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**TITLE:** Uniplexing and Multiplexing of PZT Transducer for Effective use in Structural Health Monitoring

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ABSTRACT
The future of aero, civil and mechanical (ACM) engineering is in the development of massive and ultra-large structures. Such ultra-large structures stand as a symbol for the developing technology of the modern world. Needless to say, such ultra-large structures require very large online structural health monitoring (SHM) and, noise and vibration control (NVC) systems. Piezoceramic (PZT) transducers are extensively used in SHM for damage detection and NVC of various ACM structures. They are either surface bonded or embedded inside the host structure and are excited to produce structural responses, which forms the basis of SHM or NVC models. Last couple of decades had seen many ‘single input single output’ (SISO) based single PZT – structure interaction models in fields of SHM and NVC. However present and future decade researchers are propelled to study multiple input multiple output (MIMO) or multiple input single output (MISO) based multiple PZT–structure interaction models in addition to SISO models, to deal with ultra-large structures. Thus, this paper focuses on the experimental based study of such MISO/ MIMO based multiplexing of PZT transducers, along with SISO based uniplexing on a prototype plate structure. Multiplexing is a process of active excitation and extraction of output responses from multiple PZT transducers. Where as uniplexing is active excitation and extraction of output response from single PZT in presence of other passive distributed transducers. The paper also highlights the problem of interference between transducers during uniplexing/multiplexing and their influence in output responses.

Key words: electromechanical impedance (EMI), multiplexing, uniplexing, interference, PZT, structural health monitoring (SHM), non destructive evaluation (NDE).

INTRODUCTION
The future of aero, civil and mechanical (ACM) engineering is in the development of massive and ultra-large structures like very tall buildings, large capacity planes, inflated satellites etc. Such ultra-large structures stand as a symbol for the developing technology of the modern world. Need less to say, such extra-large structures require extra large online structural health monitoring (SHM), and noise and vibration control systems. Piezoceramic (PZT) transducers are extensively used in smart material based SHM and, noise and vibration controls of various ACM structures. Last few decades had seen many ‘single input single output’ (SISO) based single PZT–structure interaction models in SHM (Crawley and Luis 1987; Liang et al. 1994; Zhou et al. 1996; Park et al. 2003; Annamdas and Soh 2006a etc.) and, noise and vibration controls (Raja et al. 2004, Park et al. 2002
etc.). However present decade researchers are propelled to study multiple input multiple output (MIMO) or multiple input single (MISO) output based multiple PZT–structure interaction models in addition to SISO models. For effectively health, noise and vibration control of ultra large structures. Ruggiero et al (2004) outlined MIMO modal analysis technique using smart materials for use in noise and vibration controls. Ruggiero and Inman (2005) stressed the need to analyse such MIMO model to extract modal parameters of ultra large (inflated / flexible) structures. But, fewer researchers (Cheng and Lin 2005a, Annamdas and Soh 2006b etc.) worked in area of SHM of ultra large structures. Thus, our present study aims to analyze MISO/ MIMO based multiplexing along with SISO based uniplexing of PZT transducers for applications in SHM of ultra large structures. In the existing single PZT–structure interaction (SISO based) models, the basic assumption made was that the PZT transducer is negligible in mass compared to host structure, i.e. PZT behave only as active actuator (PZT-AA) and active sensor (PZT-AS). However, in our SISO based uniplexing, we additionally consider that the PZT transducers also behave as mass additives (PZT-MA). Similar additional behaviour (PZT-MA) of PZT transducer was assumed in (MIMO / MISO based) multiplexing also. This is because increase in number of PZT transducers increases overall mass and it significantly influences output structural response (Cheng and Lin 2005a). The present paper focuses on the experimental study of SISO, MISO and MIMO based distributed multiple PZT transducers on a prototype plate structure. Thus, the paper highlights the following three goals (1) SISO based uniplexing (2) Interference between transducers during uniplexing (3) MISO / MIMO based multiplexing.

**The Electromechanical Impedance (EMI) Method**

The electromechanical impedance (EMI) method is one of the recent developments in the field of smart material based SHM. In the EMI methods, the PZT transducer is either surface bonded or embedded inside the host structure. The governing principle is that the PZT transducer actuates harmonically at high frequencies (10 – 500 kHz) in the presence of electric field to produce a structural response which is known as ‘electro mechanical (EM) admittance signature’. The EM admittance signature of SISO model is a function of the stiffness, mass and damping of the host structure (Sun et al. 1995) and, length, width, thickness and orientation of the PZT transducer (Wetherhold et al. 2003). Additionally for MISO or MIMO models, EM admittance is also a function of PZT mass (Cheng and Lin 2005a). The changes in the EM admittance signature, which is the inverse measure of mechanical impedance of the structure, are indicative of the presence of structural damages.
Thus, it is important for any numerical or analytical or experimental model to properly predict and describe the EM admittance signature using the actuations of PZT transducers for its successful implementation.

Researchers of noise and vibration controls (like Raja et al. 2004) apply electric field to PZT transducer along length, width and thickness direction to produce extensional (along length and width), longitudinal (along thickness) and shear actuations. However for EMI models electric field is applied only along thickness direction of PZT which producing extensional (along length and width) and longitudinal actuation.

Researchers of EMI based SHM in the past, from Liang et al. (1994) to Cheng and Lin (2005b), did not consider actuation along thickness, i.e. longitudinal actuation (LA) even though it is produced due to application of electric field. However, Annamdas and Soh (2006a) considered LA, but their formulation was applicable only for 2D plain strain conditions and it was basically a SISO model. Thus, the need for considering LA in MISO/ MIMO based formulation has been high lightened through our experimental investigations. For this purpose, four different thicknesses of PZT transducers were used in the experiments to establish the necessity of considering LA and co relationship between thickness and interference.

The EM admittance signature (unit Siemens or ohm$^{-1}$) consists of real and imaginary parts, the conductance (G) and susceptance (B) respectively. A plot of G and S over a sufficiently wide band of frequency serves as a diagnosis signature of the structure. The sharp peaks in the conductance signature correspond to the structural modes of vibration, which identifies the local structural system (in the vicinity of the transducer) and hence constitutes a unique health-signature of the structure at the point of attachment. In any circumstances, the deterioration of the structure can be assessed by extracting the signature and comparing with the initial benchmark signature.

**EXPERIMENTAL INVESTIGATIONS**

The experimental setup of the EMI model consists of an HP LF 4192A impedance analyzer, a 3499A/B switching box or multiplexer (Agilent Technologies 2004) and test specimen as shown in Figure 1. One dimensional (1D) electric field is applied along thickness direction of PZT through analyzer via multiplexer. Researchers use multiplexer (switch box) for handling multiple sensors and actuators. Multiplexer allows switching connection from one sensor (or actuator) to another sensor (or actuator) for acquiring admittance signatures using the impedance analyzer.
Experimental investigation was done in three stages, in the first stage, uniplexing with multiple (>2) PZT transducers of types $T_3$ and $T_{0.3}$ were investigated. During which, a total of twenty-four PZT transducers, twelve each from two types are surface bonded on two identical 2 mm thick aluminium plates of grade Al 6061-T6 (Table 1). Types $T_{0.3}$ and $T_3$ (Table 1) correspond to PZT dimensions 10 x 10 x 0.3 mm and 10 x 10 x 3 mm respectively. On each aluminium plate, twelve PZT transducers of same type are surface-bonded one after another consecutively at different ‘locations’ using high strength epoxy adhesive (RS Components 2004, Table 1). The numberings shown in Figure 2 indicates the sequence of installation (bonding) for each aluminium plate specimen (starting in order from 1 to 12). The PZT transducers are excited by sinusoidal alternating voltage applied across the terminals of the transducers.

In the second stage, uniplexing with only two PZT transducers of same type was used for investigation. However thicker ($T_3$) transducer type was excluded from experimenting, but two thinner types $T_{0.75}$ (10 x 10 x 0.75) and $T_1$ (10 x 10 x 1) along with $T_{0.3}$ was used for investigation. During final stage, multiplexing with multiple ($\geq 2$) PZT transducers was investigated using thicker ($T_3$) and thinner ($T_{0.3}$) types of PZT transducers.
The EM admittance signature is effected by mass, location, length, width, and thickness (Wetherhold et al. 2003) of the PZT transducers. Thus, the change in EM admittance is also effected by mass, location and dimensions of PZT as given below.

\[ \Delta Y = \Delta G + j \Delta B = f(\text{Mass, location, dimensions}) \quad \text{(1)} \]

The change in admittance (\(\Delta Y\)) is sum of change in conductance (\(\Delta G\)) and change in susceptance (\(\Delta B\)). Only the representative \(\Delta G\) is presented in the study for simplicity, however the \(\Delta B\) also behaved in the same manner. Hence we have limited our investigations solely utilizing only the real part (conductance).

**Table 1.** Key properties of epoxy adhesive (RS 850-940), Al 6061-T6 aluminium and PZT transducer

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Value</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (kg/m(^3))</td>
<td>1180</td>
<td>2715</td>
<td>7800</td>
</tr>
<tr>
<td>Young’s Modulus (N/m(^2))</td>
<td>2</td>
<td>68.95</td>
<td>66.67</td>
</tr>
<tr>
<td>x 10(^9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.4</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Thermoelastic loss factor, (\eta)</td>
<td>-</td>
<td>-</td>
<td>0.023</td>
</tr>
<tr>
<td><strong>Electrical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezoelectric strain coefficients (m/V) (d_{31}, d_{32}) x 10(^{-10})</td>
<td>-2.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezoelectric strain coefficient (m/V) (d_{33}) x 10(^{-10})</td>
<td>4.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dielectric loss factor, (\delta)</td>
<td>0.015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric permittivity, (\varepsilon_{33}) (farad/m) x 10(^{-8})</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**UNIPLEXING USING MULTIPLE (>2) PZT TRANSDUCERS**

The term ‘uniplexing’ means single input single output (SISO). It is actuation of a single PZT when subjected to excitations, resulting in structural response extracted as output from sensing PZT with other bonded PZT transducers behaving only as mass.
additives. Two types of PZT transducers, one thicker (3 mm, $T_3$) and other thinner (0.3 mm, $T_{0.3}$) compared to aluminium plate thickness (2 mm) is selected to study uniplexing.

To begin, an initial assumption made was that the mass influence on EM admittance is dominant compared to location and dimensions of actuating or non actuating PZT. Hence, the variation of conductance is expressed as a function of mass ($m$) alone, i.e, Equation 1 can be changed as

$$\Delta Y \propto \Delta g \propto f(m)$$

(2)

A total of 6 benchmark PZT transducers, representing each of the respective 6 columns (Columns A, B, C, D, E and F at Locations 1, 3, 5, 7, 9 and 11 respectively as shown in Figure 2) were selected as uniplexing locations to illustrate the function (i.e. Equation 2).

At first uniplexing location, i.e., at A[1] (benchmark PZT in column A at Location 1), a total of 11 sets of conductance difference ($\Delta G = G_{Con,A[1]} - G_{A[1]}$) due to the consecutive mass additions of 11 PZT transducers (at Locations 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12) were recorded. Only one PZT at every uniplexing location is active and excited to produce admittance and other PZT transducers which act only as mass additives are passive and are not excited. $G_{A[1]}$ means initial $G$ at location A[1] and $G_{Con,A[1]}$ means $G$ at A[1] after every consecutive PZT additions.

Similarly, at other uniplexing locations (B[3], C[5], D[7] E[9] and F[11]), similar conductance difference ($\Delta G = G_{Consecutive} - G_{Initial}$) was recorded and the number of sets of conductance differences and PZT additive locations are as listed in Table 2.

The initial and consecutive conductance signatures are given as below

$$G_{Initial} = G_{Col[Location]} \quad \text{and} \quad G_{Consecutive} = G_{Con-Col[Location]}$$

subscripts $Col$ and $Location$ represents column and location numbers respectively (i.e benchmark locations of Figure 2) and subscript $Con$ represent consecutive.

**Uniplexing using Thicker Transducer**

The variation of conductance (i.e, Equation 2) can be quantified by the differences between the initial benchmark reading (before mass addition) and consecutive mass additions (at various locations) of PZT transducers (i.e. $\Delta G = G_{Consecutive} - G_{Initial}$ as given in Table 2). Figure 3 illustrates the influence and trend of the mass accumulation for the benchmark PZT at A[1] for various locations of consecutive mass additions. The figure shows that the trends of the 11 sets of conductance difference are very consistent with peaks and troughs occurring at the same frequency after consecutive additions of PZT.
transducers, thereby demonstrating the reliability of the experimental results obtained. However, for the ‘first PZT mass addition’, the conductance difference at Location 2 (coloured pink at A[2]) has a relatively low magnitude (or parallel shifting of signature) as compared to the subsequent mass additions. This is because the PZT transducer is installed at only 50 mm distance away from the benchmark PZT (at A [1]). Such observation could imply possible interferences due to installation of the PZT transducers at extremely close proximity to the benchmark PZT. Thus, it signifies that one PZT addition is enough to conclude the existence of any interference between transducers.

Table 2: Location of benchmark PZT transducers and their mass additions

<table>
<thead>
<tr>
<th>Column</th>
<th>Location of Initial Conductance ($G_{Initial}$)</th>
<th>Locations of Consecutive Records of Conductance ($G_{Consecutive}$)</th>
<th>No. of Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 A[2], B[3], B[4], C[5], C[6], D[7], D[8], E[9], E[10], F[11] and F[12]</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>B</td>
<td>3 B[4], C[5], C[6], D[7], D[8], E[9], E[10], F[11] and F[12]</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>C</td>
<td>5 C[6], D[7], D[8], E[9], E[10], F[11] and F[12]</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>F</td>
<td>11 F[12]</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 3. Conductance differences between initial and consecutive mass additions of benchmark PZT of type $T_3$ at A[1]

Hence, the assumption of the relationship of change in conductance as a function of mass alone, $\Delta G \propto f(m)$ (Equation 2) is not valid, and the presence of location factor (denoted as x) would have to be included in the function, thus Equation 2 is modified as,

\[ i.e. \Delta G \propto f(m,x). \] (3)

Additionally, when comparing the $(\Delta G)$ conductance difference of the first and second PZT additions at location A[2] and B[3] respectively, the interferences were found to be diminishing in magnitude when the second PZT addition (at B[3]) was made at similar distances of 50mm from the benchmark PZT at A[1].

To substantiate the claim of interferences, similar analysis of the benchmark PZT at B[3] is performed. Figure 4 shows the significance of interference of benchmark PZT at B[3]. Similarly, the first PZT addition (at Location 4 i.e., B[4]) at 50 mm distance from PZT at B[3] also resulted in significant interference. Other observation made was that slight variations in conductance measurement were even found for mass additions at a far distance of $\leq 158$mm (say at C[6]) from benchmark B[3], indicating the presence of interferences with decreasing impact as the distance increases.
Figure 4. Conductance differences between initial and consecutive mass additions of benchmark PZT of type $T_3$ at B[3]

Figure 5 shows difference in conductance vs frequency plot, for a benchmark PZT transducers at location C[5]. Other benchmarks PZT transducers at D[7], E[9] and F[11] were also observed to give similar results. Similar interferences were observed for the first addition of PZT mass at 50mm distance from the benchmark PZT locations. For benchmark PZT at F[11], due to only one record of PZT mass addition, comparison of mass addition is excluded for benchmark.

Thus, it can be concluded that a distance of about 150 mm ($< 200$ mm) from benchmark PZT transducer will influence the signature, thus there exists a radius of interference between 150-200mm for 3mm (type $T_3$) thick transducer.

The above findings confirmed the presence of interferences (usually a parallel downward shift of signature) for ‘PZT mass additions’ within proximity of 50mm from a benchmark PZT transducer (coloured pink or A[2], B[4] and C[6] in Figures 3, 4 and 5 respectively). This is mainly due to the hinderance on wave propagation near the source of actuation. As such, the aluminium plate, being lighter in density (2715kg/m3) and thinner (2mm) than the PZT transducer (7800kg/m3, 3mm) would inevitably experience interference. Moreover, the PZT transducer has limited sensing range, hence would result in lower interference if the mass addition is located far away from the benchmark PZT transducer. However, if more PZT transducers are installed within the proximity of 50mm, the impact of interference was observed to be gradually diminish. This effect is verified by both benchmarks PZT at A[1] and PZT at B[3] (see Figures 3 and 4). Although the above
conclusions made are reliable, more experiments are performed to determine the persistence of interference range for other thinner type ($T_{0.3}$) of transducers.

**Uniplexing using Thinner Transducer**

To verify, if different dimensions of PZT transducers would have the same behaviour as discussed above, experiments are performed using ten times thinner transducers. Similarly, conductance difference, $\Delta G$ are computed for various benchmark locations of PZT transducers. Figure 6 shows the plot of conductance difference vs frequency, showing the influence of mass additions at benchmark PZT at A[1].

The $\Delta G$ for consecutive mass additions are found to coincide closely, especially in the lower frequency range. This indicates low significant interferences within proximity of 50mm distance from the benchmark PZT at A[1], unlike the previous 3mm thick transducers. Noticeably, apart from little significance in interference, the troughs are found to coincide and are almost similar in magnitude. The rest of the 0.3 mm thick benchmark transducers are also found to follow similar pattern. A typical illustration is shown in Figure 7. The experimental results are therefore shown to be consistent throughout the experimental testing.

![Figure 6. Conductance differences between initial and subsequent mass additions of benchmark PZT of type $T_{0.3}$ at A[1]](image)
The experiments reveal that the interferences mentioned in the previous section are valid only for thicker transducers which are heavier in mass. The aluminium plate (2mm thick) is very much thicker than the 0.3mm PZT transducers and thus has no significant impact on the vibrating wave.

Generally, PZT transducers with nominal thickness ($T_{0.3}$) had shown to be consistently less affected by interference even with the presence of nearby PZT at distance spacing of 50mm. However, possible significant interference could have been overlooked for cases where PZT are very closely located (< 50mm) from the benchmark PZT, which might have similar interferences as experienced by the 3mm thick ($T_3$) PZT. Hence, second stage of experiments were done, i.e, uniplexing with only 2 PZT transducers in which spacing between transducers were maintained less than 50mm.

**UNIPLEXING WITH ONLY TWO TRANSUDCERS**

It was observed in uniplexing of multiple (>2) PZT transducers using thicker ($T_3$) type, that the first PZT addition is enough to show substantial interference if there exists any interferences due to consecutive additions of PZT. Thus, we concentrated on only two PZT transducers to go ahead with uniplexing to study interference in thinner transducers. Three types of PZT transducers ($T_{0.3}$, $T_{0.75}$ and $T_1$) which are thinner than the thickness of aluminium plate were adopted for investigation in this second stage of experimenting.

**Uniplexing using Two Thinner Transducer (type $T_{0.3}$)**

Previously, it was observed that there is no interference for the thinner ($T_{0.3}$) PZT transducer within proximity of 50mm. However, there could be interference if PZT mass additions are made very close to the benchmark PZT (less than 50mm). However, no visible interference was observed even though they are adjacently placed (10mm distance between centres of PZT transducers) as shown in Figure 8. This is consistent with the observation made using multiple PZT arrangement.
Figure 8. Conductance differences between initial and varying distances of PZT addition for $T_{0.3}$ type of PZT transducer

Figure 10. Conductance differences between initial and varying distances of PZT addition for $T_1$ type of PZT transducer

**Uniplexing with other Thinner Transducers (type $T_{0.75}$ and $T_1$)**

In this case, the probable presence of interference (if any) for other transducers which are also thinner than the aluminium plate was investigated using PZT transducers of thickness 0.75 mm ($T_{0.75}$) and 1.0 mm ($T_1$). Both are verified to be interference-insignificant as shown in the Figures 9 and 10. Hence, it can be concluded that, it at all there exists any interference between thinner transducers then the radius of such interference could be even less then 10mm. That is, the centre to centre distance between the PZT transducers should be less then 10mm which is not possible as the length and width of transducers are 10mm.
Thus, it can be concluded that, interferences due to adjacent installations of PZT transducers may be significant if the transducer thickness is more than the thickness of host plate. On the other hand, it was observed that thinner transducers do not have significant interferences even when they were adjacently placed. Due to insignificant interference for 0.3 mm, 0.75 mm and 1 mm thick PZT transducers, a defined relationship between interference and PZT thickness was however not possible to predict. However, due to the sharp escalation in radius of interference (over 150 mm distance) in the 3 mm thick PZT transducer compared to that of other radius of interference (less than 10 mm distance) for the thinner PZT transducers. It is only obvious to conclude that the relationship is non-linear and most probably following a high order polynomial series in increasing radius of interference with increasing PZT thickness.

From uniplexing it was observed that the thickness/mass of PZT transducer can play very important role in EM admittance. Thickness direction actuation was always
neglected by researchers in the past, but Annamdas and Soh (2006a) had shown that even thickness actuation can be considered in EMI models, but it was limited to 2D plain strain. Thus it is necessary to develop 3D EMI models for SHM utilizing extensional actuations along length and width directions, and longitudinal actuation (LA) along thickness direction of PZT transducer.

**MULTIPLE PZT ACTUATIONS (MULTIPLEXING)**

In the third stage of experiments, all the PZT transducers are actuated (PZT-AA) in parallel, which resulted in output response from collective sensing (PZT-AS) of transducers. Here actuations of all transducers indicate ‘multiple’ input and collective output response indicate ‘single’ output, thus multiplexing is MISO based model. Two types of PZT ($T_3$ and $T_{0.3}$) transducers were considered, one of which is thicker and the other which is thinner then the thickness of the plate as considered previous.

For each type of transducers, multiplexing was done 11 times after every consecutive 11 PZT additions (at locations 2 – 12). An initial reading at location 1 (A[1]) was recorded prior to multiplexing, i.e. for single PZT transducer. During uniplexing, other then the bench mark transducer all other (passive) transducers behaved as mass additives (PZT-MA) where as all PZT transducers in this stage (multiplexing) will behave essentially as PZT-AA, PZT-SA and PZT-MA.

Thus, 11 MISO and 1 SISO results are obtained for each transducer type. Thus a total of 12 outputs are obtained for 12 different inputs, hence this type of combination can be referred as MIMO.

Multiplexing requires minimum of 2 PZT transducers. The collective EM admittance signature of the multiplexing is sum of EM admittance of individual PZT transducers, and is given as

$$Y_{Collective} = \sum_{K=1}^{K=N} Y_K$$

where $K$ represents the $K^{th}$ transducer in a total of $N$ multiple transducers.

Figure 11 shows the plots of initial conductance taken at location 1 (A[1]), and other 11 multiplexed conductance signatures recorded after every consecutive installations (at locations 2-12) of transducers (type $T_3$). Thus, Figure 11 shows a total of 12 conductance signatures recorded from 1 to 12 successive thicker PZT installations. Similarly, Figure 12 shows the results of 12 consecutive conductance signatures recorded for thinner transducer type $T_{0.3}$.
Figure 11. Conductance of initial and consecutive mass additions of $T_j$ type of PZT transducer in multiplexing

Negative values in conductance signature were observed for thinner type of transducers; hence, it is advisable to limit the frequency of excitations (Figure 12). Thus, as the number of PZT transducers increases, the effective frequency range (range of positive values of conductance) was found to decrease, (i.e. in the above case, the effective frequency range for 3 PZT is 60 kHz, but is 40 kHz for 12 PZT). Such behaviour was not observed for thicker (Figure 11) PZT transducers.

Figures 11 and 12 show the consistency of peaks and troughs occurring at the same frequency after consecutive additions of PZT transducers, thereby demonstrating the reliability of the experimental results obtained. Anti clock wise and clock wise Slope shifting of conductance peaks were observed respectively for thicker (Figure 11) and thinner (Figure 12) transducers with increasing magnitude, i.e., with increase in number of PZT transducers. There is a general increase in the amplitude of signatures for both the types of PZT transducers, particularly in the peaks. The opposite nature of slope shifting is due to the differences in sensitivity of the two PZT sizes. This is in accordance with the uniplexing results, which also observed opposite behaviour, i.e., the thicker transducers displayed interference qualities compared to thinner transducers. Thus, the same argument of using thickness actuation along with extensional actuation (along length and width directions) in future EMI models quality SHM holds good. i.e., the thickness / mass of PZT transducer can play very important role in EM admittance.
Figure 12. Conductance of initial and consecutive mass additions of $T_{0.3}$ type of PZT transducer in multiplexing

CONCLUSIONS

The future will see the development of massive and ultra large structures like very tall buildings, large capacity planes, inflated satellites etc.,. Such ultra large structures stand as a symbol for the developing technology of the modern world. Need less to say, such large structures require large online structural health monitoring (SHM), and noise and vibration control systems. Thus, this paper presented MIMO based multiplexing and SISO based uniplexing experiments. Four types of PZT transducers were used to illustrate interferences of PZT. It was observed that the thicker and heavier PZT will have more interference than thinner and lighter PZT transducers when placed at same distance intervals (spacing between transducers). Such a conclusion is expected to be very useful for MISO or MIMO based models. Thus the influence of thickness and mass of PZT on interferences was experimentally investigated. And it was found that actuations along thickness (LA) and mass of transducers influence admittance signature significantly. Thus it was advised to include actuations along length, width and thickness directions of transducers in any of future non destructive evaluation (NDE) based SHM models. Additionally, it was also observed that multiplexing will amplify the EM admittance signature and also multiplexing will improve the sensing range. Thinner and thicker (compared to plate) PZT transducers have respectively clock and anti clock wise slope shifting phenomena, thus the type of PZT transducers to be used and the spacing between them are interlinked. To avoid interference, spacing between the transducers should be increased and vice versa. In the past, researchers ignored thickness direction actuation for SISO or MIMO models in SHM, but uniplexing and multiplexing with different thickness
PZT transducers show that there exists a need for 3D MISO or MIMO based analytical models in SHM for effective prediction of EM admittance for NDE applications. This experimental study is expected to be useful in NDE based SHM.

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