Simulation Model of PVDF Piezoelectric Transformer for Medical Applications

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Abstract – The current paper proposes a simulation model of piezoelectric transformer model that utilizes the Polyvinylidene Fluoride (PVDF) material. Its piezoelectric properties and medical applications are still being researched and minor information about such model is present. The available models for conventional transducer are compared and adaptation is proposed. The piezoelectric transformer model is described and its parameters are discussed. A PSpice simulation and laboratory experiment are accomplished. The results are compared and discussed.

Keywords – piezoelectric transformer, PVDF, transducer model, energy transfer

I. INTRODUCTION

The piezoelectric transformers have numerous advantages like compact shape (low height) and high efficiency due to the native driver circuit soft switching [1]. They are used for high voltage step-up applications with capacitive load. Normally PZT material is used in multilayer transformer structures. The piezoelectric transformers transfer energy using mechanical acoustic wave that propagates to small distances up to few centimeters without significant energy loss. They also obtain low EMI and can be used for powering small sensitive to interference electronic devises or for charging small batteries from distance. These qualities could be meaningful for medicine for implantable devices such as pacemakers, implantable defibrillators, brain ‘Pacemakers’ for Alzheimer, cochlear implants etc. In some cases the battery life is few years on account of occupying most of the volume in the device housing. Miniaturization requires smaller battery that needs to be recharged and coils with electromagnetic waves are not always the solution because they can influence sensitive electronics or cause unwanted effects on human body. Piezoelectric transformer, working with acoustic waves within the safe regulations, can be the proper solution.

The acoustic wave propagation medium between the primary and secondary transducers in the medical piezoelectric transformer is the human tissue. The acoustic impedance of the human skin is 1.99 MRayl, bones - 5.32 MRayl [2] and of the ordinary transducer material which is lead-zirconate-titanate (PZT) - 39.71 MRayl. The mismatching of impedances causes energy reflection that can be major problem especially for the energy receiving unit. Therefore polyvinylidene fluoride (PVDF) is used as it has acoustic impedance equal to 2.7 MRayl (close to human tissue and water), develops high piezoelectric activity and is flexible and tough.

The PVDF material is extruded into thin piezo film with typical thickness between 9 and 110 μm. Electrodes are made of silver ink [3] and piezo film elements are laminated with Mylar film [4]. All these materials are compatible with the human body and are not rejected normally.

This paper focuses on PVDF piezoelectric transformer that utilizes thickness mode vibrations. It can be considered as one or multiple transduces that transmit acoustic waves and one or multiple transduces that receive these waves. Therefore conventional piezoelectric transducer models can be used, employing electroacoustic analogous circuits for analysis of the electro-mechano-acoustics. Normally piezoelectric transformers are described using electromagnetic transformers [1] and Mason’s transducer model [5]. Other option is the KLM model [6]. They are powerful tools for conventional piezoelectric transformers but they become difficult to adjust when different layers are present between the primary and secondary elements or when multiple transducer elements are used. On other hand transmission lines are useful for modelling multilayered structures where piezoelectric and non-piezoelectric layers are present. Such models are proposed by Redwood [7] and Leach [8].

This article presents a model of PVDF piezoelectric transformer that employs Leach’s model because of the use of transmission lines for the mechanical analogous circuit and controlled source technique for connection between the mechanical and electrical parts. The model is implemented in the circuit simulator PSpice, which is a part from the OrCAD software tool suite [9], where driver circuit and secondary side electronics can be included to the model.

II. MODEL THEORY

The PVDF piezoelectric transformer consists of primary and secondary piezoelectric elements that will be considered as transducers. The primary side transducer performs electrical to mechanical conversation and the secondary side – mechanical to electrical.

Ultrasonic transducers operate at wide frequency range, therefore the high frequency approximation of the transducer model should be accurate enough for the whole operational range. This is hard to obtain for materials with low quality factor \( Q \) because the difference between the model and the exact solution became unacceptable. So the acoustic losses in the material must be taken into account and lossy transmission lines should be used. Some materials like the piezoelectric polymer film have frequency dependent dielectric parameters and \( Q \) factor so that the film capacitance and lossy transmission line resistive parameter varies. However the piezoelectric transformer operates at fixed sinusoidal frequency and the
PVDF lossy transmission line parameters and the piezo-film element capacitance can be accurately determined.

Leach’s thickness-mode transducer model is used, because the acoustic wave propagates in direction of the film’s thickness which is also the direction of the electric field (electrodes are printed on both sides of the film).

For the presented simulation model the following assumptions and simplifications are made: the piezoelectric transformer model operates only in one direction as the energy flows from primary to secondary side; the acoustic wave propagates only in one dimension; the amplitudes are small enough to work in linear regions of components.

The Leach’s model consists of mechanical and electrical analogous circuits representing the electro-mechano-acoustic system.

A. Mechanical analogous circuit

The equations, describing the one-dimensional compressional acoustic wave of piezoelectric transducer, can be modified to the form of telegraphist’s equations [8]. Therefore the mechanical behavior of the PVDF transducer is described with a mechanical analogous circuit which is represented by a lossy transmission line, given on Fig. 1.

The lossy transmission line can be modeled with lumped segments, consisting of series inductance $L'$ and resistance $R'$ per unit length, and parallel capacitance $C'$ and conductance $G'$ per unit length [10].

Fig. 1. Lossy transmission line

An impedance type analogy is chosen so that the mechanical force is represented by voltage and the particles velocity is represented by current. The inductance per unit length $L'$ [H/m] and capacitance per unit length $C'$ [F/m] are given by Eq. 1 and Eq. 2:

$$L' = \rho \cdot A \quad (1)$$

$$C' = \frac{1}{c^2 \cdot \rho \cdot A} \quad (2)$$

where $\rho$ is the density [kg/m$^3$] and $c$ is the speed of sound [m/s] in the PVDF material, and $A$ is the cross sectional area [m$^2$] of the acoustic beam.

The acoustic coefficient of attenuation $\alpha$ [Np/m] for frequency dependent materials like PVDF is given by Eq. 3:

$$\alpha = \frac{\omega \cdot \sqrt{L \cdot C}}{2 \cdot Q_M} \quad (3)$$

where $\omega$ [rad/s] is the angular frequency and $Q_M$ is the mechanical quality factor. The attenuation of the acoustic waves is represented by resistance per meter $R'$ [Ω/m] which is given by Eq. 4:

$$R' = 2 \cdot \rho \cdot c \cdot A \cdot \alpha \quad (4)$$

The conductance per unit length $G$ [S/m] is considered to be 0 and the transmission line length $l$ is given in [m].

B. Electrical analogous circuit

The electrical analogous circuit and the lossy transmission line of the primary side transducer are given on Fig. 2.

The transducer front and back sides are represented by ports ‘F’ and ‘B’ and the electrical port by ‘E’.

The capacitance of the primary piezoelectric element is represented by capacitor $C_0$ and is given by Eq. 5:

$$C_0 = \frac{\varepsilon_S \cdot A}{d} \quad (5)$$

where $\varepsilon_S$ [C$^2$/N·m$^2$] is the dielectric permittivity at zero or constant strain, $A$ [m$^2$] is the surface area of the electrodes (normally same as cross sectional area of the acoustic beam) and $d$ [m] is the distance between the electrodes (normally the same as the transmission line length $l$). The dielectric permittivity of PVDF material is determined from Eq. 6:

$$\varepsilon_S = \varepsilon_R \cdot \varepsilon_0 \quad (6)$$

where $\varepsilon_0$ [C$^2$/N·m$^2$] is the dielectric permittivity of vacuum and $\varepsilon_R$ is the frequency dependent relative permittivity of PVDF material, found from Fig. 3.
The connection between the electrical and mechanical analogous circuits is accomplished with the current controlled current source \( F1 \) with gain that is equal to the transmitting constant \( h \ [N/C] \) and is given by Eq. 7:

\[
h = \frac{e_{33}}{\varepsilon}, \quad (7)
\]

where \( e_{33} \ [C/m^2] \) is the piezoelectric stress constant.

The resistor \( R \) and capacitor \( C \) integrates the current from \( F1 \) and the unity gain voltage controlled voltage source \( E1 \) isolates the integrator.

The electrical analogous circuit and the lossy transmission line of the secondary side transducer are given on Fig. 4.

![Fig. 4. Secondary side transducer schematic](image)

The capacitance \( C_0 \) of secondary piezoelectric element is determined similarly from Eq. 5. The connection between the mechanical and the electrical analogous circuits is accomplished by current controllable current source \( F2 \) with gain equal to the product of \( h \) and \( C_0 \).

### III. MODEL IMPLEMENTATION

The proposed simulation model of PVDF piezoelectric transformer is implemented in PSpice (Fig. 5). The primary side transducer circuit is placed in hierarchal block Primary Transducer and the secondary side transducer circuit – in hierarchal block Secondary Transducer. The transducers’ coating is represented by transmission lines \( Tmvl \) and the water medium – by \( Twat \). The transducer backing that reflects the acoustic wave and is accomplished with aluminum plates [11][12], is represented by resistors \( RAl \). The resistance is given in Eq 8:

\[
R = Z_0 \cdot A, \quad (8)
\]

where \( Z_0 \) is the acoustic impedance of aluminum.

The physical properties of the used materials in the PSpice simulation are summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PVDF</th>
<th>Mylar</th>
<th>Water</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho ) [kg/m(^3)]</td>
<td>1780</td>
<td>1180</td>
<td>998.2 @ 25°C</td>
<td>2700</td>
</tr>
<tr>
<td>( c ) [m/s]</td>
<td>2200</td>
<td>2540</td>
<td>1482.4 @ 25°C</td>
<td>6420</td>
</tr>
<tr>
<td>( Q_M )</td>
<td>13</td>
<td>30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( e_{33} ) [pF/m]</td>
<td>106-113</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \alpha ) [Np/m]</td>
<td>-</td>
<td>-</td>
<td>0.205 @ 500kHz</td>
<td>-</td>
</tr>
<tr>
<td>( Z_0 ) [Mrayl]</td>
<td>2.7</td>
<td>3.0</td>
<td>1.48</td>
<td>17.33</td>
</tr>
</tbody>
</table>

The PVDF transducer has capacitive nature so that high \( di/dt \) causes very high initial currents. The combination with constant transmission mode when working as transformer causes failure of the thin electrodes and the connectors caused by the high local currents. As a result sine wave transducer excitation is used that also facilitates to determine the PVDF transmission line parameters. It is accomplished with sine voltage source \( V1 \).

The PVDF film transducer elements both for primary and secondary sides are FLDT1-028K piezoelectric film elements [4] with active film (electrode) area - 12 mm wide and 30 mm long. The film size is 28 µm having thickness mode resonance at frequency 39.28 MHz due to Eq. 9:

\[
f_r = \frac{c}{2 \cdot d} \quad (9)
\]

However the simulation model operational frequency is 500 kHz because it is much easier to obtain in laboratory environment for experimental validation.

The ‘Time Domain’ PSpice simulation results are shown on Fig. 6 and simulation model parameters are given in Table 2.

![Fig. 6. Voltage over resistor \( R_{load} \) vs. time in PSpice](image)

The piezoelectric transformer output voltage, developed over 1 kΩ load resistor, has ‘pure’ sine wave shape with amplitude about 90 mV.
### TABLE 2. SIMULATION MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Element Parameters</th>
<th>Tpvdf C = 322.4n, G = 0, L = 640.8m, LEN = 28μ, R = 154.8k</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0 Value</td>
<td>1.343n</td>
</tr>
<tr>
<td>F1 Gain</td>
<td>1.256e9</td>
</tr>
<tr>
<td>F2 Gain</td>
<td>1.687</td>
</tr>
<tr>
<td>E1 Gain</td>
<td>1</td>
</tr>
<tr>
<td>R Value</td>
<td>1k</td>
</tr>
<tr>
<td>C Value</td>
<td>1</td>
</tr>
<tr>
<td>V1 FREQ</td>
<td>500kHz</td>
</tr>
<tr>
<td>VAMPL</td>
<td>100V</td>
</tr>
<tr>
<td>Rload Value</td>
<td>1k</td>
</tr>
<tr>
<td>RAl Value</td>
<td>6.239k</td>
</tr>
<tr>
<td>Tmv1 C</td>
<td>324n, G = 0, L = 486m, LEN = 88μ, R = 50.9k</td>
</tr>
<tr>
<td>Twat C</td>
<td>1266n, G = 0, L = 359.3m, LEN = 15m, R = 6.6</td>
</tr>
</tbody>
</table>

### IV. VALIDATION

To validate the PSpice model a physical experiment is accomplished. The experimental setup is given on Fig. 7.

The two PVDF film elements (FLDT1-028K) are glued with epoxy onto vertical aluminum plates which are fixed in water environment on 15 mm distance. The primary transducer excitation is accomplished with high-voltage resonant driver and series inductor which together with the piezo-film capacitance creates LC resonant circuit, so that sine voltage with boosted amplitude is obtained.

The load is realized with carbon film resistor and the output voltage is digitalized and measured with battery powered digital differential scope ‘Analog Discovery™’ of DIGILENT Inc. [13]. The experimental results are shown on Fig. 8. The piezoelectric transformer output voltage, developed over 1 kΩ load resistor, has sine wave shape with moderate noise and amplitude about 90 mV and 10 mV positive offset, which is very similar to the simulation results.

### V. CONCLUSION

The proposed PVDF piezoelectric transformer model in PSpice is a powerful tool for accurate simulation of the electrical energy transfer through human tissue and other biological and non-biological media. The model can be used for evaluation of the potential and design of PVDF piezo-electric transformer for specific medical applications. The model is limited due to frequency variation and waveform but provides freedom for multi-material and multilayer designs.

### ACKNOWLEDGEMENTS

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### REFERENCES


