COVER SHEET

Title: *Crosstalk effects in matrix of PZT sensors for SHM applications based on the electromechanical impedance principle*

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ABSTRACT:

Using PZT transducers leads to different structural health monitoring techniques, such as those based on Frequency Response Function and Lamb Waves. When two or more PZT transducers are closely placed, an important interference, namely crosstalk, appears. This approach verified that such an effect can be modelled and implemented as a technique to detect damage. Accordingly, this work aims to present a methodology for studying the crosstalk effect in arrangements of PZT, where the electromechanical impedance (EMI) is used as a parameter of a PZT arrangement modelled as a coupled transmission line. For that purpose, the eigenvalues of a coupled electromechanical impedance matrix are obtained. We anticipate that the structural damage will influence the EMI signatures and the modelled matrix will be distinct for the healthy and damaged conditions. The proposed methodology was tested by simulating a simple Structural Health Monitoring system based on the EMI technique. The simulated structure was considered as a homogeneous medium in which two small PZT transducers separated by 6mm were attached. Two independent damages were simulated in the structure at 10 mm and 30 mm from each PZT. The initial simulations were implemented using the software SPICE and the crosstalk was estimated in time-domain. Some metric damage indices demonstrated the effectiveness of the proposed methodology.

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1. INTRODUCTION

Ultrasound applications based on piezoelectric transducers (PZT) are important in different areas such as medicine and engineering, and most of them are based on more than one PZT [1]. When two or more PZT are used, it is possible that some induced interferences appear depending on the application. One induced interference that can be studied and exploited in Structural Health Monitoring (SHM) and other applications that use multiple PZTs is the crosstalk, which is a phenomenon intrinsically associated with the PZT properties that appears when one or more PZT are closely placed [2-5].

One way of modeling this problem is by using the theory of plane-wave-expansion dedicated to the simulation of piezoelectric composite structures [6-8]. The structure distribution can be represented using a Bloch-Floquet expansion and the Fahmy-Adler formulation. Such an approach provides information about the capability of structure to guide elastic waves. The model based on a plane wave expansion can be used to address the description of structures exhibiting periodicity in-plane, or bulk non-homogeneity, and to analyze composite structures, which can ensure good accuracy. This approach is an alternative to Finite Elements Method (FEM) in the case of the considered regular piezoelectric composite geometry.

In [9] was proposed a model to predict the crosstalk based on the approach of the theory of surface-acoustic wave domain and mutual admittances combined with a multiperiodic finite element. The work demonstrated that the computation of mutual and harmonic admittances provides a reliable tool for describing the crosstalk effect in piezo-composite transducers. The FEM was employed to accurately describe all the existing nodes in the structure. The main advantage of using FEM is that it can be used to model structures of PZT with complex geometries and the main drawbacks are the large amount of data and the high computational load required [10]. As an alternative for modeling structure where more than one PZT is placed, in this work, it is proposed a novel hybrid modeling for crosstalk approach that combines a model of coupled transmission lines with an electroacoustic model of a piezoelectric transducer. The hybrid model has two physical restrictions. The first one is that each propagation velocity in an uncoupled mode line needs to be unique. The second restriction is that the transmission line and the piezoelectric transducer are assumed to be lossless. Although not implemented in this paper, the proposed hybrid model can be extended to a lossy problem.

The proposed model was developed considering controlled sources of current and voltage for modelling the coupling between the electrical and the mechanical systems instead of transformers [11-12]. The main issue with using transformers is that they can lead to unfeasible impedance elements [13]. The multiconductor transmission line models are derived from the integral and/or differential form of the Maxwell's equations [14]. The model was evaluated through an experiment consisting of two piezoelectric transducers placed, one distant from the other, in a homogeneous environment. The first PZT was excited by a pulsed signal and the induced voltage in the other PZT was measured at the same time. Using the software SPICE, it was implemented the Branin's method for two conductor lines, which is an exact method for the time solution of transmission line equations of lossless multiconductor lines [15].

II. THEORETICAL ANALYSIS

A. The Thickness Mode of a PZT Transducer

Different factors such as material, mechanical and electrical construction affect the behavior of a piezoelectric transducer. In this sense, the geometric shape of PZT transducers is an important factor considered in its modelling. Figure 1 shows the diagram of the thickness mode of a disc piezoelectric transducer, in which *lx*, *ly* and *lz* are the dimensions in the axis *x*, *y* and *z*, respectively, *f* is the external force applied on the face of the piezoelectric (*z*-axis), *u* the wave velocity and *i* the electric current.

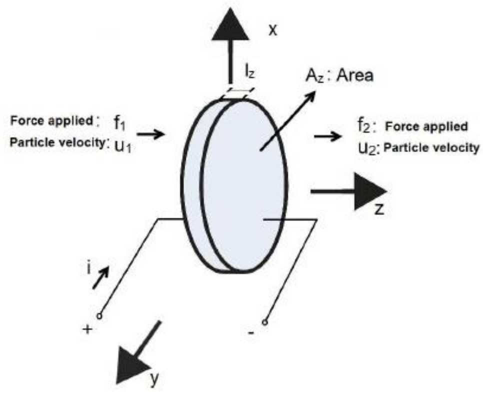


Figure 1. Diagram of the thickness mode transducer.

Considering that ρ is the transducer areal density, *Az* is the cross-sectional area perpendicular to the *z* axis, *c* is the relative elastic constant, *h* is a piezoelectric constant and ϵ is the permittivity constant, the equations that model the behavior of such PZT are given by [13]:

$$\frac{df}{dz} = -\rho A_z s u \tag{1}$$

$$c\frac{d\zeta}{dz} = -\frac{1}{A_z} f + hD \tag{2}$$

$$E = -h\frac{d\zeta}{dz} + \frac{1}{\epsilon} D \tag{3}$$

In equations (1), (2) and (3), *s* is the complex frequency associated with the charge by $q = i/s$, *E* is the electric field intensity, *D* is the electric flow density given by $D = q/Az$ and ζ is the wave-particle displacement given by $\zeta = u/s$. Considering that the electric flow density is constant in the *z-direction*, $dD/dz = 0$, the voltage between the transducer electrodes is given by:

$$v = \frac{h}{s}[u_1 - u_2] + \frac{1}{sC_0} i \tag{4}$$

where $u_1 = u(0)$, $u_2 = u(lz)$ and the term $C_0 = \epsilon A_z/lz$ represents the capacitance between the electrodes of the transducer. Then, the PZT is modeled using Leach's equivalent circuit model [13] as shown in Figure 2.

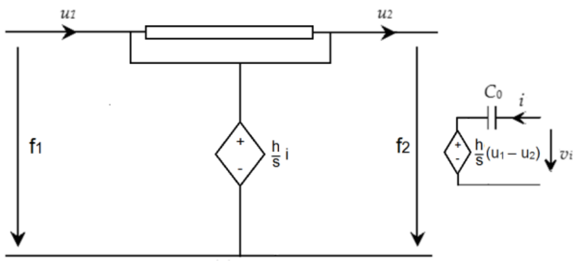


Figure 2. Electrical circuit for the thickness-mode transducer.

In equation (4) and in the Figure 2, the term hi/s represents the voltage V and the term u represents the current I. Thus, from the transmission line parameters, the inductance per-unit-length is $\boldsymbol{L} = \rho A_z$, the shunt capacitance per-unit-length is $\boldsymbol{C} = 1/cA_z$ and the characteristic impedance is $\boldsymbol{Z} = (L/C)^{1/2}$. Therefore, the current variation is $(dI/dz) = -CsV$ and the voltage variation is $(dV/dz) = -LsI$.

B. Multiconductor Transmission Lines Model

Assuming a powered Multiconductor Transmission Line (MTL) formed by n conductor and a ground line. According to [16], the transmission line equations for two perfect conductors immersed in a lossless medium are given by:

$$c\frac{\partial V(z,t)}{\partial z} = -L\frac{\partial I(z,t)}{\partial t} \tag{5}$$

$$c\frac{\partial I(z,t)}{\partial z} = -L\frac{\partial V(z,t)}{\partial t} \tag{6}$$

where L and C represent the inductance and conductance of the line per-unit-length, respectively. Decoupling of the couple MTL equations into an uncoupled set of two conductor lines is achieved by variables changing [16]. Considering that Vm and Im are vectors of voltages and currents modes, the transformation between the voltages is $V(z,t) = T_V Vm(z,t)$ and between currents is $I(z,t) = T_I Im(z,t)$. The $n \times n$ matrices T_V and T_I define a change of variable between the actual phasor line voltages and currents. Therefore, a set of decoupled equations using controlled sources, as shown in Figure 3, can be obtained as follows:

$$V_i = T_{Vi1}V_{m1} + \cdots\cdots T_{Vij}V_{mj} + \cdots\cdots T_{Vin}V_{mn} \tag{7}$$

$$I_{mi} = T_{Ii1}^{-1}I_1 + \cdots\cdot T_{Iij}^{-1}I_j + \cdots\cdot T_{Iin}^{-1}I_n \tag{8}$$

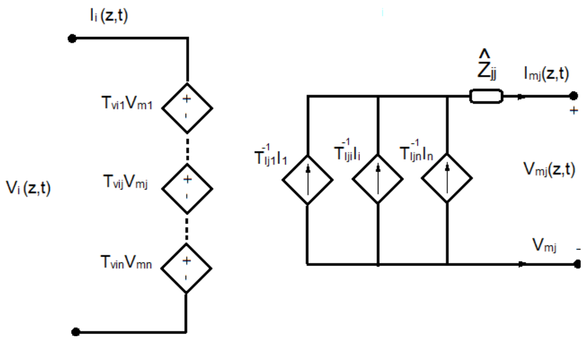


Figure 3. Decoupling transformation.

III. THE PROPOSED METHOD

Considering ($n+1$) piezoelectric transducers attached to a homogeneous structure where each transducer is modeled as an equivalent transmission line, the proposed model is shown in the Figure 4. The idea is to apply the method of decoupling MLT equations to analyze the arrangement of PZT transducers. Since the particle displacement is related to the voltage, the crosstalk can be calculated independently for each transducer. Based on equation (7), the voltage across the transducer electrodes is given by:

$$v(t) = T_{Vi1}V_{m1}(L,t) + \cdots \; T_{Vin}V_{mn}(L,t) \qquad (9)$$

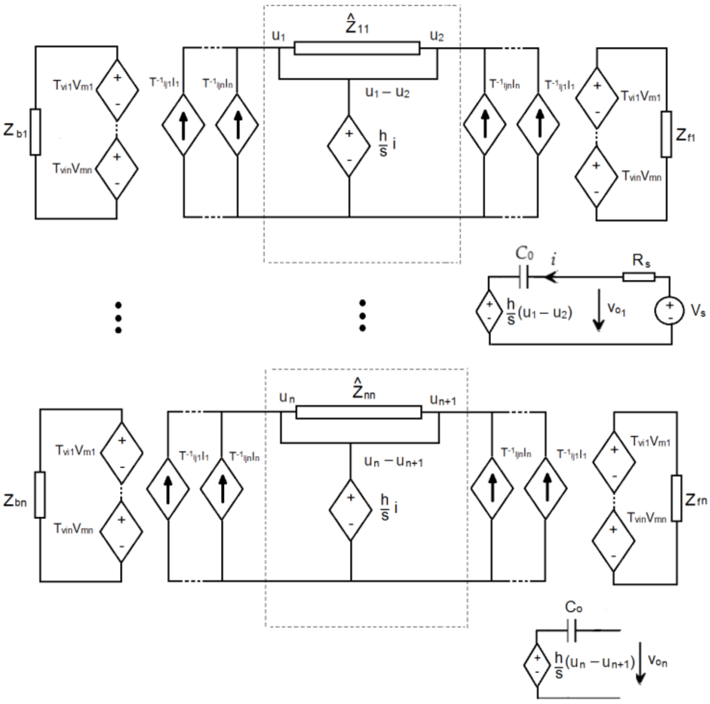


Figure 4 - Model for decoupling arrangements of piezoelectric transducers.

Instead of computing the inductance and capacitance, the impedance matrix Z is built using the theory of EMI and mutual impedances as shown in equation (10).

$$Z = \begin{bmatrix} Z_1 & \frac{V_{11}}{I_{12}} & \cdots & \frac{V_{11}}{I_{1n}} \\ \frac{V_{12}}{I_{11}} & Z_2 & \cdots & \frac{V_{12}}{I_{1n}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{V_{1n}}{I_{11}} & \frac{V_{1n}}{I_{12}} & \cdots & Z_n \end{bmatrix} \qquad (10)$$

The main diagonal of the matrix Z represents the magnitude of the EMI obtained from each PZT in the arrangement. The other elements of the matrix Z represent the magnitude of the mutual impedance between the PZT transducers. In this case, considering a transducers array $n \times q$ where all electrodes are grounded, except one, and Vm,p as the potential applied to the electrodes of piezoelectric transducer at index (m, p), the induced voltage in the electrodes (n,q) is given by:

$$V_{n,q} = \begin{cases} V_{m,p} & for\ n = m \text{ and } q = p \\ 0 & for\ n \neq m \text{ and } q \neq p \end{cases} \quad (11)$$

Assuming that the current induced in electrodes is *In,q*, the mutual impedance between two piezoelectric transducers is given by:

$$Z_{m-n,p-q} = \frac{V_{m,p}}{I_{n,q}} \quad (12)$$

III. SIMULATIONS AND RESULTS

To illustrate the proposed hybrid model, it was simulated an application based on two PZT transducers in a lossless condition by using software PSPICE®. The PZT are separated by 6 *mm* and attached to a homogeneous medium as shown in Figure 5. The mechanical load on the back and front sides of the transducer 1 and the mechanical load on the back of the transducer 2 are assumed Poly Methyl Methacrylate (PMMA). The damage was simulated by changing the electrical properties of the PMMA.

Based on the proposed model, the electric diagram for the two PZTs attached to a homogeneous medium is presented in Figure 6. The PZT1 was excited by a pulse signal *Vs* with an amplitude of 30 *V*, a rise/fall time of 12.5*u*s and width of 20 *u*s. Then, the crosstalk effect at PZT2 was measured by voltage across R_{b2} (Z_3 in Figure 6) and R_{f2} (represented by V_{o2} in Figure 6), respectively. The EMI and the mutual impedances were simulated and computed in a frequency range from 400 kHz to 4 MHz.

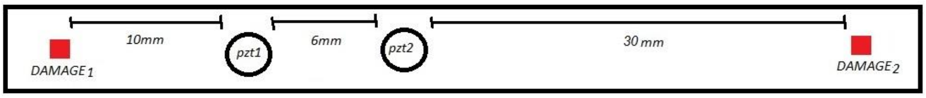


Figure 5. Topo view of the simulation setup.

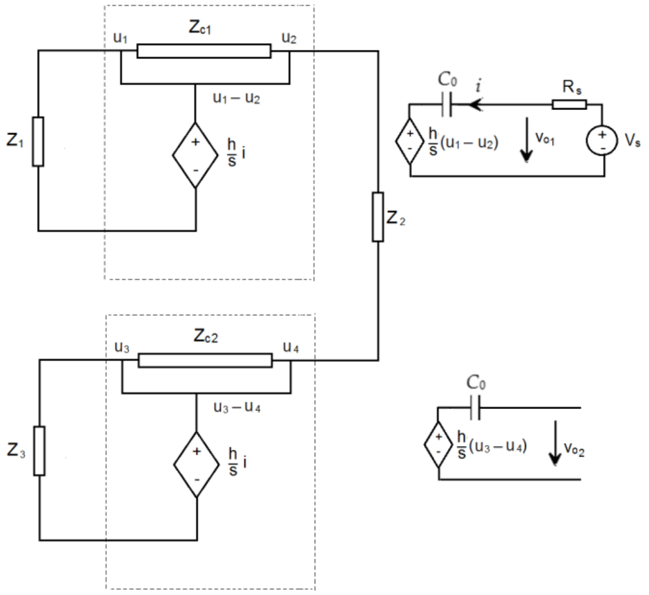


Figure 6. Electric diagram for two PZT.

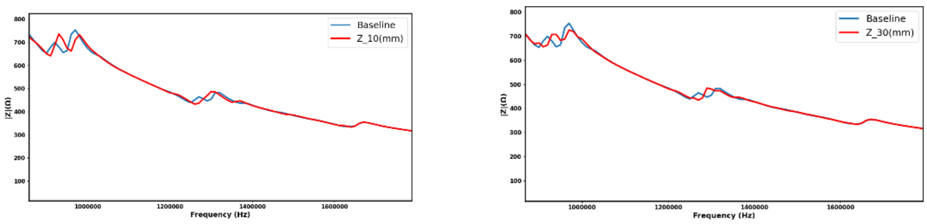
Firstly, the EMI was obtained in healthy and damage conditions to assure that the simulations are correct. The results are presented Figure 7. As expected, the damage can be determined by comparing the EMI between healthy and damage conditions.

Secondly, it was applied the model of coupled impedance and the results are presented in Figure 8. By direct comparison, one can observe that the proposed method presents an impedance signature with much more variations than the original EMI.

To verify the capability and sensitivity to detect damage, the root mean square deviation (RMSD) and the mean absolute percentage deviation (MAMPD) were calculated. The results presented in Table I confirm that the proposed method is more sensitive than the original EMI method. Furthermore, it can be observed (Figure 8 and Table I) that the proposed method is sensitive to damage position, which suggests that it can be used not only to detect damage, but also to locate it.

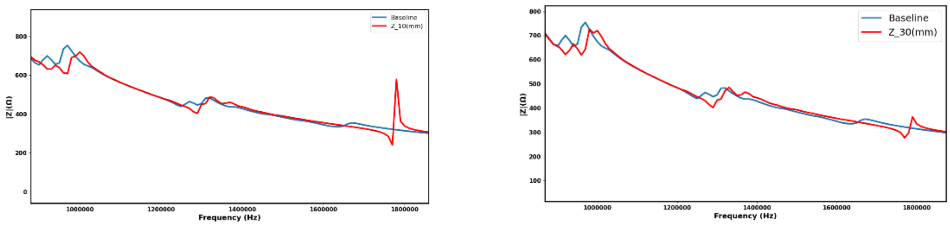
TABLE I. DAMAGE INDEXES.

	RMSD 10mm	**RMSD 30mm**	**MAPD (x 10^{-5}) 10mm**	**MAPD (x 10^{-5}) 30mm**
EMI	0.0022	0.0022	0.5089	4.002
COUPLED IMPEDANCE	0.1637	0.0557	49.93	22.68



(a) (b)

Figure 7. EMI for damage at 10mm (a) and 30mm (b).



(a) ……………………………………….(b)

Figure 8. Uncoupled impedance for damage at 10mm (a) and 30mm (b).

IV. CONCLUSION

This work presented a methodology for detecting crosstalk in an arrangement of piezoelectric transducers in a homogeneous medium. The analysis of the influence of a piezoelectric transducer over another was based on a multiconductor transmission line model applied to PZT transducers and the crosstalk effect. The electromechanical impedance of a PZT sensor was used as a parameter to model a piezoelectric transducer arrangement as coupled transmission lines. As a result, it was obtained a hybrid model for a crosstalk approach that combines a model of coupled transmission lines with an electroacoustic model of a piezoelectric transducer. The proposed technique was tested by simulating a PZT sensors arrangement applied to structural damage detection. The results demonstrate the model can significantly improve structural health monitoring (SHM) techniques based on the EMI principle. However, it is important to remark that tests were carried out based on circuit analysis, which limit physical modelling of both PZT and structure, such as temperature variations. Therefore, new studies are being focused on physical parameter analysis of the set PZT/Structure in SHM systems.

ACKNOWLEDGMENT

This study was financed in part by FAPESP (Grant 2022/00113-9).

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