Chapter 1: INTRODUCTION

1.1 BACKGROUND

There is a great interest in the engineering community, in the development of real-time, in-service health monitoring techniques to reduce cost and improve safety, based on a preventive inspection schedule.

The definition by Rogers [1] for intelligent materials is as follows: "Intelligent material systems, defined from a technology standpoint, are the integration of actuators, sensors, and controls with a material or structural component". Rogers [1] defines the goal of intelligent material systems as "material systems with intelligence and life functions integrated in the microstructure of the material system to reduce mass and energy and produce adaptive functionality".

The crucial factors that are of concern when any Non-Destructive Evaluation (NDE) technique is considered are:

- The principle behind these techniques is 'preventive inspection', i.e., inspect the structure in question at frequent intervals in an attempt to detect damage in the early or incipient stages.
- The capability of the technique to perform on-line health monitoring, i.e., monitor the integrity of the structure *while* it is in service.
- Ideally, an NDE technique should rely on the usage of small, non-intrusive sensors and actuators.

The new impedance-based health monitoring technique relies on small patches of piezoelectric (PZT) materials, surface bonded or embedded onto the structure in question to actively conduct on-line health monitoring. The basic principle behind this technique is the use of high frequencies (typically >50 kHz) to detect changes in structural point impedance due to internal cracks, surface cracks or loose connections. The PZT behaves as a co-located actuator and sensor; it is driven by a fixed alternating electric field to induce vibration in the structure. The resultant vibrational response, which is characteristic of the particular structure, modulates the current flowing through the PZT; the modulation is a function of the degree of mechanical interaction between the PZT and the structure over the considered frequency range. The resultant frequency response function (FRF) is analyzed to predict change or damage.

As opposed to traditional NDE techniques which provide precise information about the exact nature, size and location of the damage, the impedance-method is a *qualitative* technique. While it can only provide limited information on the nature of damage, its strength lies in its ability to conduct on-line, real-time health monitoring, with high speed and with limited access to the structure. The entire analysis can also be conducted and controlled remotely.

Current NDE techniques, such as ultrasonic (A, B and C scans), x-radiography, passive thermography and laser Doppler vibrometry [2] can provide significantly more detail about the nature of the damage than the impedance method. However, they often require clear access to the structure in question, involve bulky equipment and may take the structure out of service.

Table 1.1 gives a comparison of conventional NDE techniques versus sensor systems.

Table 1.1: Comparison of conventional NDE versus sensor systems.

CONVENTIONAL NDE	**SENSOR** system
Eg: ultrasonics, x-radiography, passive thermography, laser doppler vibrometry	Eg: surface bonded PZT
Pinpoints microscopic damage	Monitors relatively larger areas

Requires access to structure, involves bulky equipment	Can access remote areas, size of equipment is small, can be portable and remotely controlled
May take structure out of service, causes major disruptions, labor intensive, expensive	On-line, real-time health monitoring
May be intrusive	Non-intrusive

Table 1.2 provides a comparison of NDE using strain gauges versus sensors.

Table 1.2: Comparison of strain gauges versus sensors.

Strain gauges	Sensors
Use calibrated load	No calibrated load, PZT acts as a co-located actuator and sensor
Measures smaller area	Relatively larger area
Exact sensing range of strain gauges is known	Sensing range is not exactly known

NDE techniques based on modal analysis rely on the fact that damage to the structure leads to a change in the modal stiffness of the structure [3]. This technique relies on lower-order global modes and as such are not sensitive to incipient-type damage. Also, this technique is sensitive to changing boundary conditions. Thus few modal analysis techniques exhibit engineering feasibility because of the low reliability in locating damage, complicated modeling, intensive computation and sophisticated instrumentation [2].

1.2 PRINCIPLES OF THE IMPEDANCE-BASED HEALTH MONITORING TECHNIQUE

The basic principle is to measure variation in the mechanical impedance caused due to structural damage. The electromechanical coupling property of piezoelectric materials couples the mechanical impedance to the electrical impedance, making the latter a metric sensitive to damage.

A piezoceramic, commonly referred to as PZT (Lead, Zirconate, Titanate) exhibits a bi-directional 'piezoelectric' effect. Piezoelectricity describes the phenomenon of the generation of an electric field in a material when subjected to a mechanical stress; this constitutes the *direct* effect. A mechanical strain is generated when an electric field is imposed; this constitutes the converse effect. For a linear piezoelectric material, the relation between the electrical and mechanical variables can be described by linear relations [2]:

$$S_i = s_{ij}^E T_j + d_{mi} E_m$$

$$D_m = d_{mi} T_i + \varepsilon_{mk}^T E_k \tag{1}$$

where:

S = strain

T = stress

E = electric field

D = displacement

D = piezoelectric constant

s = compliance

ε = permitivity

The superscripts T and E signify that these quantities are measured at zero stress and constant field respectively. The first equation describes the converse piezoelectric effect and the second equation describes the direct effect.

The impedance-based health monitoring technique utilizes the PZT as a co-located actuator and sensor. A PZT bonded onto the structure and driven by a fixed alternating electric field excites and induces vibrations in the structure (converse effect). The resultant vibrational response, which is characteristic of the particular structure, modulates the current flowing through the PZT (direct effect); this modulation is a function of the degree of mechanical interaction between the PZT and the structure over the considered frequency range. In electrical terms, variation in the current modulates the electrical impedance.

The electrical impedance is defined as the ratio of the energizing voltage to the resulting current. The mechanical impedance is defined as the ratio of the applied force to the resulting velocity. Electromechanical transducer materials such as piezoelectrics provide a means of coupling the mechanical and electrical impedance. This property facilitates the extraction of the mechanical impedance information of the structure by measuring the electrical impedance. This is done with the use of commercially available impedance analyzers. With these analyzers high resolution amplitude and phase measurements can be made from 5 Hz to 4 GHz frequency range. The analyzer can be operated manually, in self-scanning mode, under the control of a microcomputer or remotely controlled by a portable laptop computer. Hence, the electrical impedance measurements can provide the same information as conventionally used transfer functions.

1.3 ELECTROMECHANICAL PRINCIPLES

The interaction between a PZT and a one degree of freedom system can be qualitatively described by considering the PZT as a thin bar undergoing axial vibration in response to uniform applied alternating voltage. One end of the bar is considered fixed and the other end is connected to the external structure [4]. *Figure 1.1* shows the diagrammatic representation.

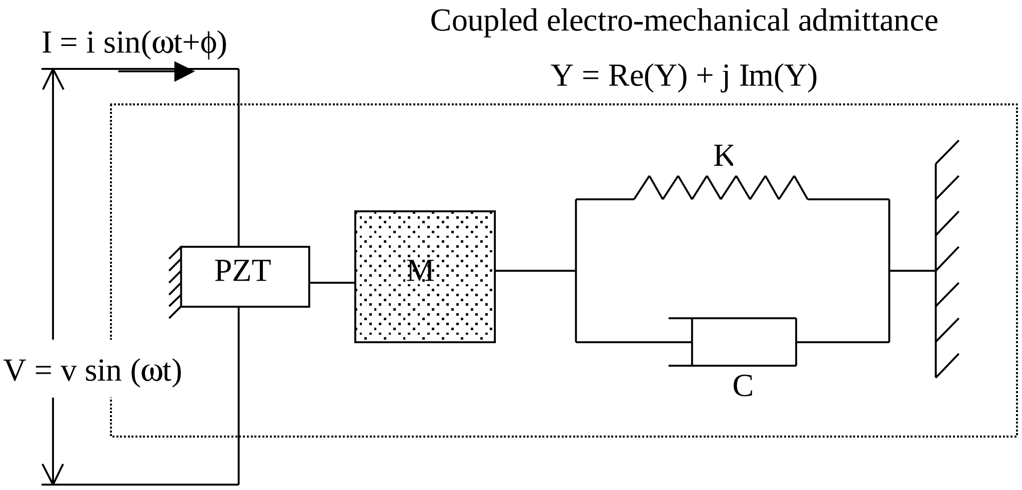

Figure 1.1: 1-D model used to represent a PZT-driven dynamic structural system

The assumption about interaction of the PZT at two discrete points is consistent with the mechanism by which forces are transferred from the bonded PZT actuator to the substrate structure [5]. Solving the wave equation for the PZT bar connected to the external mechanical point impedance of the structure leads to the following equation for the following frequency-dependent electrical admittance [6]:

$$Y = i\omega a\left[\varepsilon_{33}^{T}(1-i\delta)-\frac{Z_{s}(\omega)}{Z_{s}(\omega)+Z_{a}(\omega)}.d_{3x}^{2}Y_{xx}^{E}\right] \tag{2}$$

where:

Y = electrical admittance (inverse of impedance)

Z_a = mechanical impedance of the PZT

Z_s = mechanical impedance of the structure

Y_{xx}^{E} = complex Young's modulus of the PZT at zero electric field

d_{3x} = piezoelectric coupling constant in the arbitrary x direction at zero stress

ε_{33}^{T} = dielectric constant at zero stress

δ = dielectric loss tangent of the PZT

α = geometric constant of the PZT

The first term in the above equation is the capacitive admittance of the free PZT and is the baseline gradual increase in admittance with frequency. The second term includes the mechanical impedance of both the PZT and the external structure. When a PZT is bonded onto a structure, its own impedance, Z_a is fixed. Hence, it is Z_s, the external structure's impedance that uniquely determines the contribution of the second term to the overall admittance. This contribution shows up in the 'admittance versus frequency' plots as sharp peaks around the baseline electrical capacitive admittance [2]. Since these peaks correspond to specific structural resonances, they constitute a unique signature of the dynamic behavior of the structure. Hence, any changes in the impedance signature are attributed to damage or change in the structure.

In electrical terms, the impedance analyzer provides a constant alternating voltage signal (1 V rms) at the selected frequency to the PZT actuator/sensor. The magnitude and phase of the steady state current (after transient behavior has decayed) taken by the PZT is recorded and converted into real and imaginary impedance. The frequency is then augmented to the next step and the process is repeated over the entire selected frequency range. The PZT sees the structure as a frequency dependent boundary stiffness. Hence, variation in the electrical impedance over the entire frequency range due to the electrically capacitive nature of the PZT and to the interaction between the PZT and the host structure is obtained.

Based on this capacitive contribution of the PZT, it is found that given a certain volume of piezoceramic material, increase in the thickness of the PZT slice (bonded onto the host structure) causes a decrease in the capacitive contribution of the PZT and hence a decrease in the height of the peaks in the impedance signature. Increase in the cross-sectional area of the PZT, in contact with the structure in question, causes an increase in the capacitive contribution and hence causes an increase in the height of the peaks in the impedance signature. This increase implies a greater dynamic interaction between the host structure and the PZT and this is desirable. It is found that a PZT slice, 0.5 sq. in. and 0.01 in. thick allows for non-intrusive installation and gives a good vibration measurement.

1.4 RELATED PREVIOUS WORK

Analytical works such as the characterization of the dynamic output of piezoelectric actuators [7] in which the PZT is considered as an actuator-driven 1 d.o.f. spring-mass-damper system to illustrate the dynamic characteristics of the PZT actuator have been done. C. Liang et al [4] provide an insight into the impedance method for dynamic analysis of active material systems. An experimental modal testing using piezoceramic patches as co-located actuators and sensors is presented by F. P. Sun et al [8]. Analysis of the temperature rise and thermal stress in piezoelectric elements in active structures was conducted by Su-Wei Zhou et al [9]. The effects of temperature on the electrical impedance of PZT sensors and the compensation of this effect is presented by Karthik Krishnamurthy et al [10]. A theoretical modeling of wave propagation and energy dissipation in joints is presented by Jaime Esteban et al [11]. The analysis [12], results

[13] and supporting results [14] of a theoretical modeling of wave localization due to material damping is presented by Jaime Esteban et al.. A parametric study on the sensing region of a driven PZT actuator-sensor is conducted by Jaime Esteban [15]. Experimental [16] and analytical [17] results of variations in structural dynamic characteristics caused by changes in ambient temperature are presented by C. E. Woon et al.

Experimental implementation of the impedance-based health monitoring technique has been conduced on several complex structures. Local-area health monitoring of an aircraft structure via piezoelectric actuator/sensor patches is presented by Z. Chaudhry et al [18]. Health monitoring of space structures using impedance measurements has been conducted by Zaffir Chaudhry et al [19]. Monitoring the integrity of composite patch structural repair via piezoelectric actuators/sensors is presented by Zaffir Chaudhry et al [20]. Qualitative health monitoring of a steel bridge joint via piezoelectric actuator/sensor patches has been conducted by John W. Ayres at al [21]. High frequency impedance analysis for NDE of complex precision parts is presented by F. Lalande et al [22].

An overview of the impedance-based technique with related examples and proof-of-concept demonstrations is presented by Frederic Lalande et al [2], Craig Rogers at al [3] and F. P. Sun at al [23].

1.5 CONTRIBUTION AND GOALS OF THIS WORK

This work is an experimental study of the application of the impedance – based health monitoring technique on complex structures. It attempts to solve issues related to the practical application of this technique in real-life practical applications. Based on the kind of application or the concept being proved, the work as a whole can be divided into three parts.

The first part deals with the aspects related to the technique itself. The effect of various voltage levels in the interrogation of the piezoelectrics (PZT's) is studied. In this topic, a simple beam element is considered and damage or change in the structure is induced by the presence or absence of a screw. The effect of voltage levels in the sensing area of PZT's and the impact of damping when the PZT's are interrogated at various voltage levels is studied. Next, the effect of the test wire length that runs between the impedance analyzer and the PZT's, on damage detection abilities is studied. The issue of concern was the possibility of decrease in the ability to detect damage with increase in the test wire length. Another issue of concern was the behavior of the impedance signature with change in test wire length. In these two experiments mentioned, simple beam elements are used for the experimental set-up. The impact of implementing this technique in field applications with uncontrollable ambient conditions is also considered. In this case, a relatively complex truss structure is analyzed to obtain data. The effects of external boundary conditions, ambience and other structural variations on the impedance-based health monitoring technique are considered. The variation of the impedance signature with addition of weights on the structure being interrogated, vibration of the structure and increase of ambient temperature are issues that are dealt with. Variation of the signal over a given time period is also monitored.

The second part primarily deals with the application of this health monitoring technique on complex metal structures. A truss structure is analyzed and the concept of multiplexing the PZT's is explored. The effect of interrogating multiple piezoelectrics (PZT's) to detect damage is investigated. An aluminum truss structure is used as the test rig. Damage is induced at specified points on the structure; the effects of using a single PZT versus the use of several PZT's to detect damage are studied. Next, a preliminary set of experiments is conducted on a massive steel steam header. The possibility of implementing the impedance-based health monitoring technique to detect damage on large, dense structures was to be investigated. Practical issues such as positioning of the

PZT's, optimal frequency level and range, and the extent of damage that could be detected were the issues that are dealt with.

The third part deals with a detailed experimental study of monitoring the integrity of composite-reinforced concrete structures. An initial experiment with a small composite-reinforced concrete wall is conducted. The behavior of the impedance signature under loading and delamination is studied. The results from this experiment are then utilized in the analysis of 5 by 5 feet concrete walls with various composite materials bonded onto them. The walls are diagonally loaded to promote early failure. Five PZT's are mounted at strategic points and they are interrogated at each increase in the loading cycle. Four separate walls, each with a different composite reinforcement are analyzed.

In this concrete-composite application mentioned above, a new method of interrogating the PZT's and acquiring data is used. A HP 4192 low frequency impedance analyzer, which is smaller in size than existent models and hence more portable, is used. The analyzer is controlled remotely by a laptop computer. A software package was developed using Visual Basic for Applications to enable remote control of the analyzer. Using this package, the user only has to set the parameters for a given reading and then depress the 'Start' button. The software controls the analyzer, downloads and processes the data and puts up pertinent frequency response and damage metric charts. In a matter of minutes the user is shown the damage metric chart and a decision about the integrity of the structure can be made immediately. This new method opens up many possibilities in applications where portable equipment with a high degree of automation is required. Set-up time for the equipment is also minimal. The interface is very user-friendly and adjustments can be made even by a novice. Details of the software package and the code are presented in the appendix.

1.6 PARAMETERS IN THE IMPEDANCE BASED HEALTH MONITORING TECHNIQUE

1.6.1 LOCALIZATION OF SENSING AREA

Under the high frequency ranges (typically in kHz) used in the impedance method, the sensing region of the PZT is limited. The frequency response is dominated by local modes. Incipient damage like small cracks, loose connections and delaminations produce measurable changes in the vibration characteristics. It has been found that the sensing area as a minimum extends to the boundaries of the solid member to which the PZT is bonded. Contribution to change in the signature pattern is more due to local modes than global modes. This limited sensing area helps in isolating change in the impedance signature due to other far-field changes such as mass loading, stiffness and boundary conditions. This insensitivity to far-field effects comes at the cost of limited sensing area.

1.6.2 FREQUENCY RANGE

The sensitivity of the technique in detecting damage is closely related to the frequency band selected. To sense incipient-type damage which does not result in any measurable change in the structure’s global stiffness properties, it is necessary for the wavelength of excitation to be smaller than the characteristic length of the damage to be detected [24]. Hence, the frequency range typically used in this technique is in the range of a few hundred kHz. The range for a given structure is determined by a trial and error method. There is little analytical work that can be done about the vibration modes of complex structures at ultrasonic frequencies. It has been found that a frequency range with a high mode density exhibits a higher sensitivity since it generally covers more boundary condition information [23]. A frequency range, with a large number of peaks is chosen; this usually implies that there is a greater dynamic interaction over that frequency range. It must be noted that higher frequencies limit the sensing area of the PZT.

1.7 FREQUENCY RESPONSE CHARTS

This work relies mainly on frequency response charts to present the data and to arrive at conclusions. Depending on the application the frequency response charts in this work vary with respect to the term on the y-axis.

Two HP impedance analyzers are used to interrogate the PZT's and acquire the data: the 'HP 4192A Impedance/Gain-phase analyzer' and the 'HP 4194A Low frequency Impedance analyzer'. Both analyzers measure impedance by simultaneously measuring two independent, complimentary impedance parameters in each measurement cycle. This combination of measurement parameters represents both the resistive and reactive characteristics of the sample. A total of fifteen measurement parameters are available; of these, two are used in this work:

1. 'R – X' function (R: real and X: imaginary); units: R, ohms and X, ohms
2. 'Cs – Rs' function; units: Cs, farads and Rs, ohms

Since the analyzers are used in the equivalent series circuit mode the impedance (and not the admittance) is measured as R+jX.

For example, if the 'R – X' function is used, (R is the real or resistive part and X is the imaginary or capacitive part), two separate frequency response plots are obtained: 'R vs. Frequency' and 'X vs. Frequency'. If the absolute impedance or phase at a given frequency is required, a simple calculation permits it:

$$Z = \sqrt{R^2 + X^2}$$

and

$$\theta = \tan^{-1}\left(\frac{X}{R}\right) \qquad \text{If } R \geq 0$$

$$\theta = 180(\deg) - \tan^{-1}\left(\frac{X}{|R|}\right) \qquad \text{If } R < 0$$

(3)

where,

Z = absolute impedance

R = resistance

X = reactance

θ = phase angle

It is found that the ‘R’ portion of the frequency response is more reactive to damage or change in the structure’s integrity than the ‘X’ portion. This is because change in the impedance signature of the PZT-structure combination is solely due to the contribution of the changing impedance of the structure. This change in the structure’s impedance is attributed to change in integrity of the structure due to damage. This characteristic is exhibited only in the resistive portion of the impedance signature (‘R’ portion). The reactive portion (‘X’ portion) of the impedance remains unchanged; any change in this portion is more due to change in boundary conditions such as loading effects, temperature changes and increase in test wire length.

The ‘Cs – Rs’ function is employed in a similar fashion. Two frequency response plots, ‘Cs vs. Frequency’ and ‘Rs vs. Frequency’ are used for the analysis. The reactance can be extracted form the ‘Cs’ portion and the resistance from the ‘Rs’ portion. Using these values of resistance and reactance, the absolute impedance and phase angle can then be obtained.

$$Cs = \frac{1}{-\omega X} = \frac{1}{-2\pi . f . X} \tag{4}$$

where,
f = frequency
X = reactance

It is found that the ‘Rs’ portion of the impedance signature is more reactive to damage or change in the structural integrity than the ‘Cs’ part. Hence, if the ‘Cs – Rs’ function is used for the analysis, attention is paid to the ‘Rs vs. Frequency’ plots.

1.8 DAMAGE METRIC CHARTS

While the frequency response plots serve to give a qualitative approach to the analysis, damage metric charts, which are based off the frequency response plots, attempt to quantify the data. They are found to be extremely useful in summarizing and comparing data sets. Damage metric charts help in giving a quick quantitative overview of the information from the frequency response charts. Several mathematical formulations lead to various types of damage metrics. In this work, two types of damage metrics are used; a brief description of the characteristics of each type of metric and the mathematical formulation follows.

A damage metric referred to as the ‘Average Square Difference’ (ASD) metric is used. The mathematical formulation for this metric is simply the average of the squared differences between the initial and subsequent sets of data and is represented as follows:

$$ASD = \sum \left[Z_{before} - \left(Z_{after} - \delta\right)\right]^2$$

$$\text{where } \delta = Average_{before} - Average_{after} \tag{5}$$

where:

ASD = ‘Average Square Difference’ Metric

Z_{before} = initial value

Z_{after} = subsequent value

$Average_{before}$ = average value of the initial curve

$Average_{after}$ = average value of the subsequent curve

With the use of this damage metric, vertical shifts in the curve are accounted for. Hence, it is very useful when there are *uniform* vertical shifts in the subsequent curves when compared to the baseline curve. However, if the vertical shift is not uniform, i. e., there is a vertical shift but the shift is not across the complete frequency range, this damage metric introduces an error. Hence, another metric referred to as the ‘Correlation’ metric is employed in such cases. In a damage metric chart, using the ASD formulation, the greater the numerical values of the metrics the larger the difference between the baseline reading and the subsequent reading. When this is interpreted with reference to the impedance-based health monitoring technique, the larger the metric, the greater the damage or change in the integrity of the structure.

A scalar damage metric, referred to as the ‘Correlation’ metric is used to interpret and quantify the information from different data sets. The mathematical formulation is one minus the correlation coefficient between the reading in concern and the baseline. Hence, if the baseline reading and the reading in concern are exactly the same, the correlation equals one, and 1 – correlation equals zero. The range for this metric, from above, is deduced to be 0 to 2.0.

Statistically, the ‘Correlation’ function returns the correlation coefficient between two arrays and determines the relationship between two properties. The mathematical representation is as follows:

$$\begin{aligned} \rho_{x,y} &= \frac{Cov(X,Y)}{\sigma_x . \sigma_y} \\ Cov(X,Y) &= \frac{1}{n}\sum_{j=1}^{n}\left(x_j - \mu_x\right)\left(y_i - \mu_y\right) \end{aligned} \tag{6}$$

In this work, the metric is calculated as ‘1 – Correlation’; this is done merely to ensure that with increasing damage or change in structural integrity, the metric values also increase. This provides an aesthetic metric chart and is consistent with other metrics in which metric values increase when there is an increase in damage. The ‘1 – Correlation’ metric account for vertical shift. It has been found to be the better of the two metrics described and as such is used in most of the analysis.

Though the damage metric charts are very useful in giving a quantitative approach to the analysis, it must be noted that they are based off the frequency response charts. The primary information *must* be obtained from the frequency response plots. Damage metric charts should be used only when a quantitative comparison between data sets needs to be made.

1.9 CONFIGURATION FOR DATA ACQUISITION

The data acquisition and processing is carried out using two configurations.

In the first configuration, the lead wires from the PZT, bonded onto the structure are connected to the terminals of the HP 4194A impedance analyzer. This analyzer is relatively large and has its own display unit. The PZT’s are interrogated after setting the parameters in the analyzer. The data from the analyzer is then transferred from the analyzer to a PC (486) via a General Purpose Information Bus (GPIB). The data is in the form of ‘*.dat’ files. This data is then manually posted into Excel workbooks and processed to obtain frequency response and damage metric charts. *Figure 1.2a* shows the configuration used for the HP 4194A impedance analyzer.

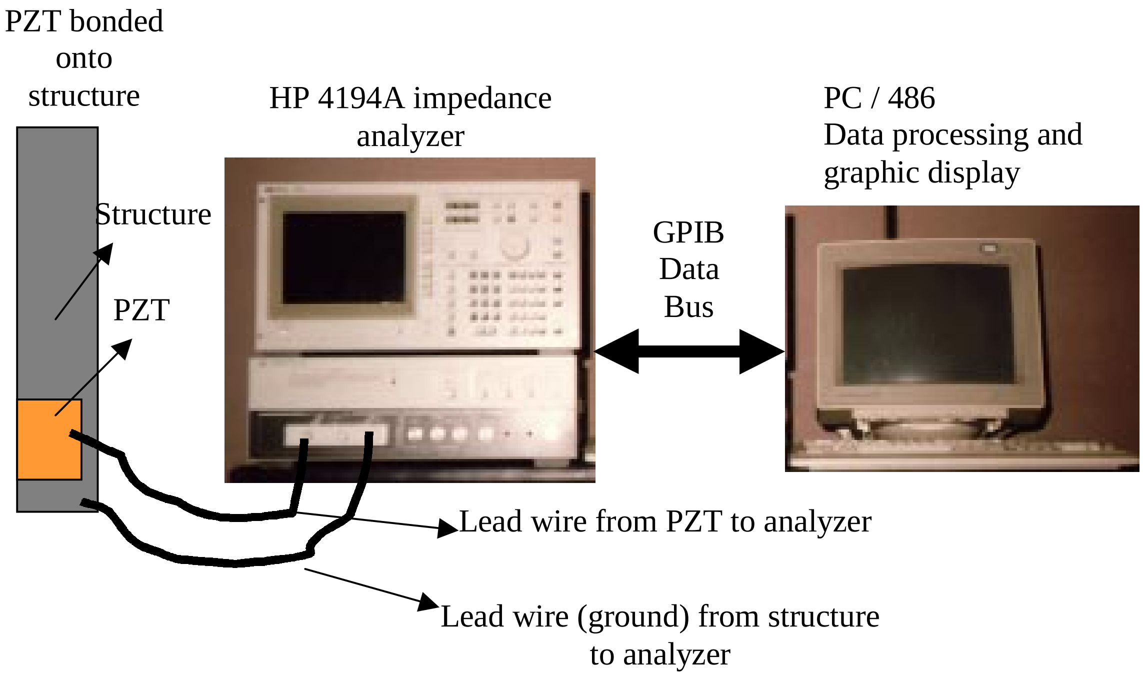

Figure 1.2a: General configuration of test set-up and instrumentation using the HP 4194A impedance analyzer.

The disadvantage of this configuration is that the equipment used is relatively bulky and not very portable. Moreover, the analyzer cannot be remotely controlled. While this configuration is perfectly suited for applications within the laboratory, in field applications where there is a need for portable equipment and remotely controlled, automated systems, this configuration is not practical.

In the second configuration the lead wires from the PZT, bonded onto the structure are connected to the terminals of the HP 4192A impedance analyzer. This analyzer is relatively small and does not have a display unit; the laptop computer serves as the display unit. The analyzer is connected to the laptop via a PCMCIA-GPIB data acquisition bus and is remotely controlled by the laptop. A software package was developed using Visual Basic for Applications (VBA) to enable remote control of the analyzer. Using this package, the user only has to set the parameters for a given reading on the laptop and then depress the 'Start' button. The software controls the analyzer, downloads and processes the data and puts up pertinent frequency response and damage metric charts. In a matter of minutes the user is shown the damage metric chart and a decision about the integrity of the structure can be made immediately. Details of the software package and the code are presented in the appendix. Figure 1.2b shows the configuration used for the HP 4192A impedance analyzer.

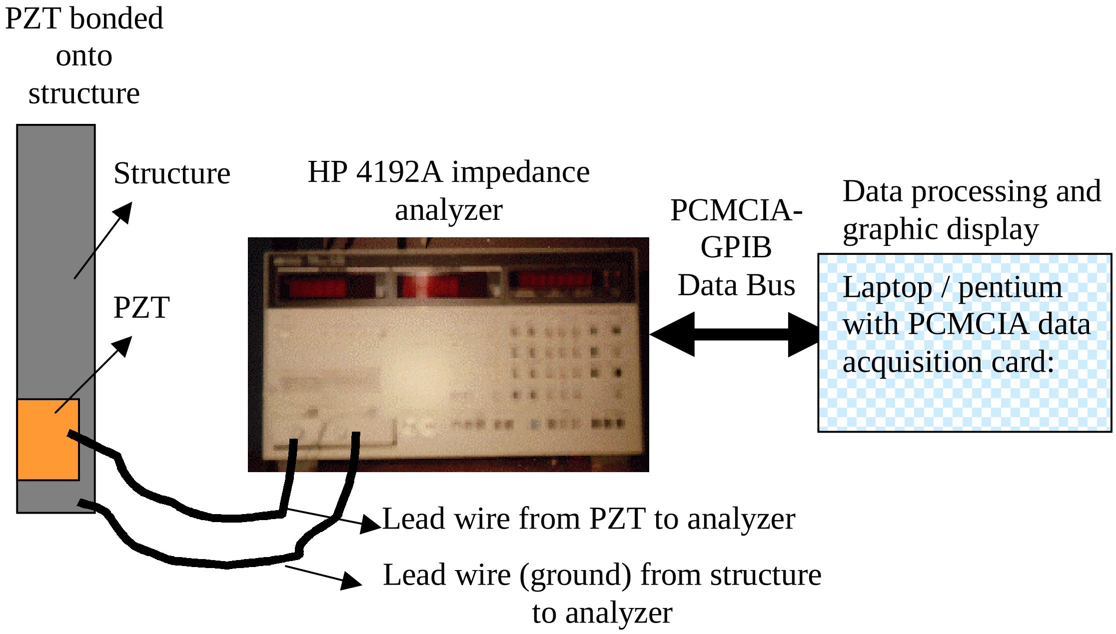

Figure 1.2b: General configuration of test set-up and instrumentation using the HP 4192A impedance analyzer.

This configuration offers a portable and automated system to acquire and process the data. It also offers the advantage of remote control of the analyzer. This new method opens up many possibilities in applications where portable equipment with a high degree of automation is required. Set-up time for the equipment is also minimal. The interface is very user-friendly and adjustments can be made with little technical expertise. This configuration is perfectly suited for field-applications and was successfully tested on a project site. It is a very viable and highly suggested configuration.