DEPARTMENT OF CIVIL ENGINEERING

IIT DELHI

PART (I)

INTEGRATION OF GLOBAL VIBRATION AND EMI TECHNIQUES

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DIFFERNCES BETWEEN GLOBAL VIBRATION TECHNIQUES AND EMI TECHNIQUE

Since now you have personal experience of both the techniques in lab, you can find out differences with regard to following points:

- Frequency range
- Sensor range
- Data acquisition (time/ frequency domain)
- Level of experience needed

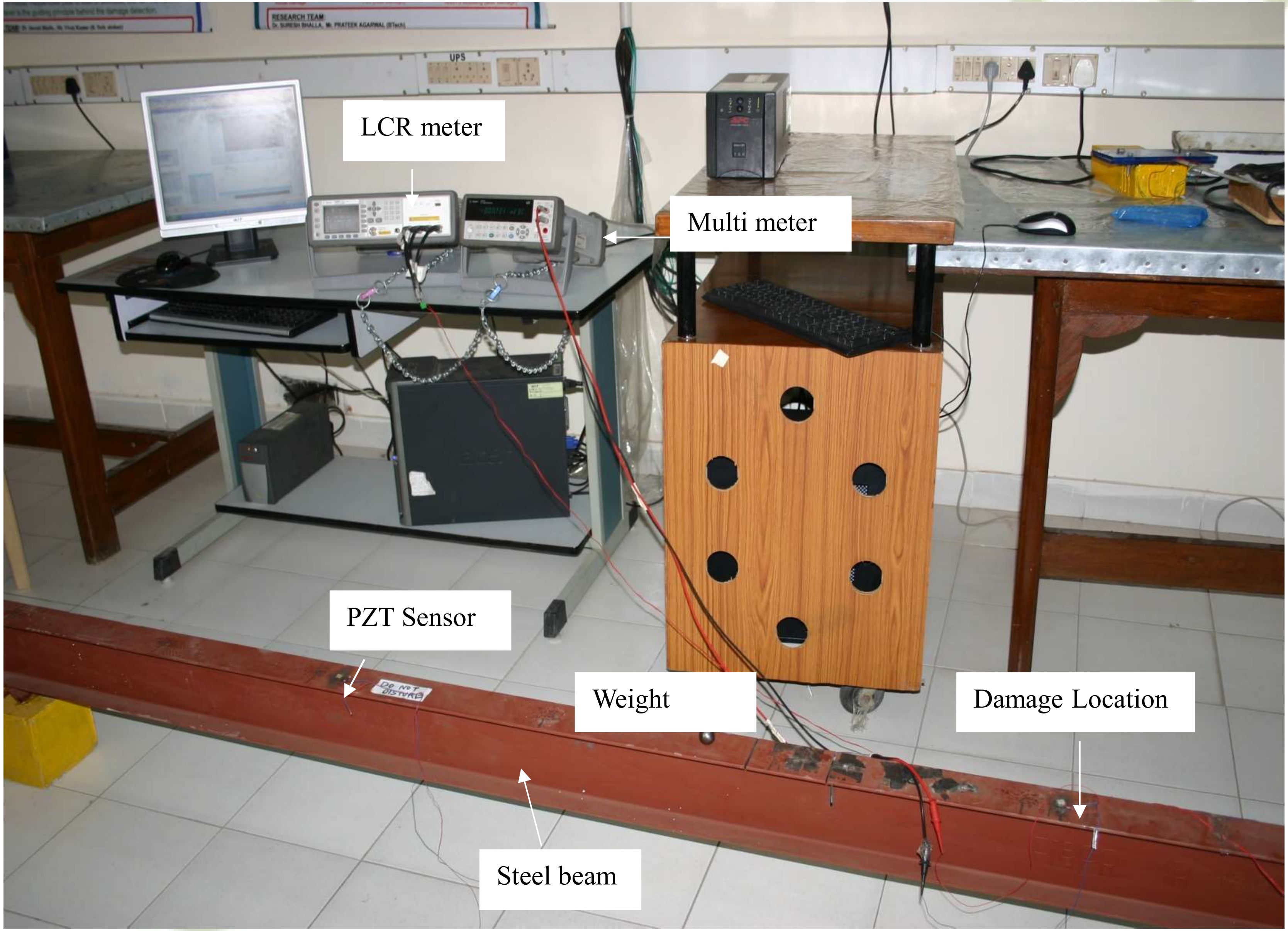
Please do self-assessment and comment on the above points with regard to both the techniques

ANY COMMON GROUND ?

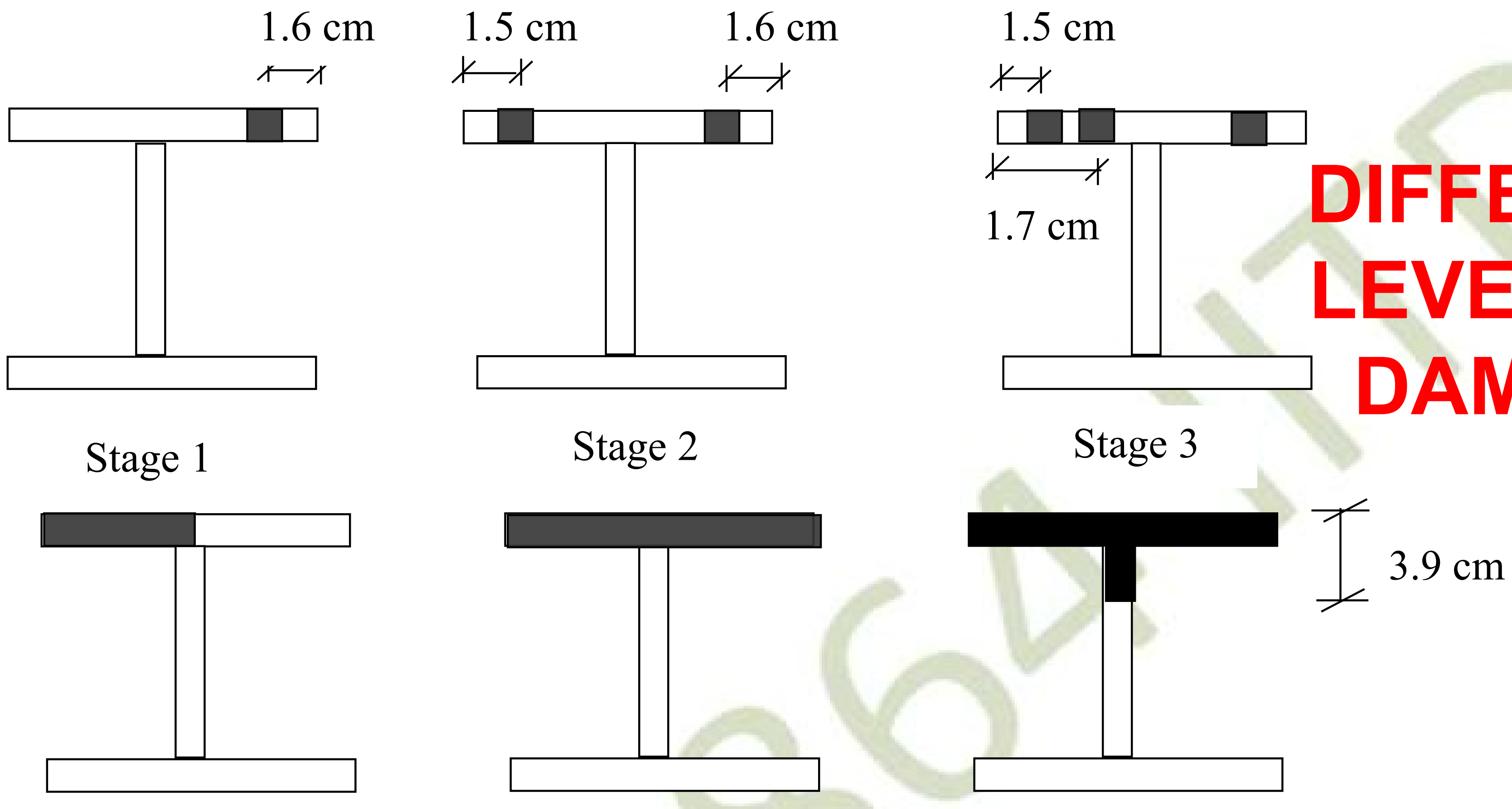
- Piezo sensors suitable for both
- Involve vibration
- Baseline healthy data needed to arrive at damage assessment

Can the two techniques be integrated? Let us go through a case study.

CASE STUDY 1:
SHANKER et al. (2011)

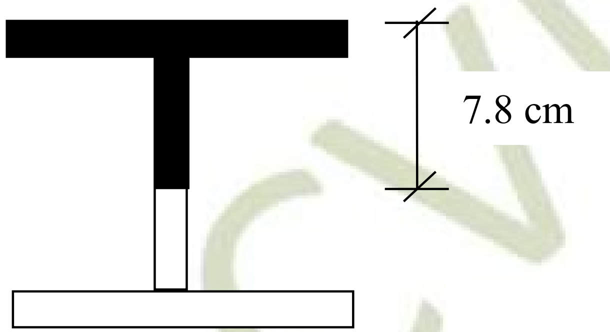


DIFFERENT LEVELS OF DAMAGE



Stage 1 Stage 2 Stage 3

Stage 4 Stage 5 Stage 6



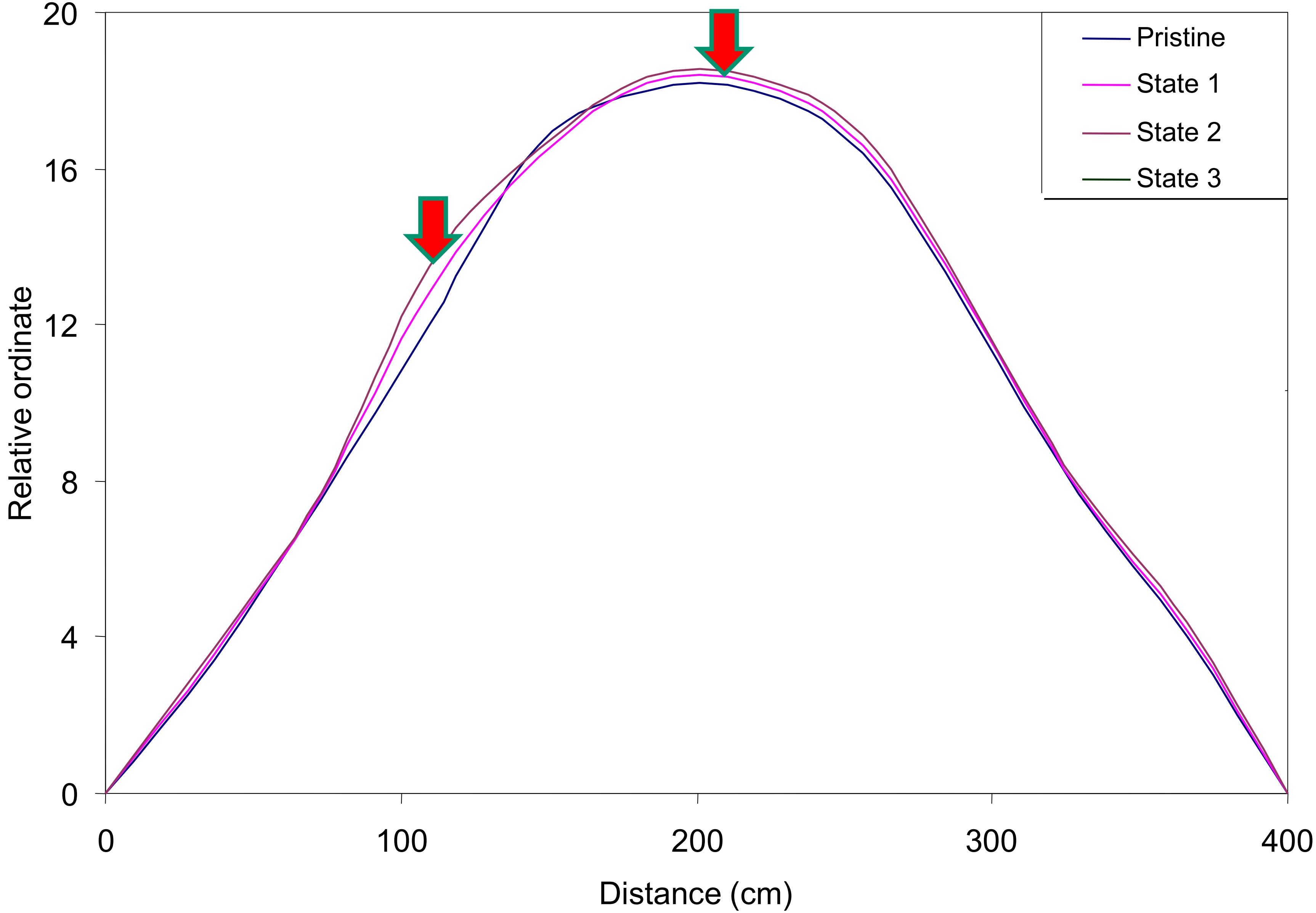
Stage 7

GLOBAL VIBRATION TECHNIQUE:
NATURAL FREQUENCIES

S.No.	State	First natural frequency / (% change)	Second natural frequency / (% change)	Third natural frequency / (% change)
1	Undamaged	45 (-)	190 (-)	410 (-)
2	State-1	45 (0.0%)	189 (0.52%)	410 (0.00%)
3	State-2	45 (0.0%)	189 (0.52%)	408 (0.49%)
4	State-3	41 (8.9%)	185 (0.97%)	402 (1.95%)
5	State-4	39 (13.3%)	182 (4.21%)	399 (2.68%)
6	State-5	37 (17.8%)	179 (5.79%)	392 (4.39%)
7	State-6	36 (20%)	174 (8.42%)	387 (5.61%)
8	State-7	34 (24.4%)	170 (10.52%)	380 (7.32%)

Changes not discernible in beginning (incipient damage)!!

GLOBAL VIBRATION TECHNIQUE: CURVATURE



Curvature mode shape from piezo patches (damage location doubtful)

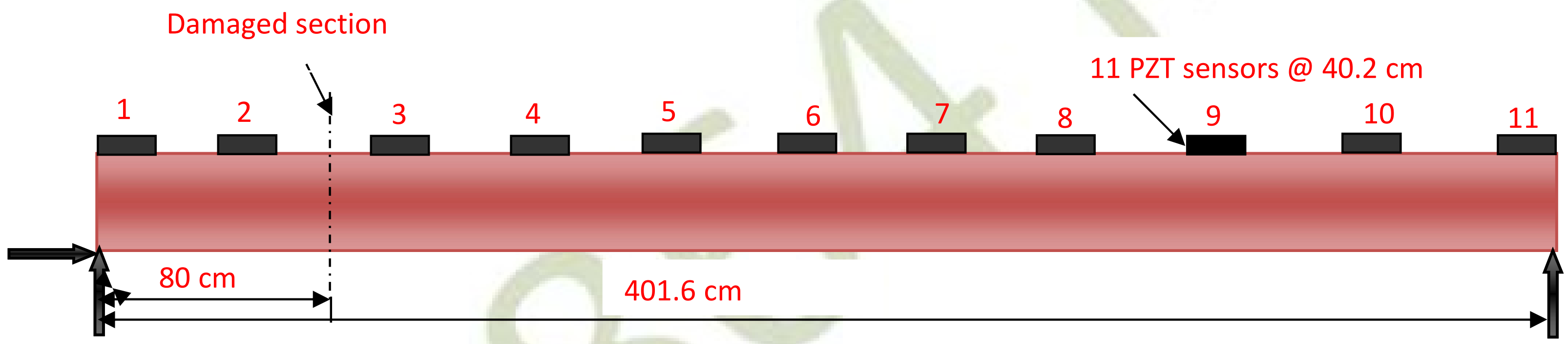
GLOBAL FREQUENCY CHANGES

S.No.	State	First natural frequency / (% change)	Second natural frequency / (% change)	Third natural frequency / (% change)
1	Pristine	45 (-)	190 (-)	410 (-)
2	State-1	45 (0.0%)	189 (0.52%)	410 (0.00%)
3	State-2	45 (0.0%)	189 (0.52%)	408 (0.49%)
4	State-3	41 (8.9%)	185 (0.97%)	402 (1.95%)
5	State-4	39 (13.3%)	182 (4.21%)	399 (2.68%)
6	State-5	37 (17.8%)	179 (5.79%)	392 (4.39%)
7	State-6	36 (20%)	174 (8.42%)	387 (5.61%)
8	State-7	34 (24.4%)	170 (10.52%)	380 (7.32%)

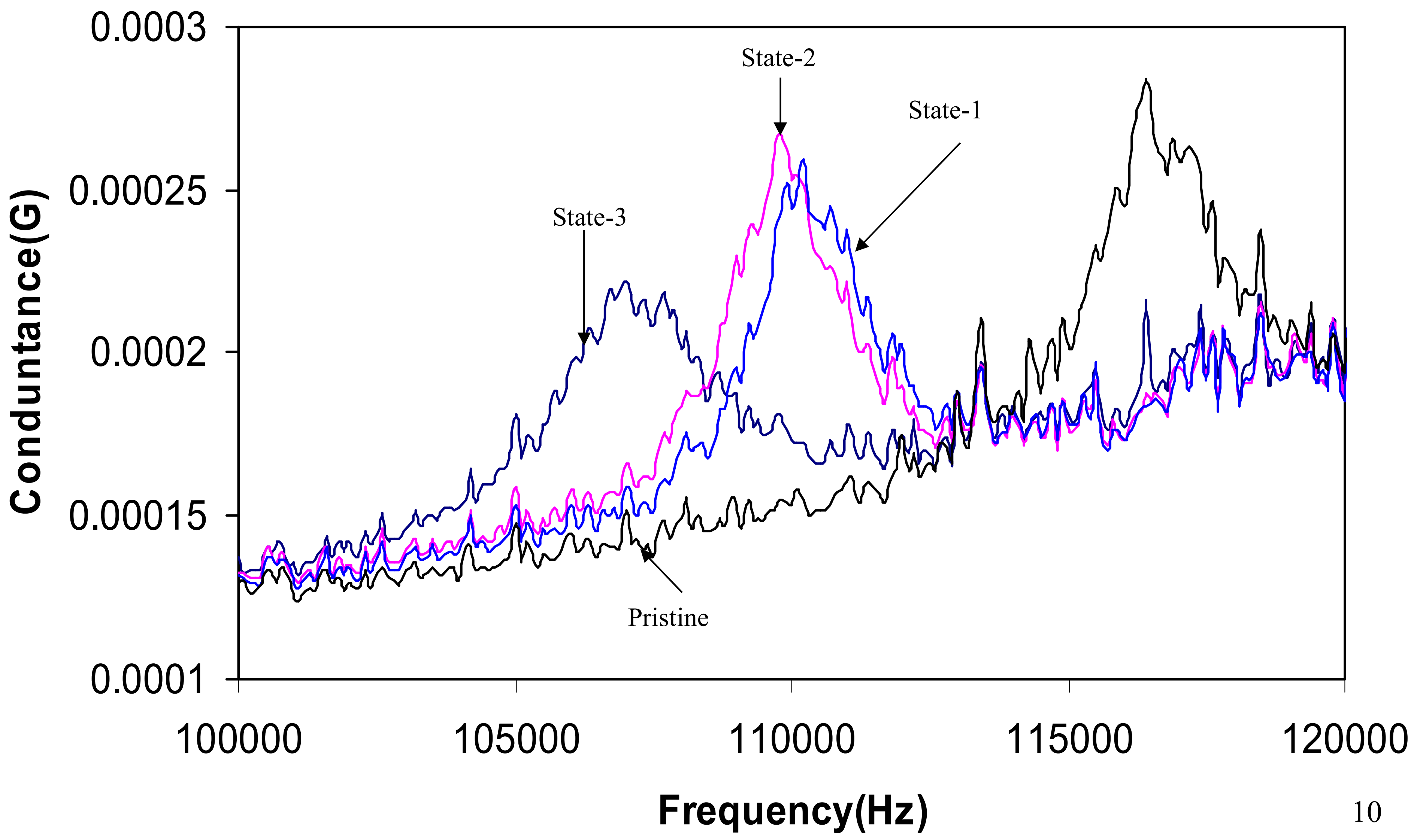
In real scenarios, such small changes might arise out of statistical variations!!!

LOCALIZATION MORE UNREIALBLE

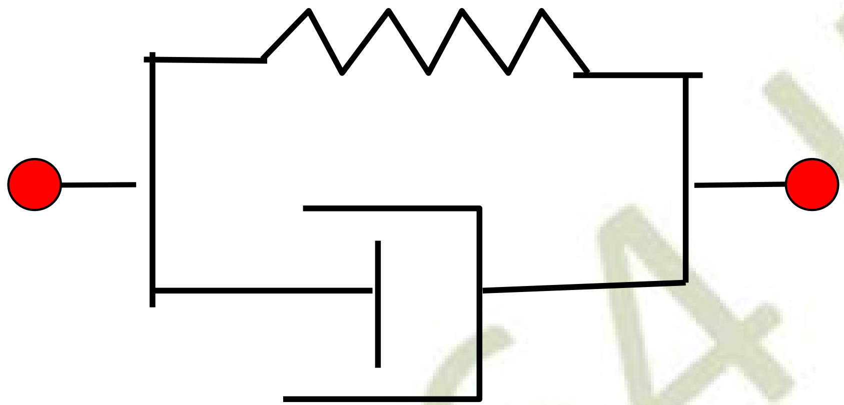
APPLICATION OF EMI TECHNIQUE USING ARRAY OF PZT PATCHES ON SAME BEAM



CONDUCTANCE SIGNATURES OF PZT PATCHES



IMPEDANCE BASED STRUCTURAL IDENTIFICTION



$$Z_{s,eff} = x + y\,j$$

$x = c$ and $y = -k/\omega$

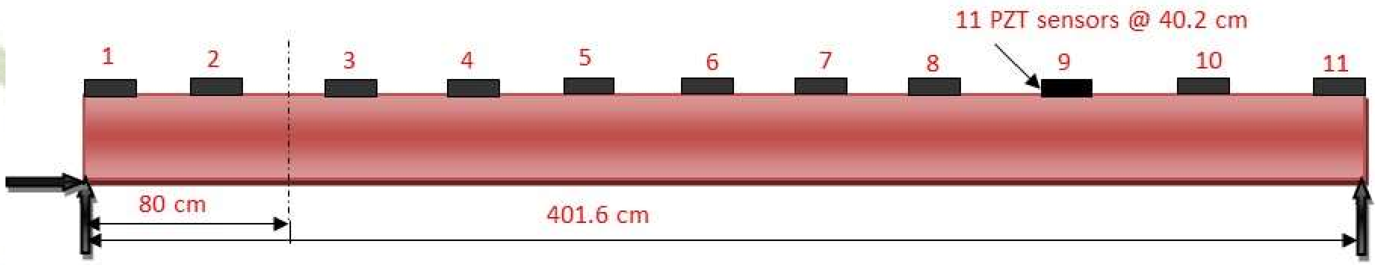
VARIATION OF EQUIVALENT PARAMETERS (EMI TECH.) PZT 5

S.No.	State	Equivalent Stiffness (k) (N/m)	Equivalent Damping (c) (Ns/m)	% change	
				k	c
1	Pristine	6.53×10^6	8.94	0	0
2	State-1	6.73×10^6	8.50	2.9	4.9
3	State-2	6.83×10^6	8.45	5.4	5.5
4	State-3	7.04×10^6	8.39	7.2	6.2
5	State-4	7.05×10^6	8.35	7.4	6.6
6	State-5	7.06×10^6	8.32	7.5	6.9
7	State-6	7.09×10^6	8.30	7.8	7.2
8	State-7	7.09×10^6	8.30	7.8	7.2

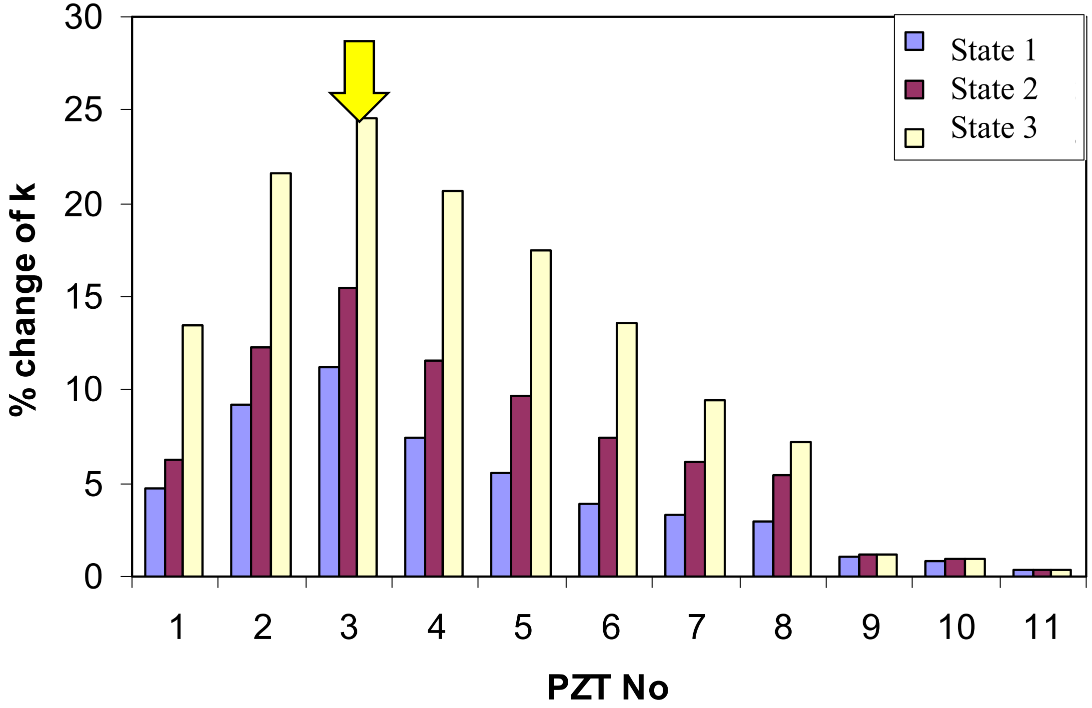
Changes of discernible magnitude even for incipient damage (in contrast to natural frequencies/ curvature!!!!)

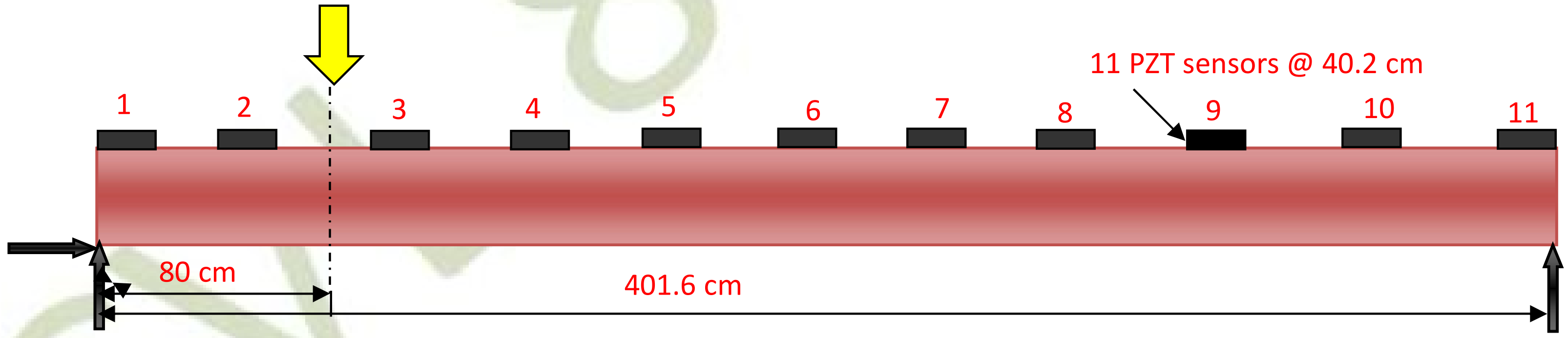
VARIATION OF EQUIVALENT PARAMETERS FOR ALL PZT PATCHES

PZT No	Pristine k(N/m) × 10^6	State 1		State 2		State 3	
		k(N/m) × 10^6	Change (%)	k(N/m) × 10^6	Change (%)	k(N/m) × 10^6	Change (%)
PZT 1	6.56	6.86	4.7	6.97	6.3	7.44	13.5
PZT 2	8.67	9.47	9.2	9.73	12.3	10.54	21.6
PZT 3	7.65	8.51	11.2	8.83	15.5	9.53	24.6
PZT 4	5.97	6.41	7.4	6.67	11.6	7.20	20.7
PZT 5	8.45	8.92	5.6	9.26	9.7	10.03	17.5
PZT 6	6.78	7.04	3.9	7.28	7.4	7.70	13.6
PZT 7	8.56	9.44	3.3	9.09	6.2	9.37	9.5
PZT 8	6.53	6.73	2.9	6.83	5.4	6.83	7.2
PZT 9	8.56	8.65	1.1	8.66	1.2	8.66	1.2
PZT 10	6.63	6.68	0.8	6.69	0.9	6.69	0.9
PZT 11	7.89	7.92	0.4	7.92	0.4	7.92	0.4



LOCALIZATION OF INCIPIENT DAMAGE





ANY LIMITATIONS OF EMI TECHNIQUE?? (SEE PZT 5)

S.No.	Damage state	Equivalent Stiffness (k) (N/m)	Equivalent Damping (c) (Ns/m)	% change	
				k	c
1	undamaged	6.53×10^6	8.94	0	0
2	State-1	6.73×10^6	8.50	2.9	4.9
3	State-2	6.83×10^6	8.45	5.4	5.5
4	State-3	7.04×10^6	8.39	7.2	6.2
5	State-4	7.05×10^6	8.35	7.4	6.6
6	State-5	7.06×10^6	8.32	7.5	6.9
7	State-6	7.09×10^6	8.30	7.8	7.2
8	State-7	7.09×10^6	8.30	7.8	7.2

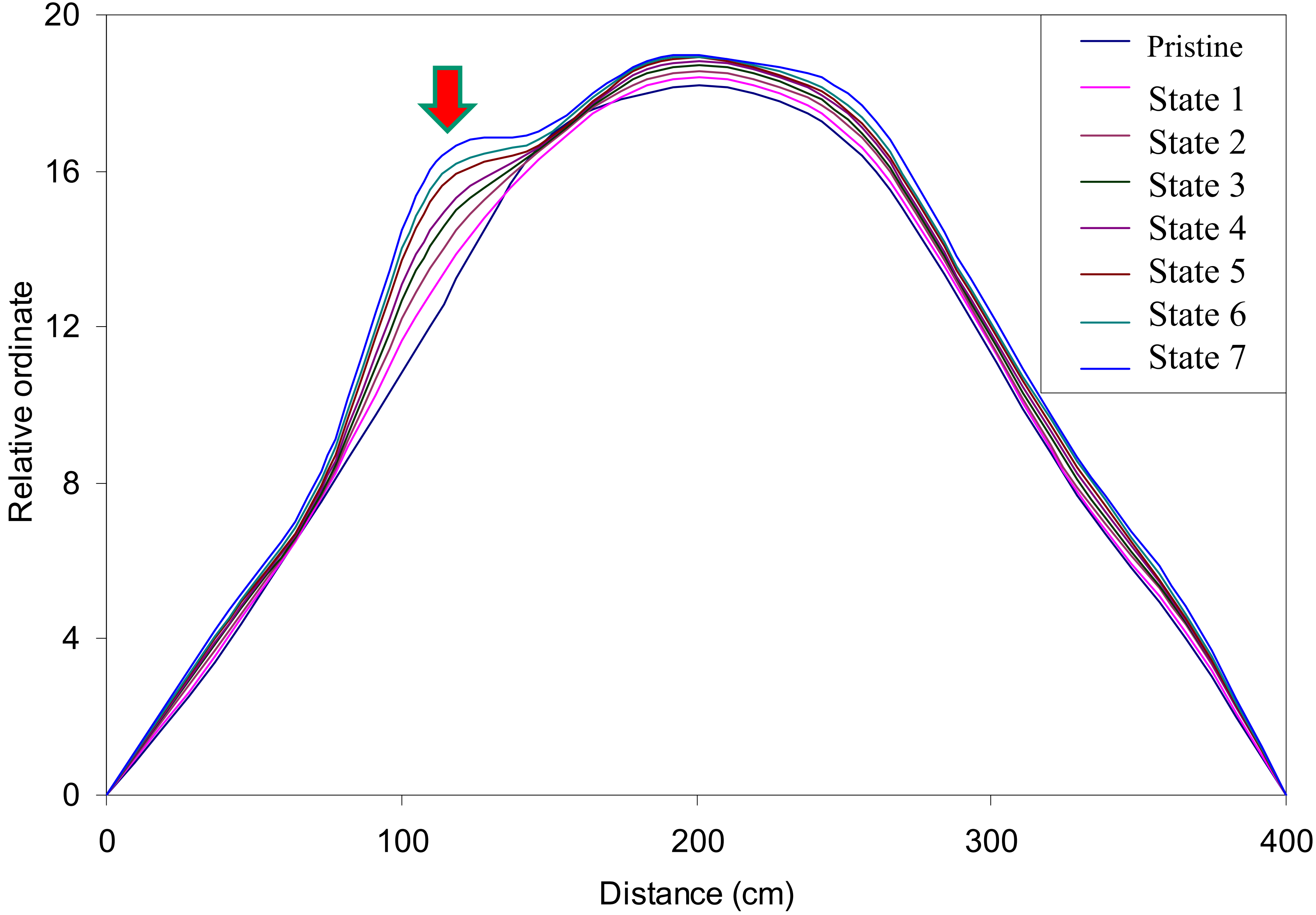
Hardly any further change after damage reaches moderate level….

GLOBAL VIBRATION INDICATORS CAN ALLEVIATE THIS PROBLEM

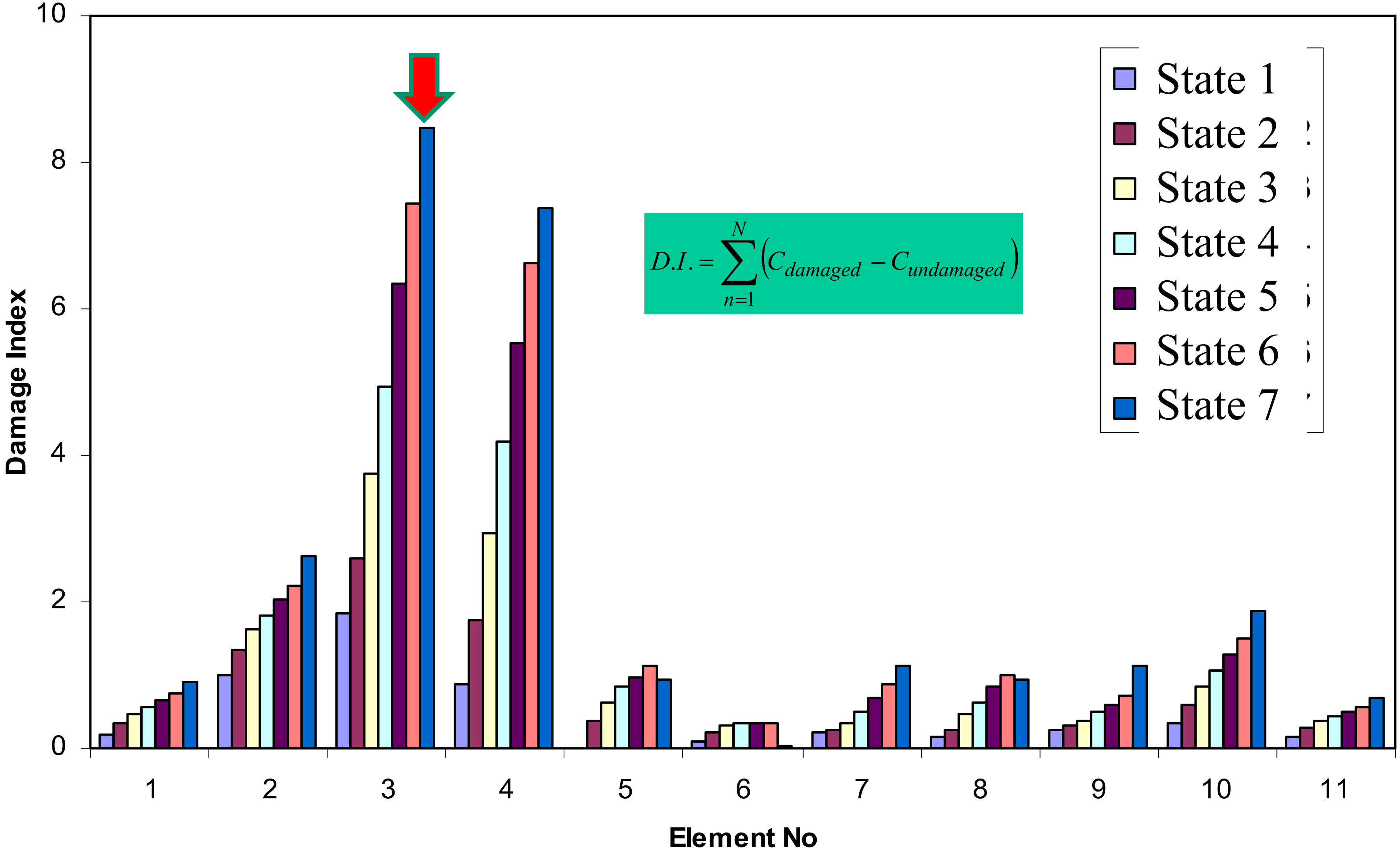
S.No.	Damage state	First natural frequency / (% change)	Second natural frequency / (% change)	Third natural frequency / (% change)
1	Undamaged	25 (-)	190 (-)	410 (-)
2	State-1	25 (0.0%)	189 (0.52%)	410 (0.00%)
3	State-2	25 (0.0%)	189 (0.52%)	408 (0.49%)
4	State-3	23 (8.0%)	185 (0.97%)	402 (1.95%)
5	State-4	22 (12.0%)	182 (4.21%)	399 (2.68%)
6	State-5	21 (16.0%)	179 (5.79%)	392 (4.39%)
7	State-6	21 (16.0%)	174 (8.42%)	387 (5.61%)
8	State-7	19 (24.0%)	170 (10.52%)	380 (7.32%)

Changes discernible for moderate to severe damage

DAMAGE LOCATION IDENTIFICATION USING GLOBAL TECHNIQUE (MODERATE DAMAGE)



DAMAGE LOCATION IDENTIFICATION USING GLOBAL DYNAMIC TECHNIQUE



$$D.I. = \sum_{n=1}^{N} \left(C_{damaged} - C_{undamaged} \right)$$

IN CONCLUSION……

- **EMI TECHNIQUE CAN FACILITATE CAPTURE OF INCIPIENT DAMAGE.**

- **IT CAN ALSO ENABLE DAMAGE LOCALIZATION.**

- **FURTHER ADVANTAGE OF THE EMI TECHNIQUE CEASES AFTER THE DAMAGE REACHES MODERATE TO SEVERE LEVEL.**

- **SEVERE DAMAGE CAN BE MORE REALISTICALLY QUANTIFIED BY GLOBAL VIBRATION TECHNIQUES.**

- **BOTH TECHNIQUES MEANINGFULLY COMPLEMENT EACH OTHER.**

SUGGESTED READING:
Shanker et al. (2011)

PART (II)

LOW-COST ADAPTATIONS AND PRACTICAL CONSIDERATIONS

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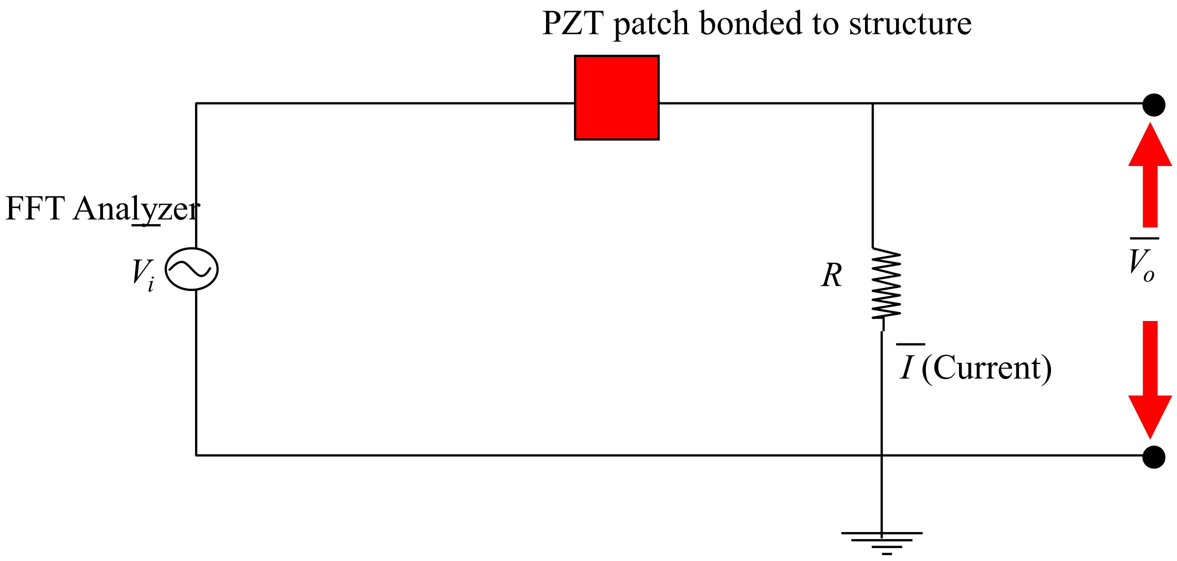
COST-EFFECTIVE ADAPTATION OF EMI TECHNIQUE

Conventionally, the EMI technique employs impedance analyzer (or the LCR meter), which typically costs Rs 8 to 15 lakh.

Peairs et al. (2004) proposed a low cost electrical admittance measurement technique based on FFT analyzer (which typically costs Rs 5 lakh) in place of the impedance analyzer.



Circuit employed by Peairs et al. (2004).

$$\bar{I} = \frac{\bar{V}_o}{R}$$

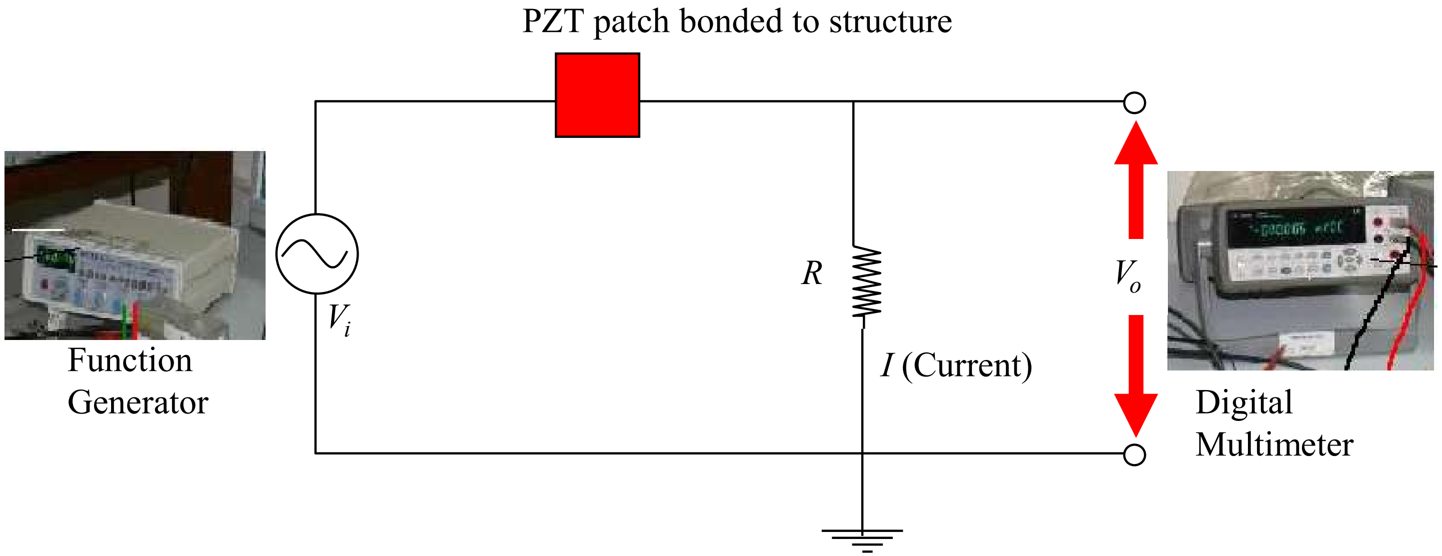
$$\bar{Y} = \frac{\bar{I}}{\bar{V}_i - R\bar{I}} \approx \frac{\bar{V}_o}{R\bar{V}_i}$$

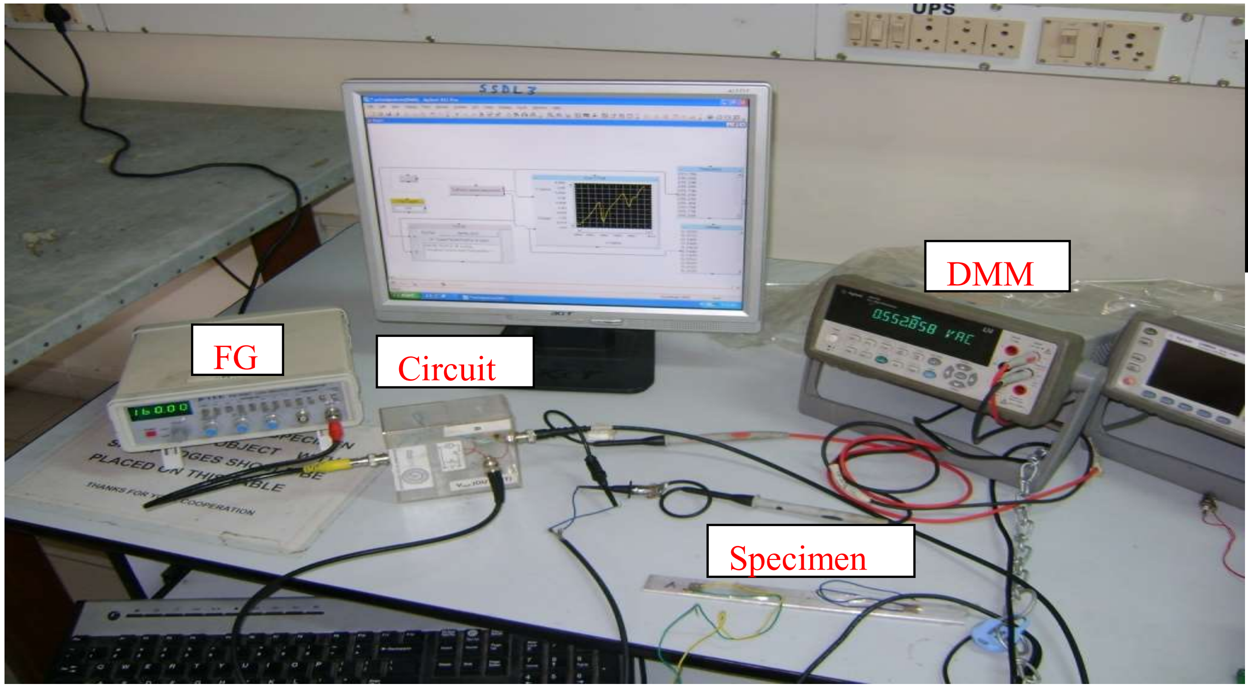
COST-EFFECTIVE ADAPTATION OF EMI TECHNIQUE

TWO HARDWARE SOLUTIONS DEVELOPED AT IIT DELHI

1. SELF IMPEDANCE APPROACH
2. TRANSFER IMPEDANCE APPROACH

PROPOSED SELF IMPEDANCE APPROACH (Bhalla et al, 2009)

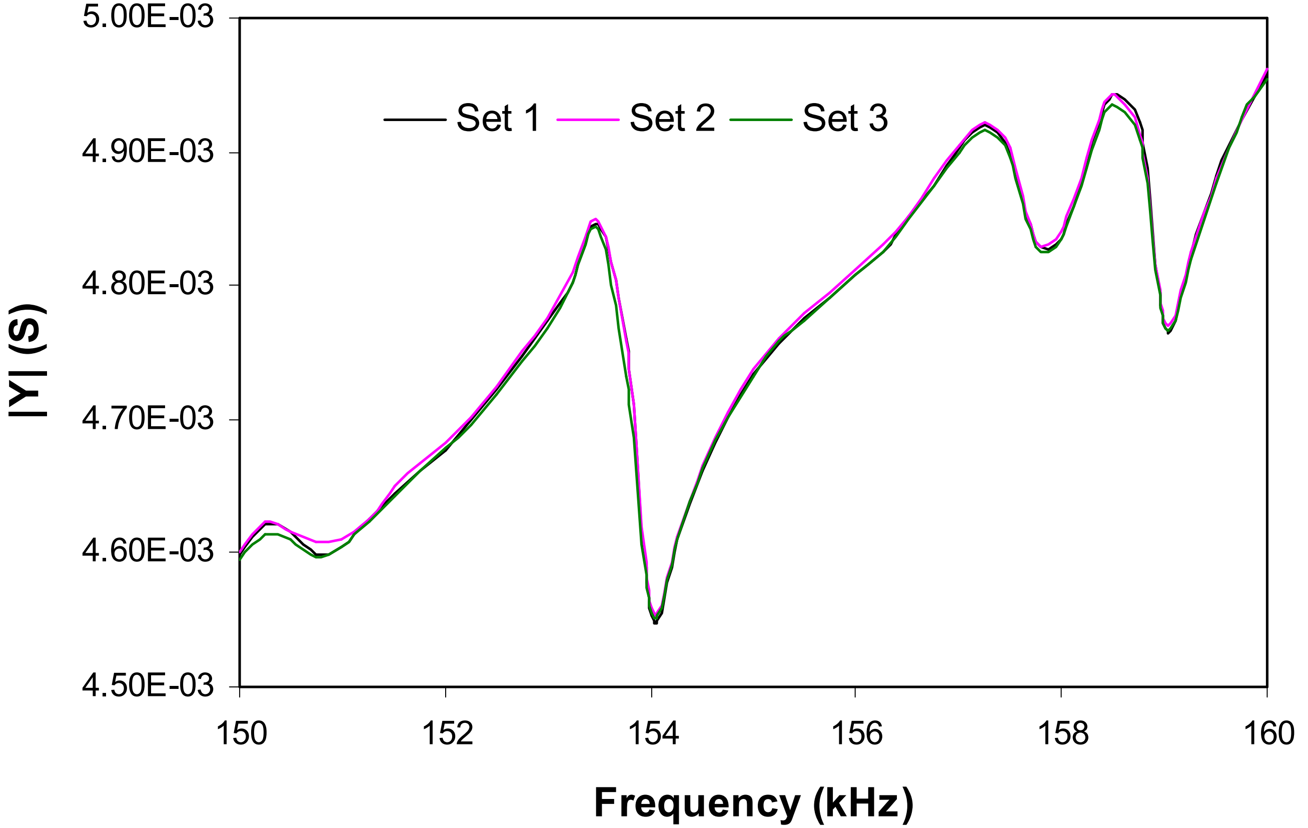




Hardware cost

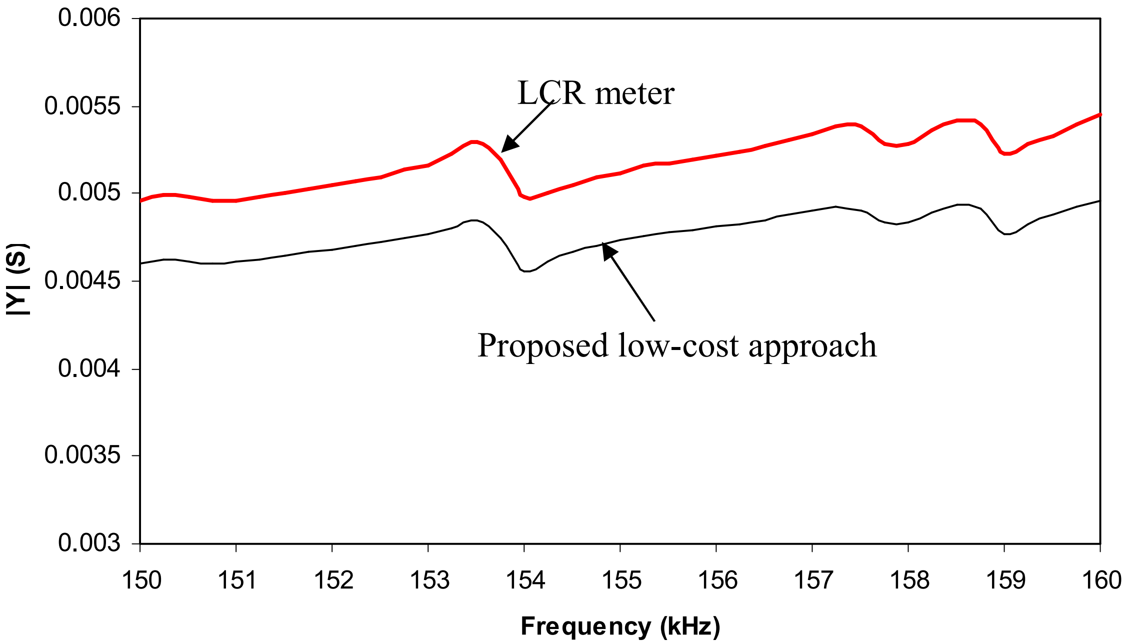
< Rs 1 lakh !!!

REPEATIBILITY TEST



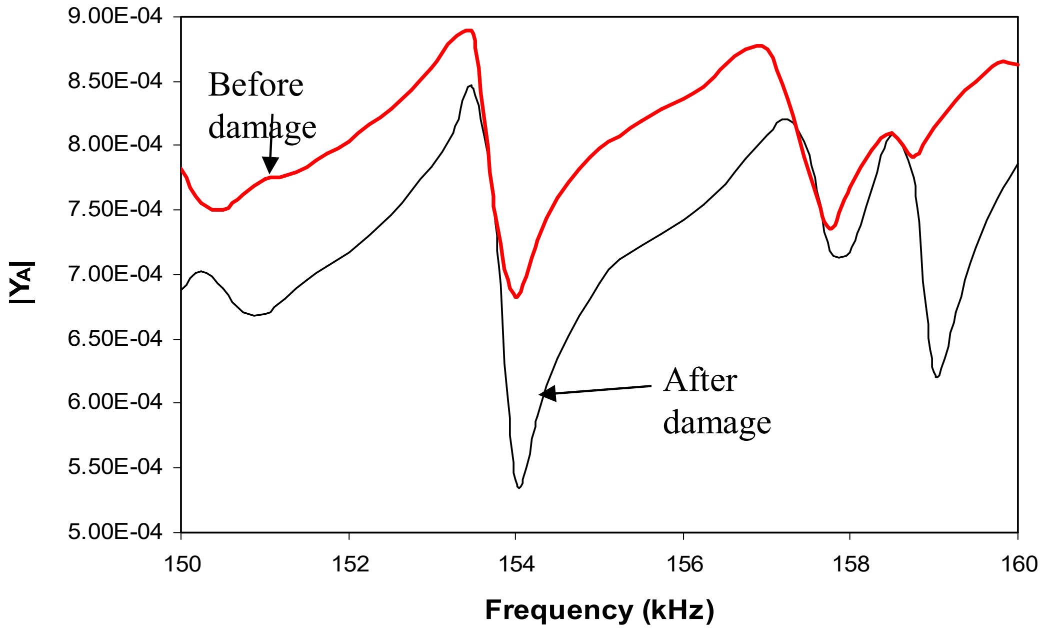
Excellent Repeatability

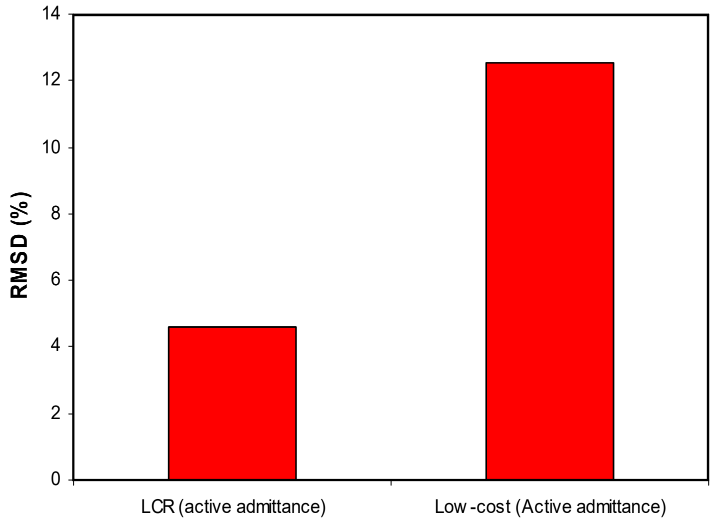
However, we need to be content with absolute magnitude only…..



~ 5% deviation

This deviation is not very significant since EMI technique depends upon “change” in signature rather than the absolute value





ENHANCED SENSITIVITY VIA SIGNATURE DECOMPOSITION

$$\overline{Y} = G + Bj = 4\omega\, j\,\frac{l^2}{h}\left[\overline{\varepsilon_{33}^{T}} - \frac{2d_{31}^{2}\overline{Y^{E}}}{(1-\nu)} + \frac{2d_{31}^{2}\overline{Y^{E}}}{(1-\nu)}\left(\frac{Z_{a,eff}}{Z_{s,eff} + Z_{a,eff}}\right)\overline{T}\right]$$

$$\overline{Y} = \overline{Y_P} + \overline{Y_A}$$

PASSIVE

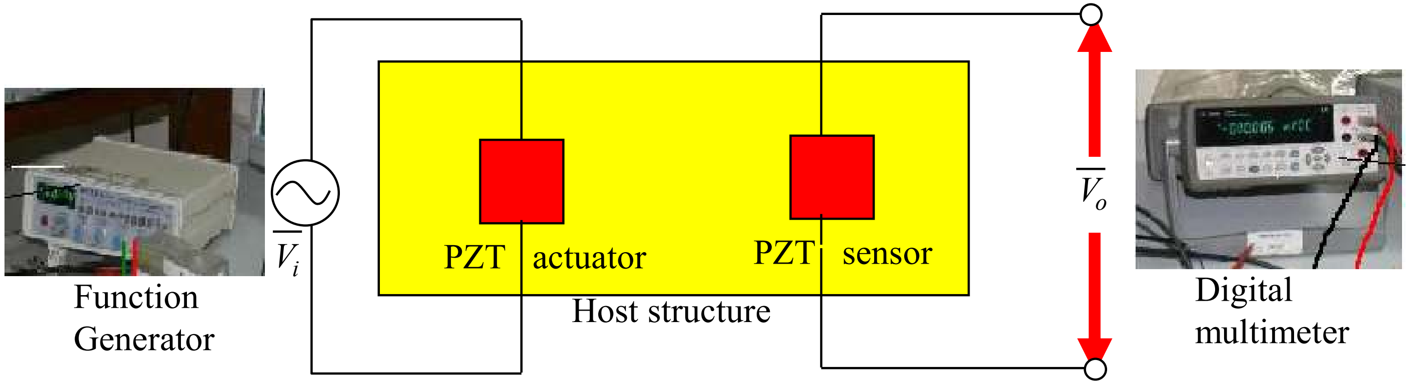
$$\overline{Y_P} = 4\omega j\,\frac{l^2}{h}\left[\overline{\varepsilon_{33}^{T}} - \frac{2d_{31}^{2}\overline{Y^{E}}}{(1-\nu)}\right]$$

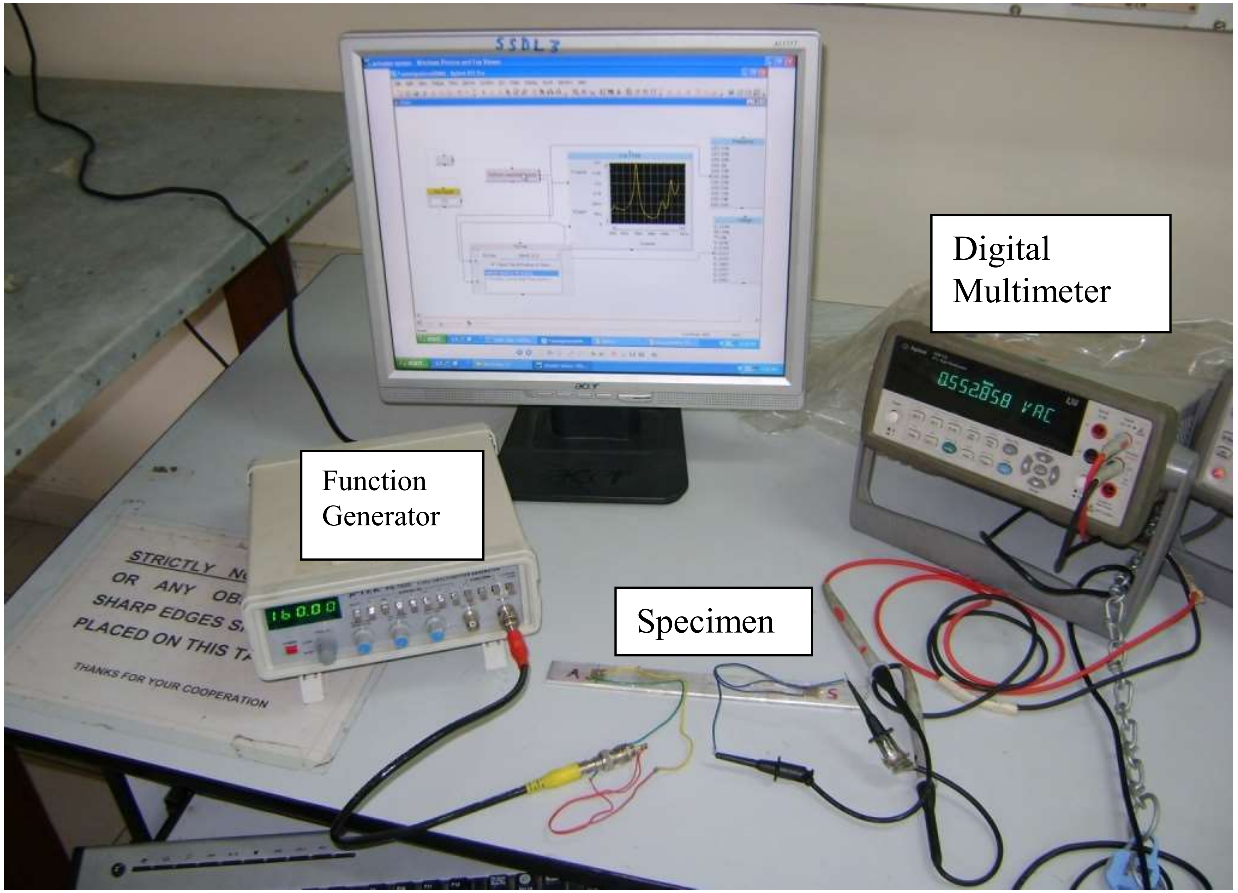
ACTIVE

$$\overline{Y_A} = \frac{8\omega d_{31}^{2}\overline{Y^{E}}l^2}{h(1-\nu)}\left(\frac{Z_{a,eff}}{Z_{s,eff} + Z_{a,eff}}\right)\overline{T}j$$

$$\left|Y_A\right| \approx Y - Y_P$$

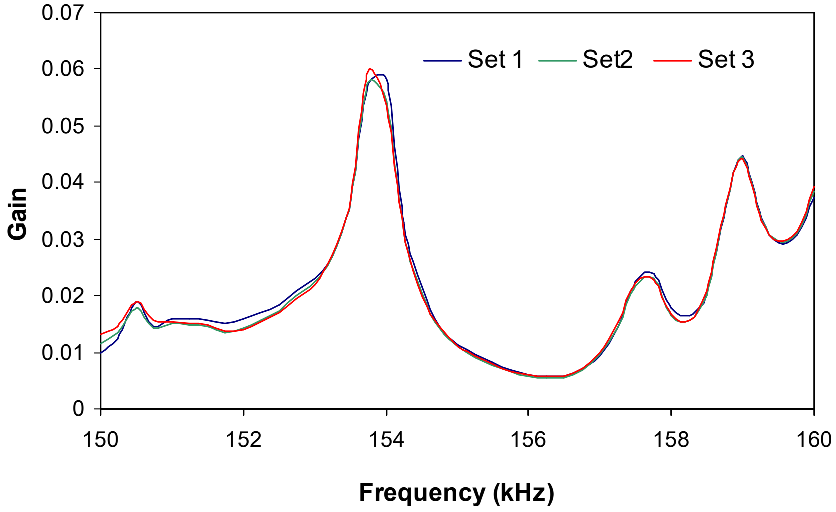
PROPOSED TRANSFER IMPEDANCE APPROACH (Bhalla et al., 2009)





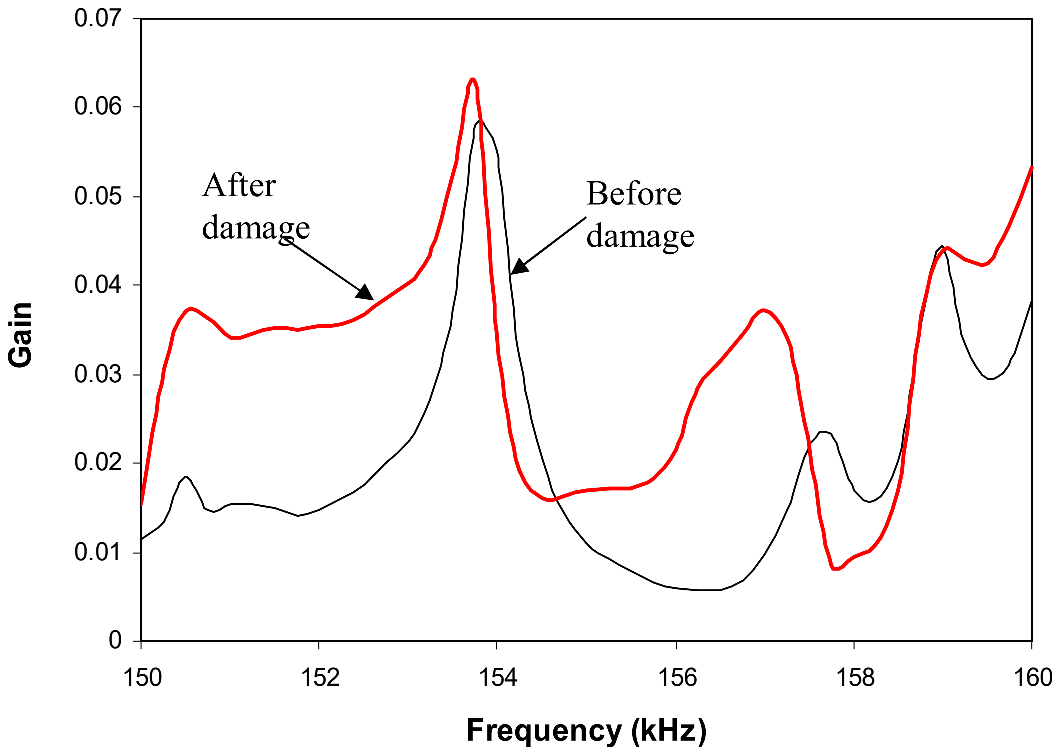
Hardware cost

< Rs 1 lakh !!!



Excellent Repeatability

Effect of damage

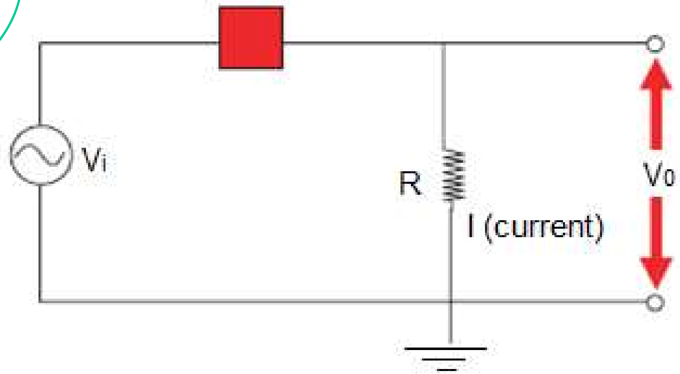


FURTHER REFINEMENT AND FULL AUTOMATION (Chudamani, 2011)

Bhalla et al., 2009

FG model 702C (μ-TEC Electronic Measuring Instruments)

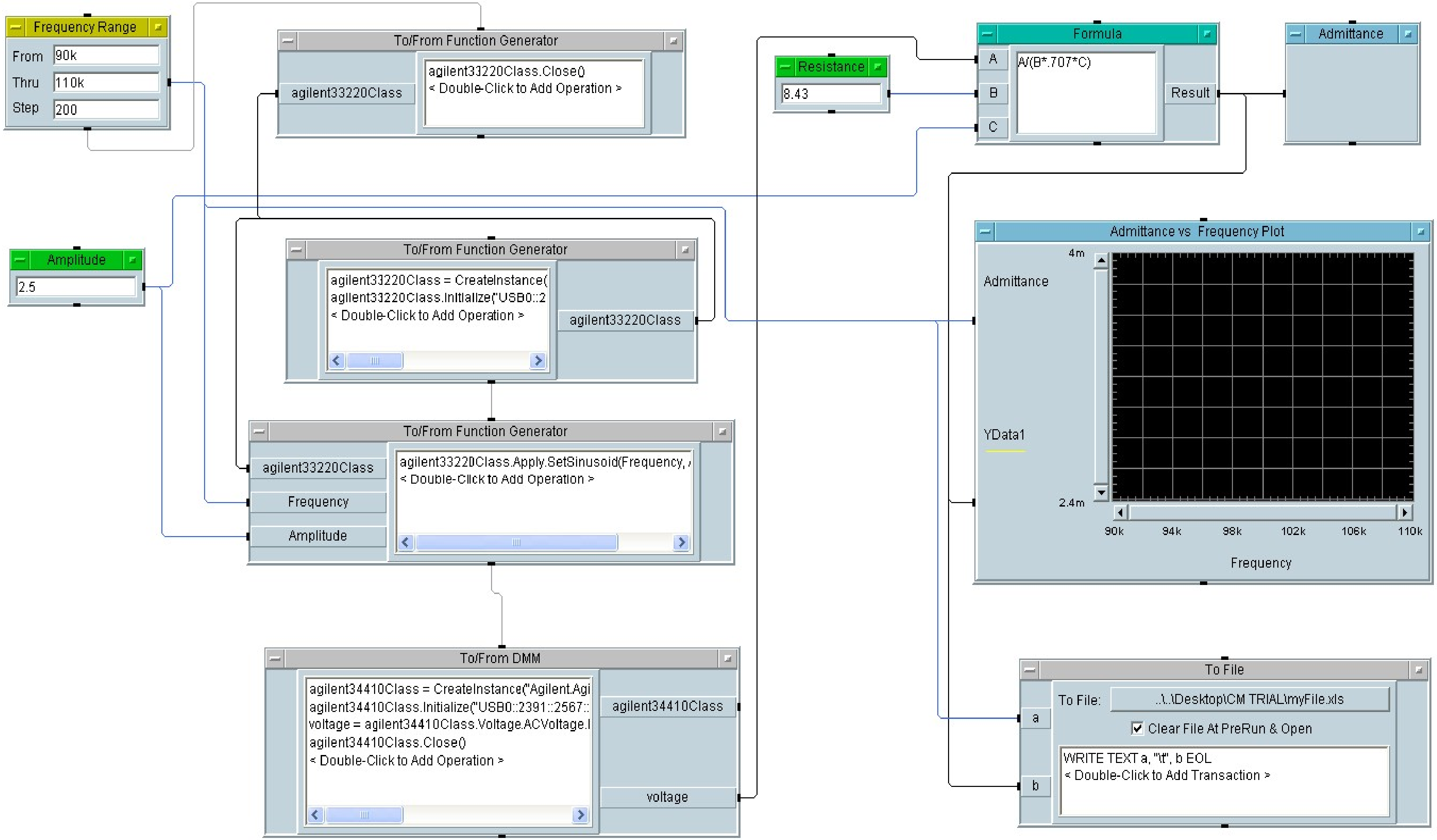
Earlier model (not suitable for VXI control)



- Frequency input : both Quasi-sweep and Step by Step manner, while
- Can be control by VEE PRO software.
- In FG model 702C, active human intervention is necessary.

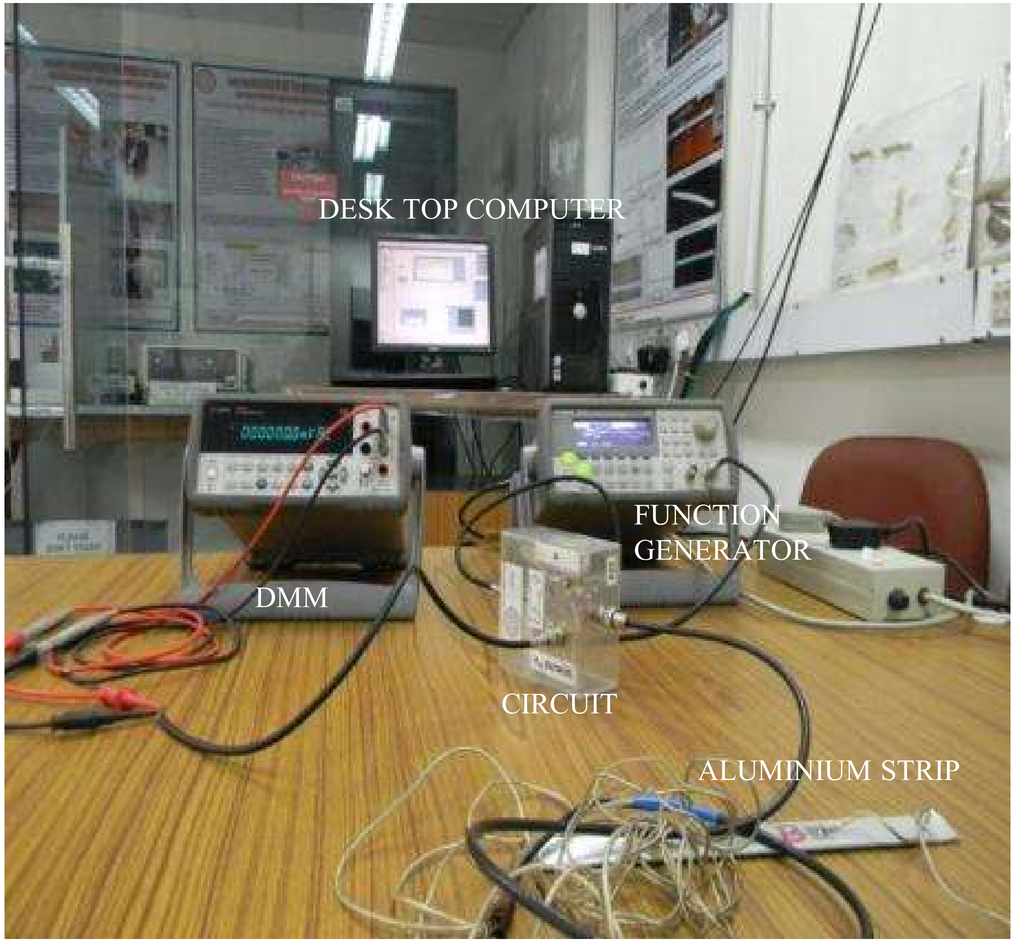
AUTOMATION OF LOW-COST HARDWARE SET-UP

Low-Cost Hardware Set-up VEE PRO



CONTD….

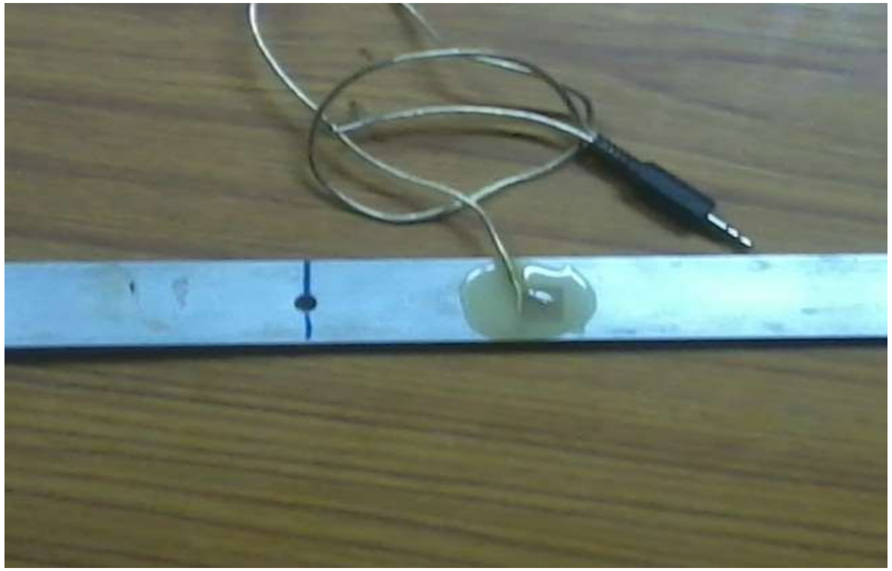
EXPERIMENT I: REPEATIBILITY STUDY



Low Cost Hardware Set-up

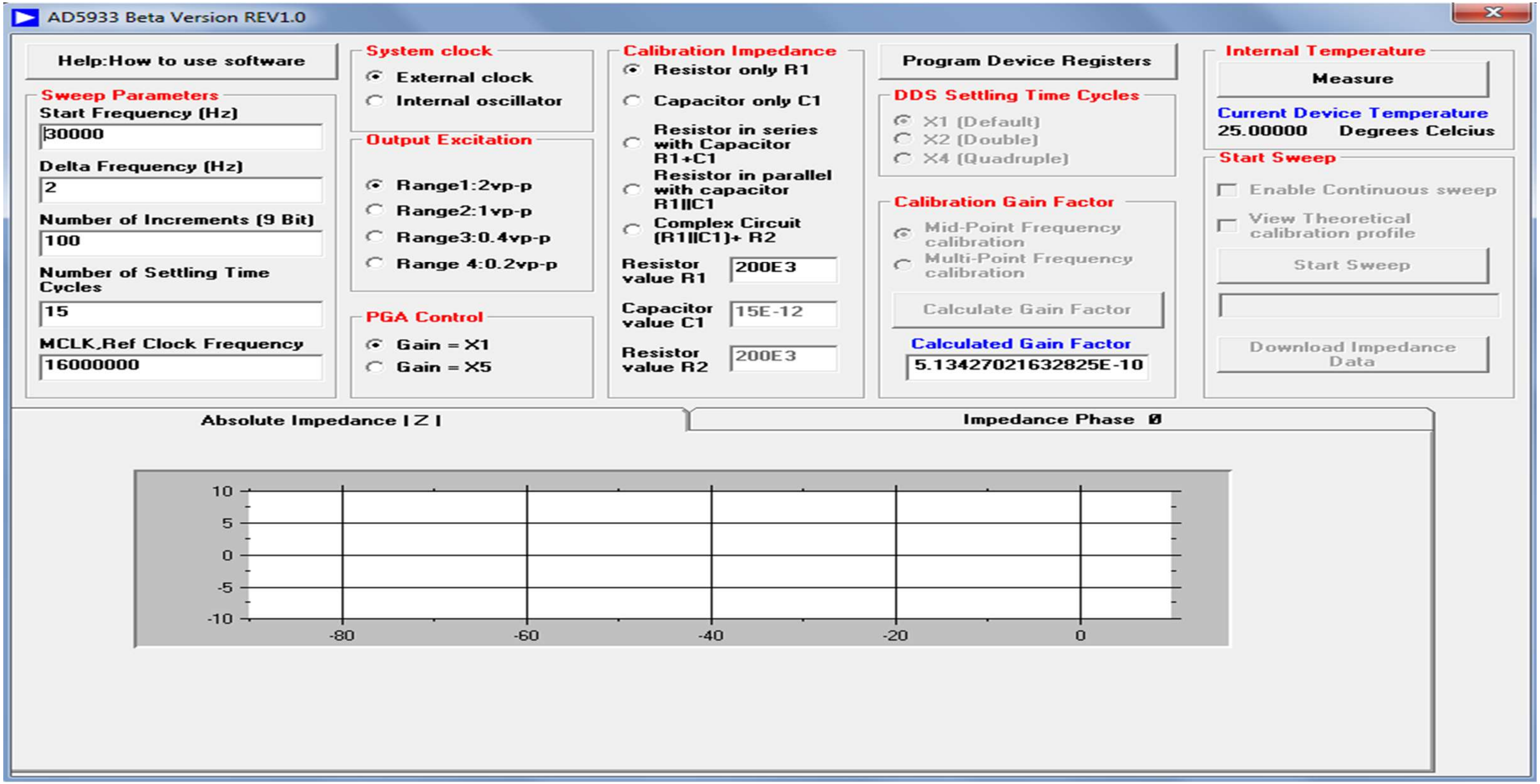
LCR Meter

MINIATURE IMPEDANCE ANALYZER

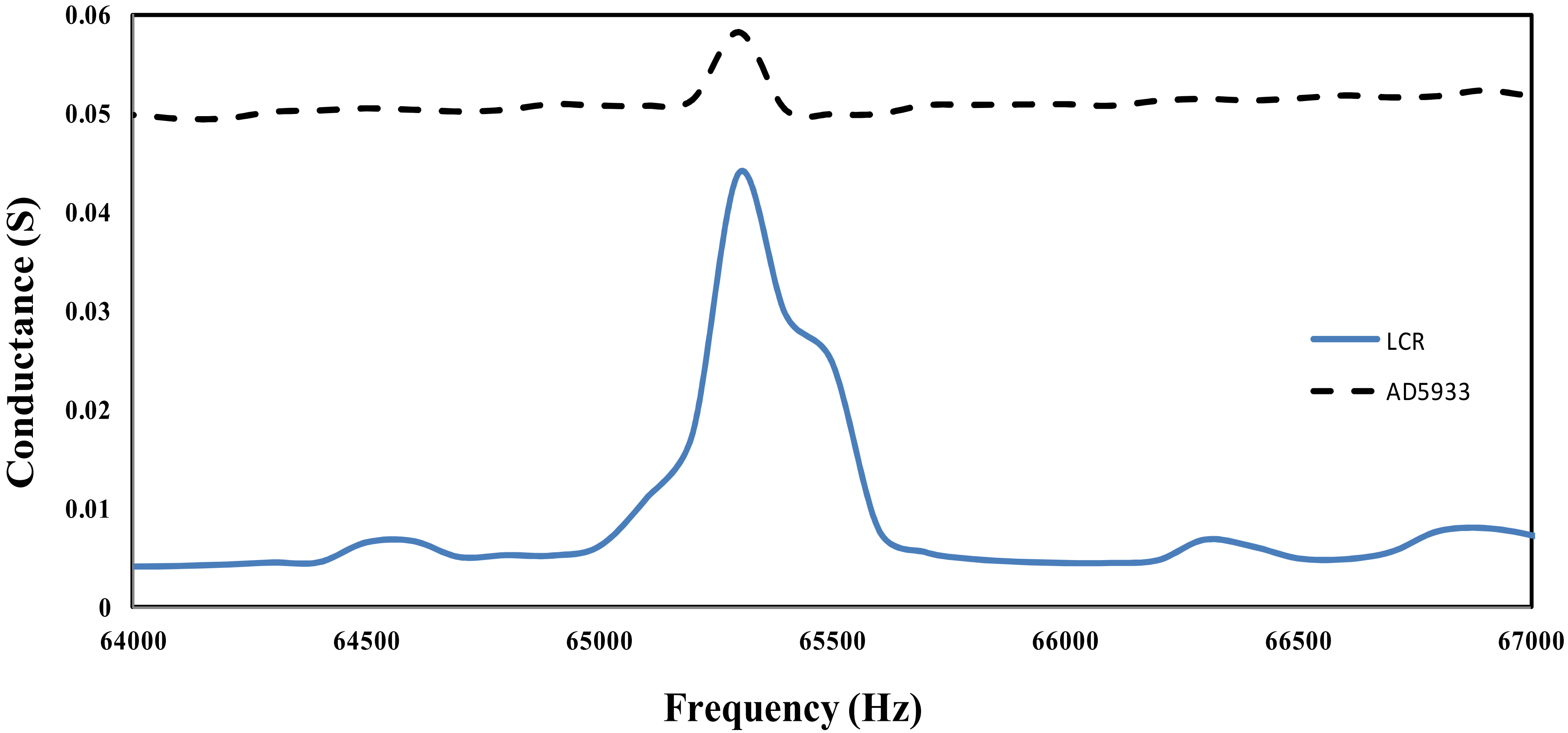


COST COMPARISION	
LCR Meter	$ 20000
Low-cost EMI	$ 2000
AD5933	$ 200

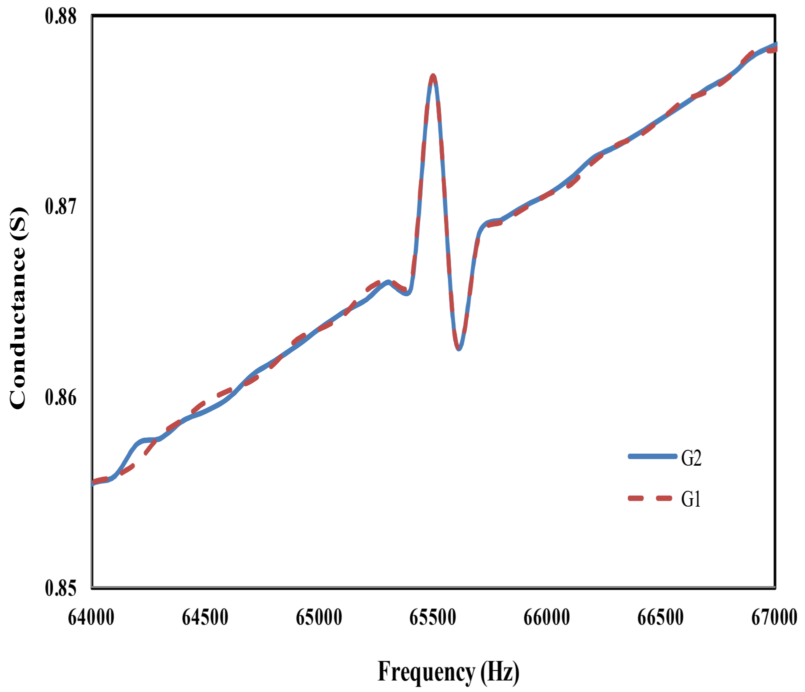
USER INTERFACE OF AD5933

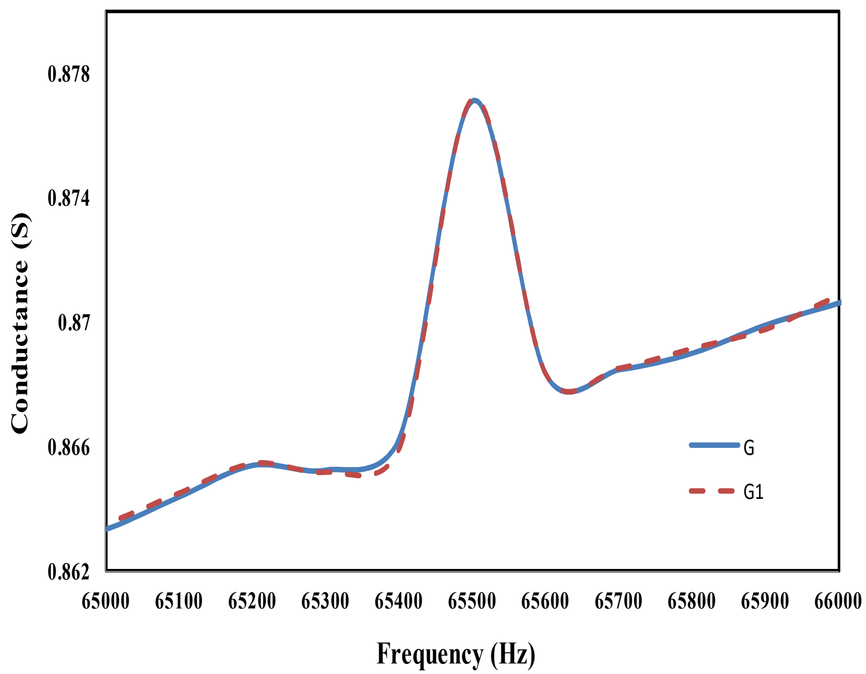


COMPARISON WITH LCR

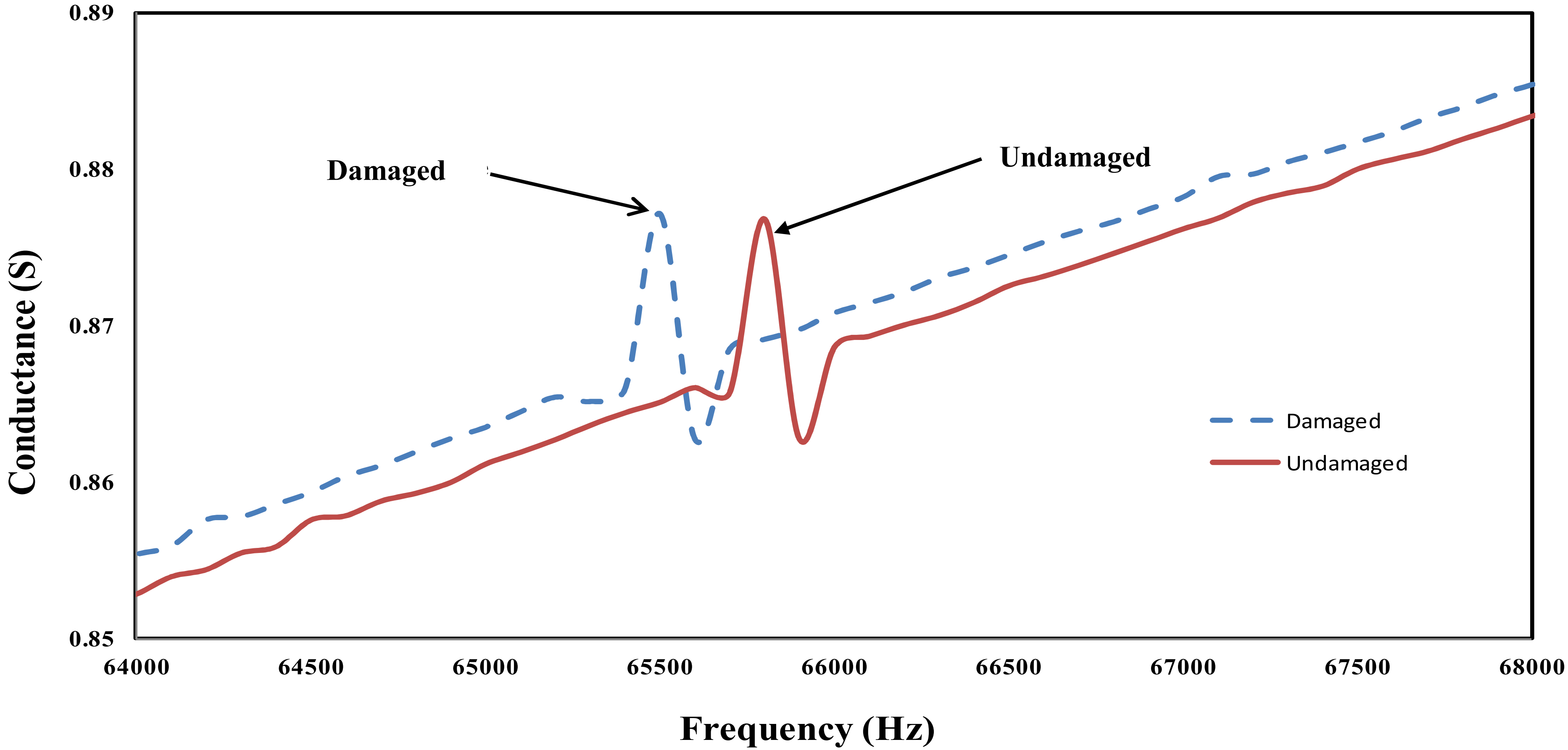


REPEATIBILITY TEST

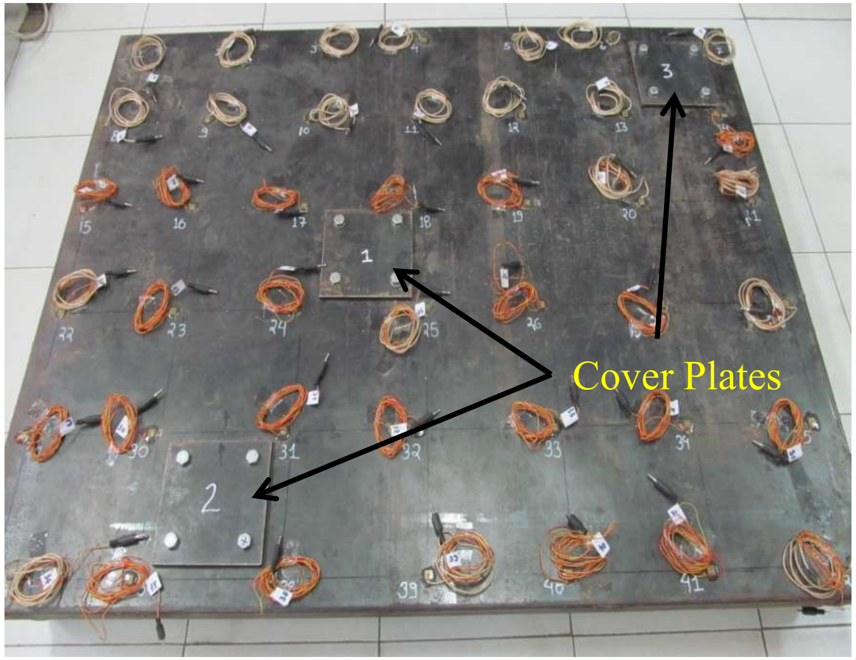




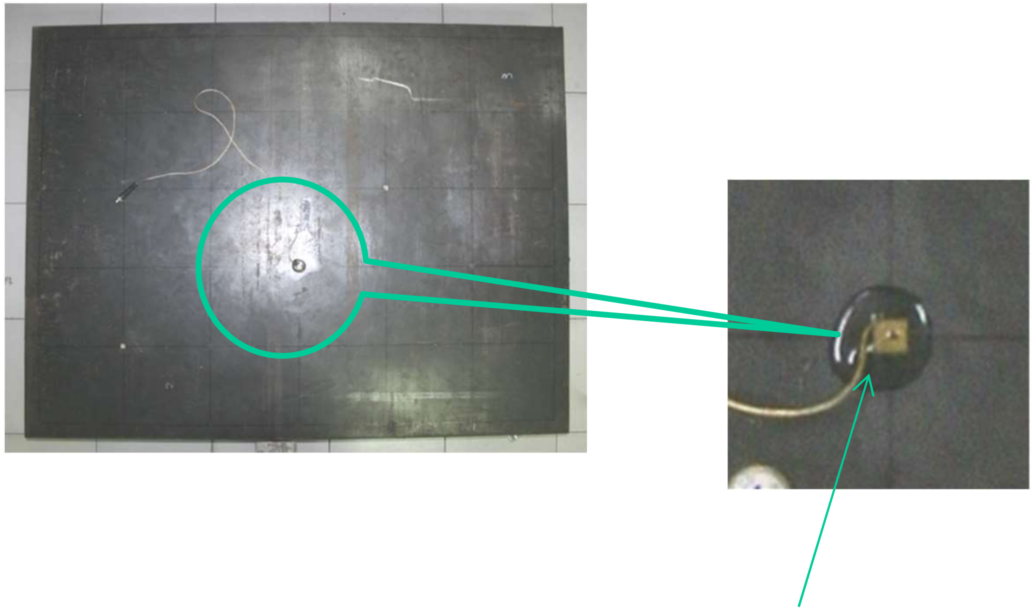
DAMAGE INDUCTION



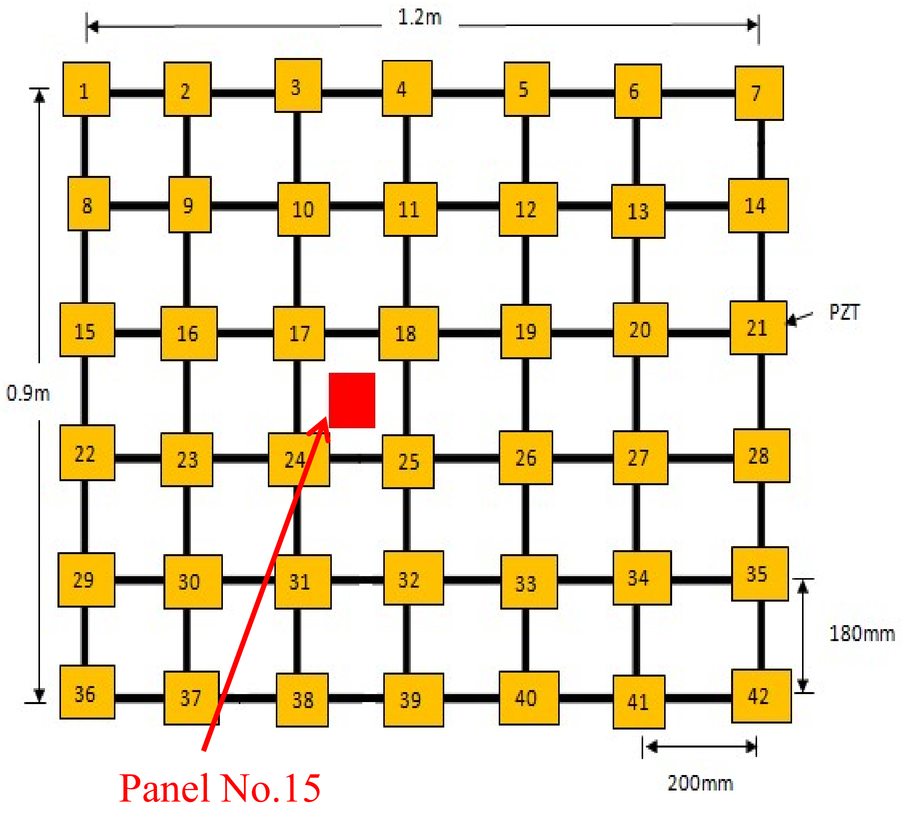
EXPERIMENTAL SETUP



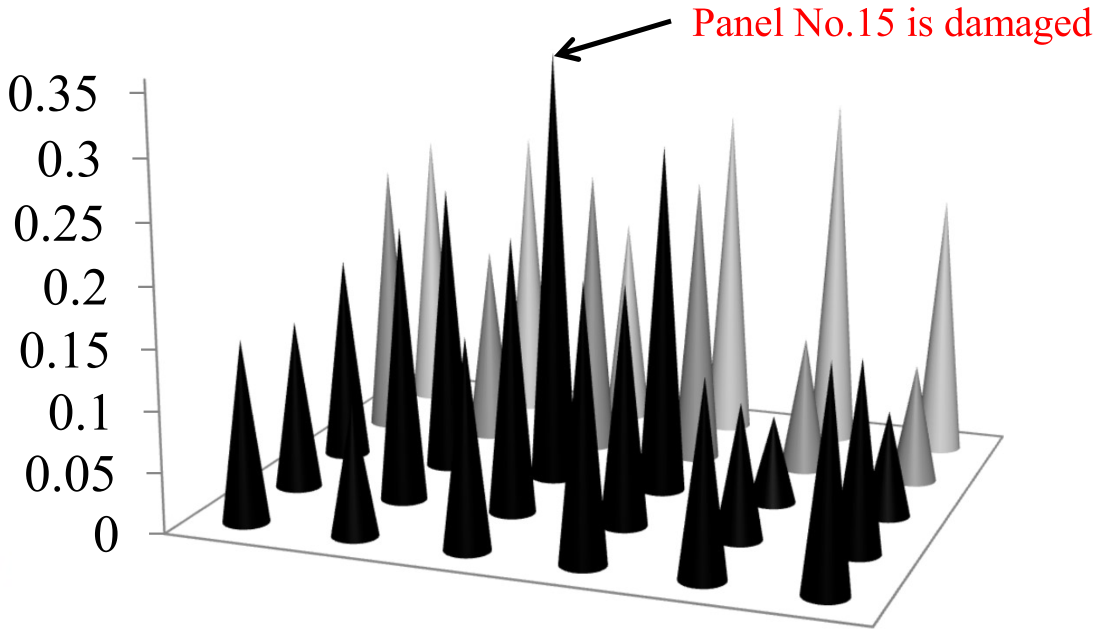
MS flat plate (1270x965x8 mm) welded on box section pipe of size 38x38 mm parametrically and supported on rollers at the corner with cover plates and PZTs patches.



DAMAGE DETECTION IN PROTOTYPE STRUCTURES



STEEL PLATE WITH PZTs AND DAMAGE

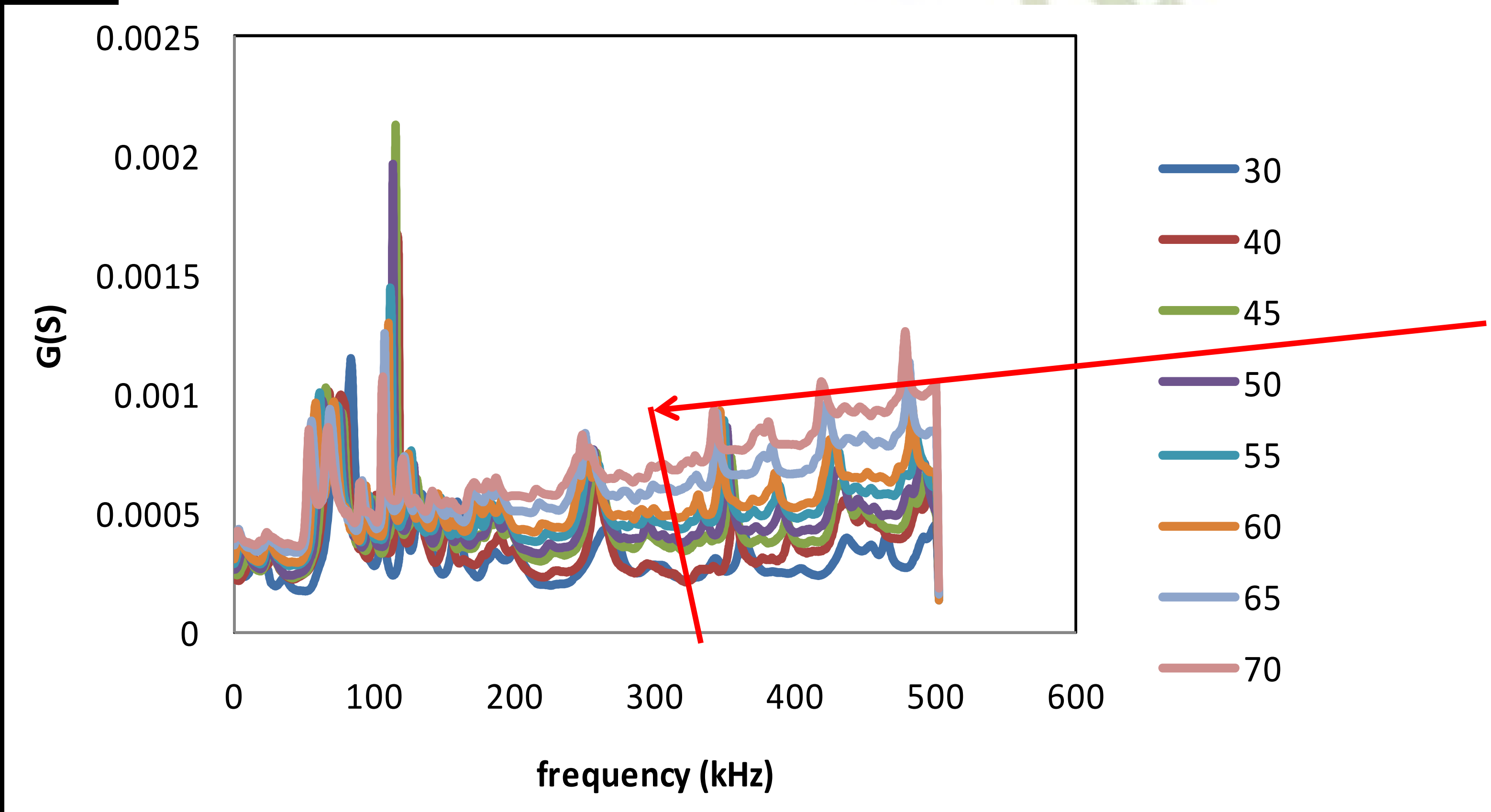


INFLUENCE OF TEMPERATURE AND ITS COMPENSATION

EXPERIMENTAL DETAILS

PZT Patch on

Ter effect the structure and piezoelectric sensor, the impedance variation could lead to the co si the inte , hence the importance to distinguish temperature effects and determine damage.



TEMPERATURE EFFECTS

COEFFICINT OF CORRELATION IS KEY PARAMETER

✓The coefficient of correlation was determined similar to Park (2000).

✓Observed to be positive for all cases (and between 0 and 1). CC =1 means signatures exact match. Value goes to negative if starkly different.

✓ As commented by Park (2000), this means that the signature are correlated to each other .

$$Cov(G^o, G^1) = \frac{1}{N}\sum_{i=1}^{N}(G_i^0 - \overline{G^0})(G_i^1 - \overline{G^1})$$

where G_i^1 is the post-damage conductance at the ith measurement point and G_i^0 is the corresponding pre-damage value.

$$CC = \frac{Cov(G^0, G^1)}{\sigma_0 \sigma_1}$$

where σ_0 and σ_1 are the standard deviations of the baseline signature and the signature after damage respectively. $\overline{G^0}$ and $\overline{G^1}$ respectively are the mean values of the baseline signature and the signature after damage.

TEMP °C	30-40	30-45	30-50	30-55	30-60
CC	0.604	0.468	0.364	0.2769	0.207

T

- Change in temperature leads to a horizontal shift and magnitude change of the impedance peak.

- The procedure to apply the correction scheme is based on the reconstruction of the damage metric.

- The **vertical shift** is simply corrected by the difference in overall average value of the original and the interrogated impedance patterns :

$$\delta_v = \frac{\sum_{i=1}^{n} \mathrm{Re}(Y_{i,2})}{n} - \frac{\sum_{i=1}^{n} \mathrm{Re}(Y_{i,1})}{n}$$

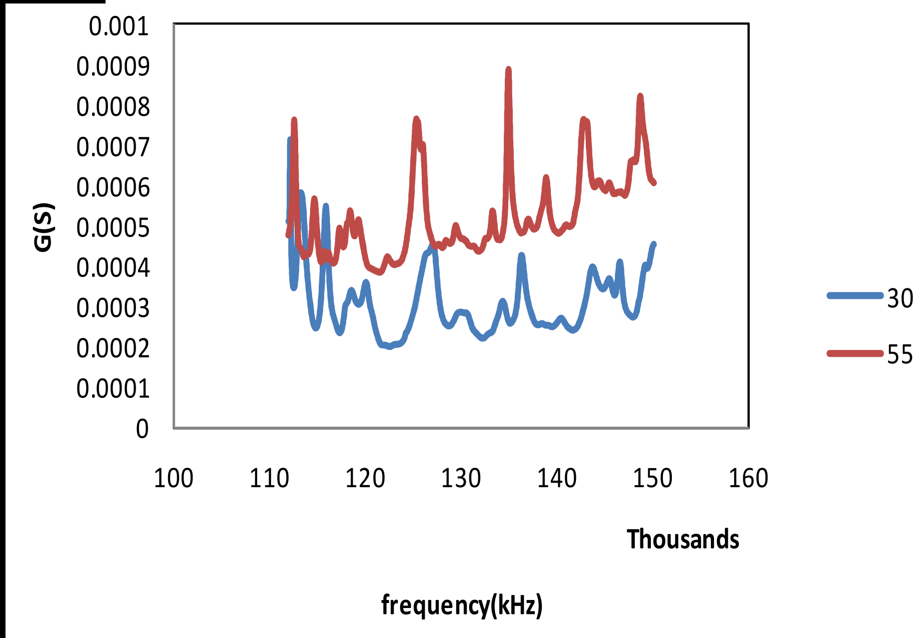
HORIZONTAL SHIFT=> MINIMIZE

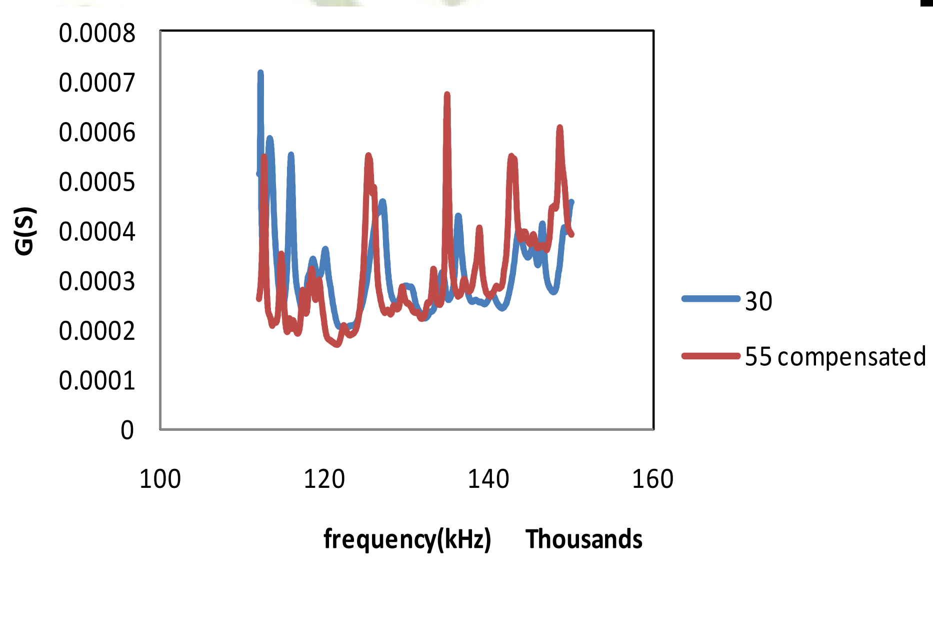
$$M = \sum_{i=1}^{N} \left[\mathrm{Re}(Y_{i,1}) - \left\{ \mathrm{Re}(Y_{i+\delta_h,2}) - \delta_v \right\} \right]^2$$

EXAMPLE SIGNATURE COMPENSATION

Vertical shift = 3.6367e-004

Horizontal shift = - 1.6 KHz

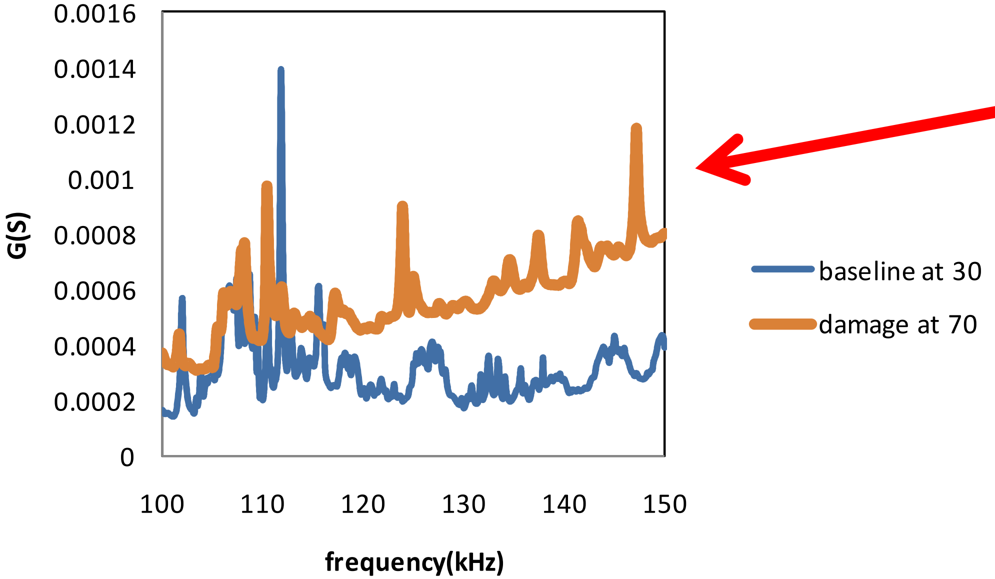




ACE

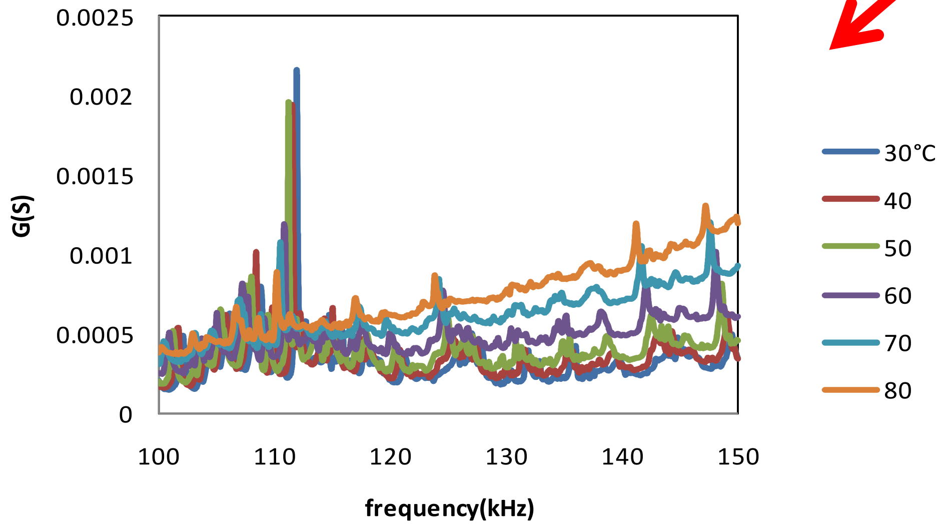
minium Spe

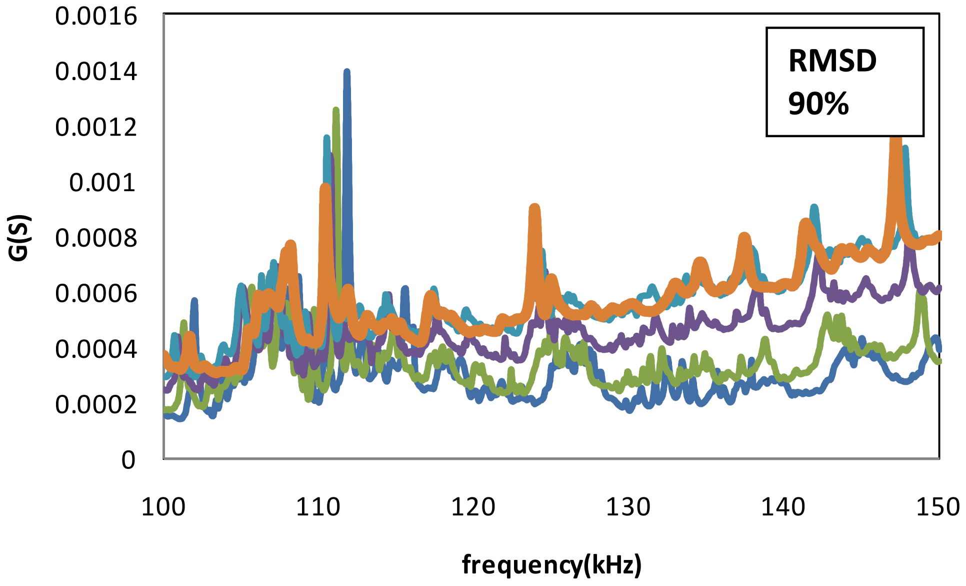
Hot

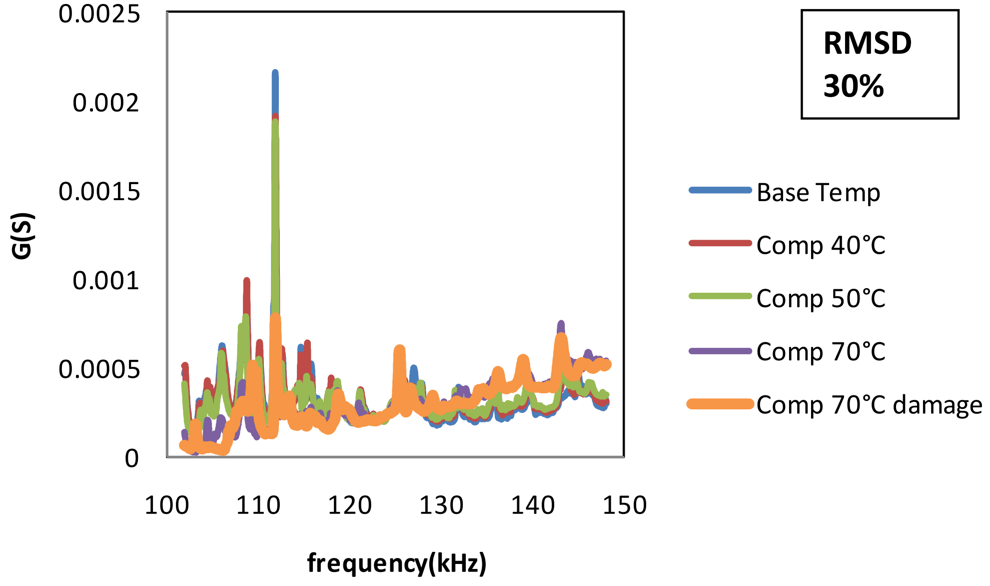


Base line signatures at 30°C and damage at 70°C

Un damaged signatures at different temperatures







Uncompensated signatures with damage at 70°C

All signatures compensated to baseline signature.

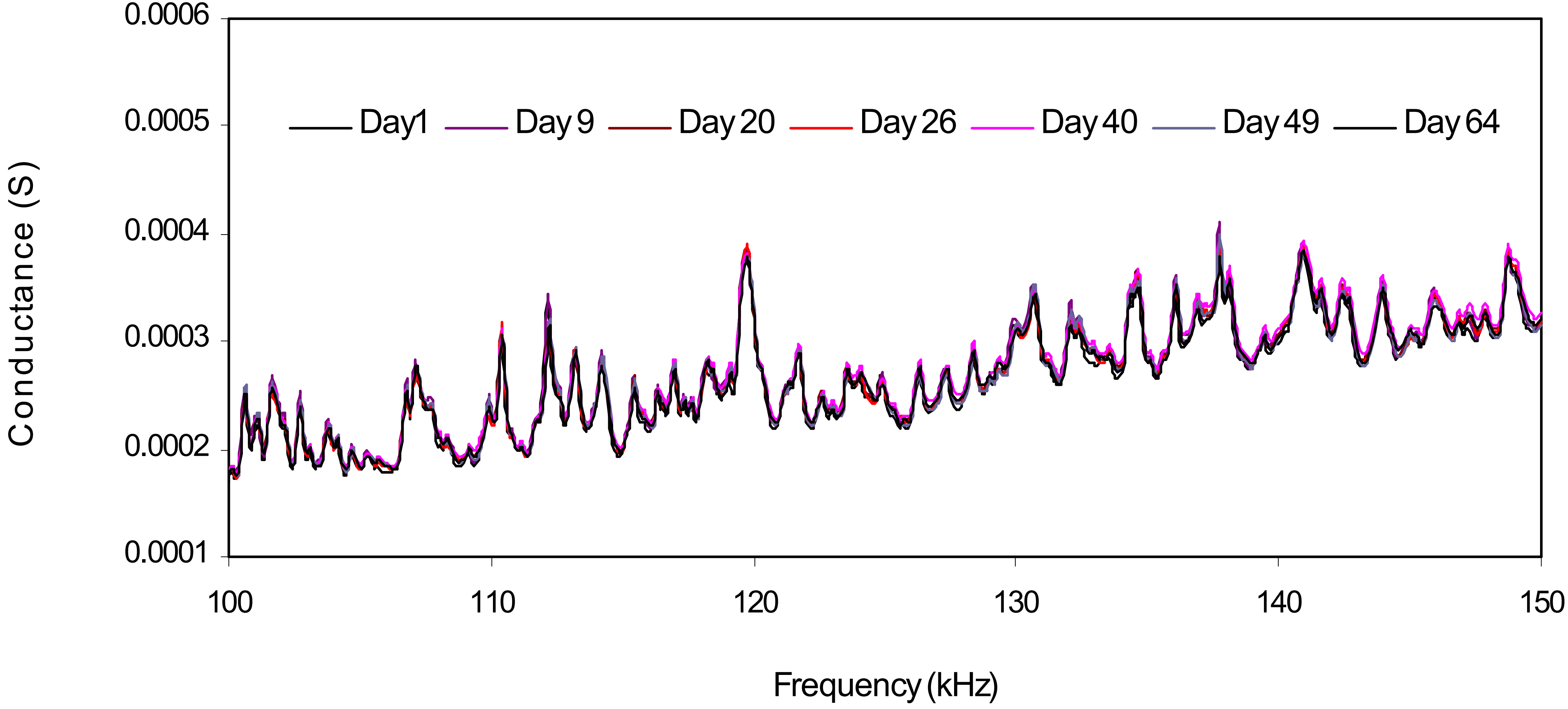
PRACTICAL ISSUES

LONG TERM REPEATABILITY

SENSOR PROTECTION

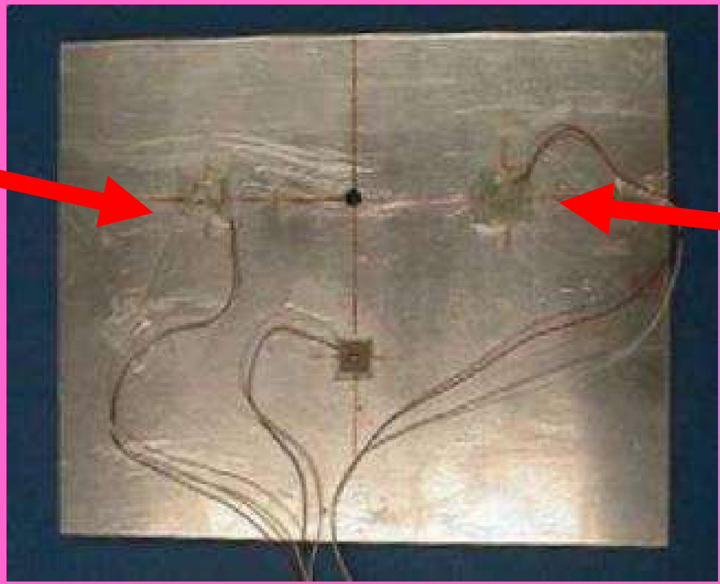
POSSIBLE MULTIPLEXING

LONG TERM REPEATABILITY



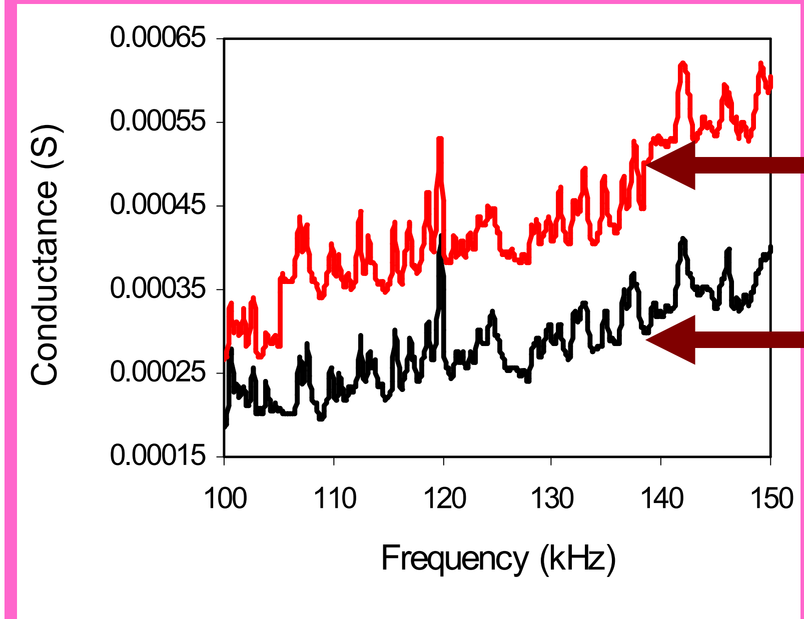
PROTECTION FROM HUMIDITY

Unprotected patch



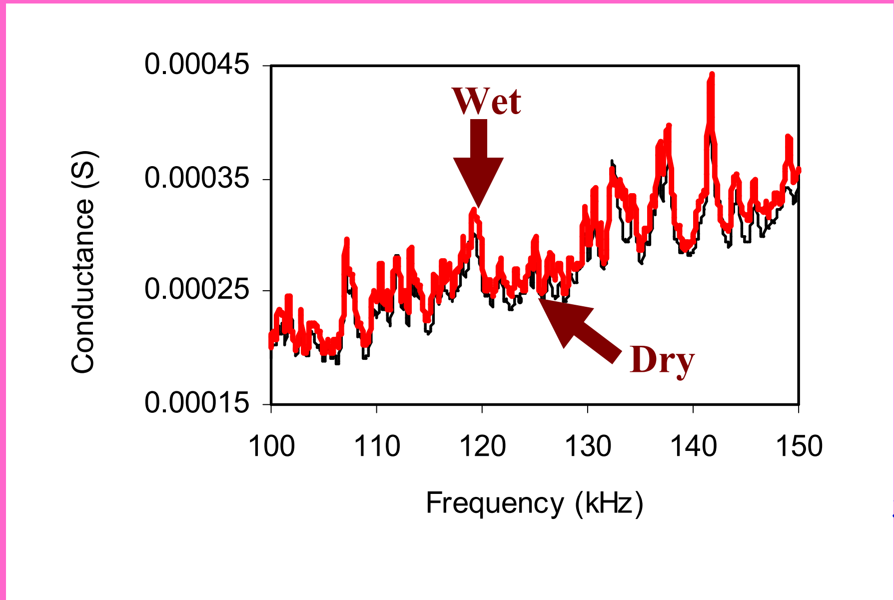
Much economical than commercially available packaged PZT patches

Patch protected by silica gel



Wet

Dry



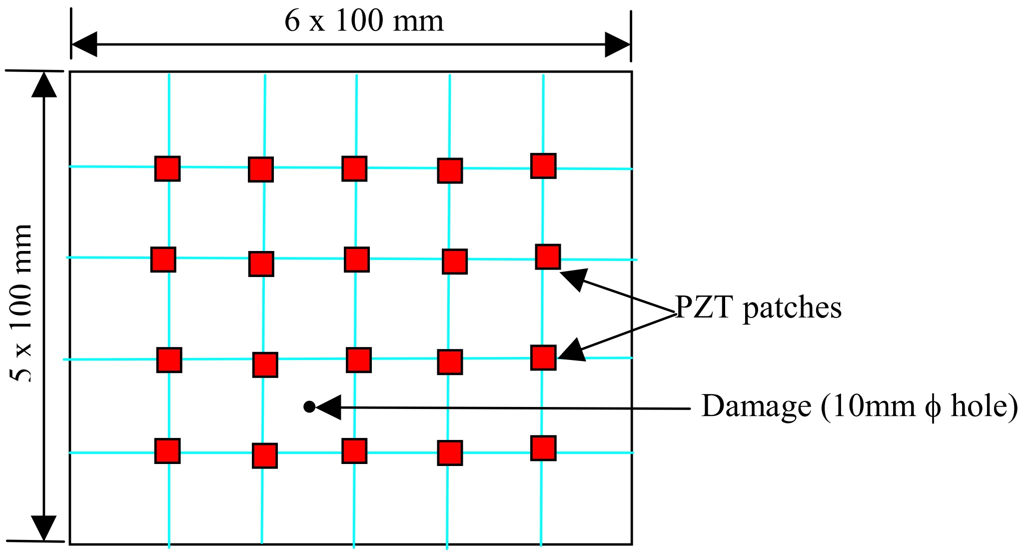
MULTIPLEXING OF SIGNALS

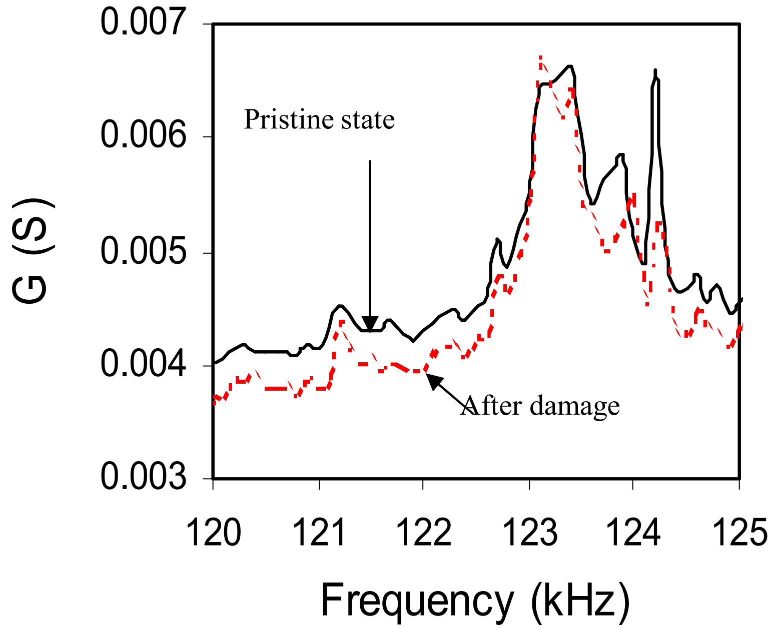
Controlling personal computer

3499B switch control system housing N2260A multiplexer module

HP 4192A impedance analyzer

DAMAGE DETECTION BY MULTIPLEXED SIGNATURE





- **Acquire the multiplexed signature in routine checks**
- **Go for individual only after "signs" of damage reflected**
- **This saves on time of acquisiton**

THANK YOU

SUGGESTED READING:

BHALLA ET AL. (2009)

Lim et al. (2006)