

Chapter 3

REFINEMENTS OF THE IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING TECHNIQUE

Part II. Analyzing Effects of Boundary and Environmental Condition Changes

3.1 Introduction

The objective of this chapter is to examine and obtain a better understanding of practical issues that are a result of monitoring the health of structures in an uncontrolled field environment. The effects of external boundary and environmental condition changes and other structural variations on the impedance-based health monitoring technique are investigated. Examples of the factors that considered in this research are loading of the structure, vibration of the structure or connected parts and change in the ambient temperature.

A previous research effort (Raju, 1997) concluded that the impedance-based method is able to detect structural damage with reasonably small boundary condition changes. Raju suggested however, a more complete understanding of the variation of the impedance signatures, and application of signal processing methods to reduce the variation would aid towards a more effective damage detection with the use of the impedance method.

With the established temperature compensation procedure, as described in chapter 2, which can reduce impedance variations, the impedance-based health monitoring technique was tested under uncontrolled environmental conditions and its ability to detect and distinguish damage from these variations has been investigated.

3.2 A Quarter Scale Bridge Section

A quarter scale model of a steel truss bridge joint is investigated. A model of a steel bridge joint is shown in Fig. 3.1. The bridge model consists of steel angles, channels, plates, and joints connected by more than 200 bolts. The size of this structure is 1.8 m tall and has a mass of over 250 kg. Four PZT sensors/actuators are bonded on the critical sections to actively monitor the conditions of this typical high-strength civil structure.

The preliminary sets of experiments were conducted on this structure and a clear variation in the impedance measurements due to the induced damage could be observed (Ayers *et al*, 1996). The purpose of experiment investigated here however, is to examine the effect of external boundary conditions on the impedance signature and the ability of the impedance-based method to distinguish and detect structural damage from variation due to changes in environmental conditions.

The following three ambient boundary conditions were imposed on the structure in an attempt to simulate real-life variation;

- repeatability - variations of the signal over a given time period are monitored.
- vibrations - structure is manually hammered while the measurements are being taken
- loading - a 15 kg. mass is added to the structure. The weight is placed in the vicinity of PZT sensors, so that it induces the stresses on bolted connections within the sensing range of PZT sensor/actuators.

These sets of readings from four PZTs are repeated over a period of three weeks.

After identifying the range of the impedance signature variations due to boundary condition changes, damage was introduced by loosening the bolts over several locations on the structure. The HP 4194 impedance analyzer is used to interrogate each PZT. Throughout the analysis, the compensation technique to minimize the effects of temperature changes was applied.

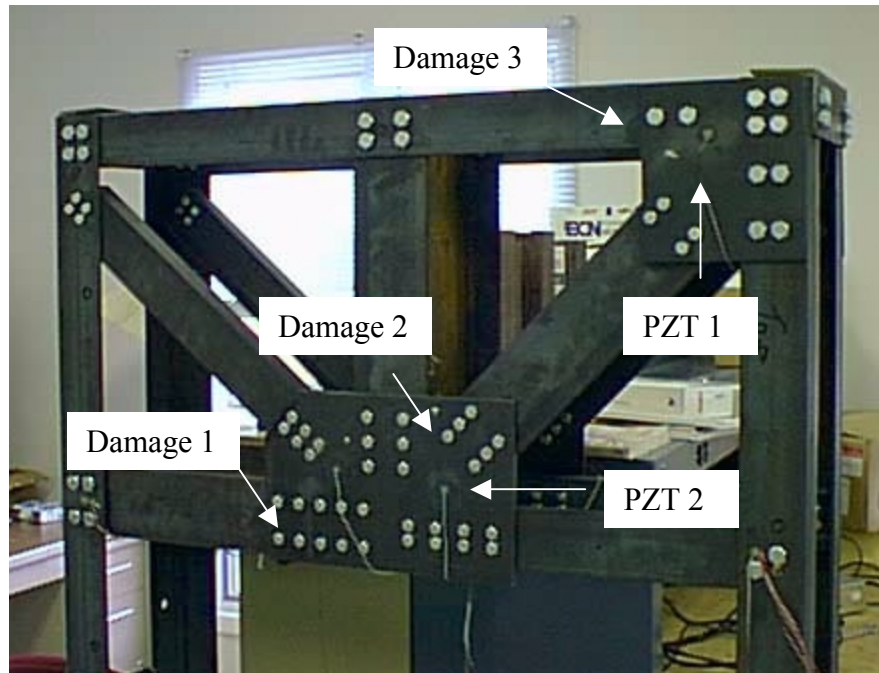
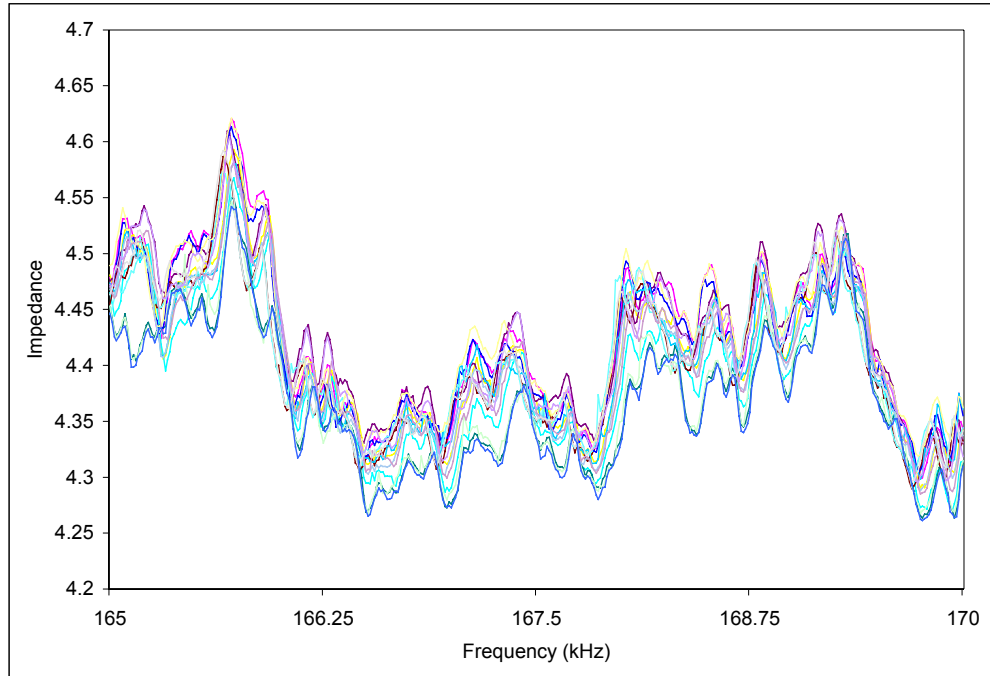
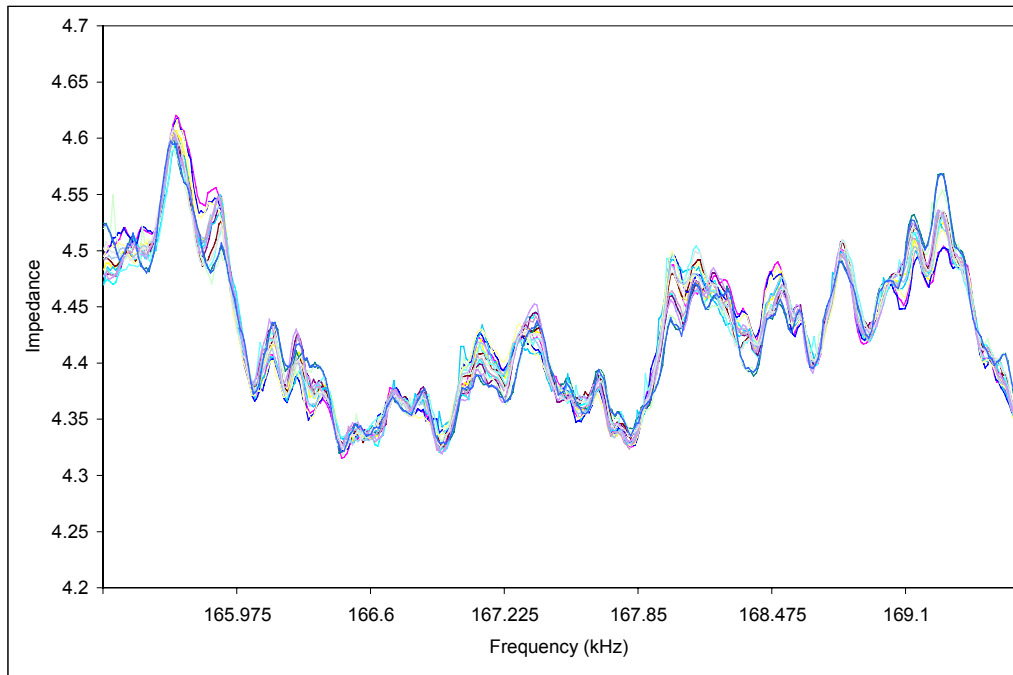


Figure 3.1 A $\frac{1}{4}$ scale steel bridge section

The impedance measurements of PZT 1 and PZT 2 are presented in Fig. 3.2 and 3.3, respectively, for both compensated and uncompensated cases. Each plot shows the variations of the impedance signature with three ambient conditions imposed on the structure. Only a total of fourteen measurements, which show the largest variations, are shown without the labels. As can be seen, some variations with the ambient condition changes were clearly observed. Although, the essential signature pattern remains, random peaks and valleys were found with the ‘vibration’ and large line drifts of impedance curves were observed with the progress in time, mainly from temperature changes. The variations, however, could be reduced and be considered as minor changes with the aid of the compensation technique. The vibration produced the largest variations, however it was expected as the structures were being hammered while measurements were being taken. As compared to modal analysis experiments, where a small orientation change results in marked changes in resonant frequencies, mode shapes, and modal damping, the impedance signature patterns shows relatively small variations. The measurements were found to be repeatable and no noticeable degradation was observed.

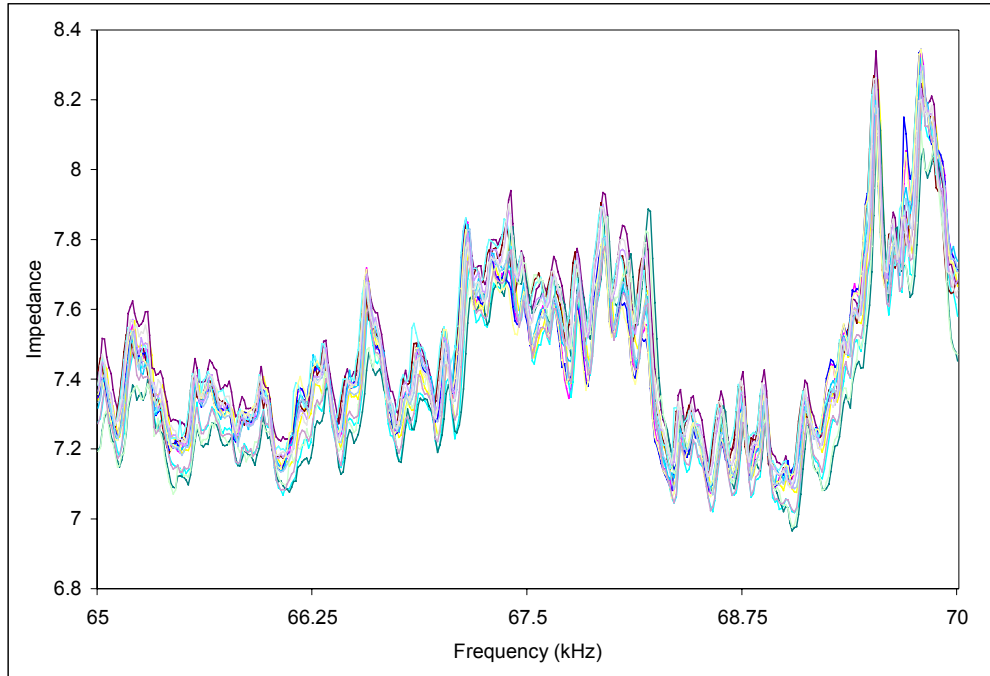


(a) uncompensated impedance

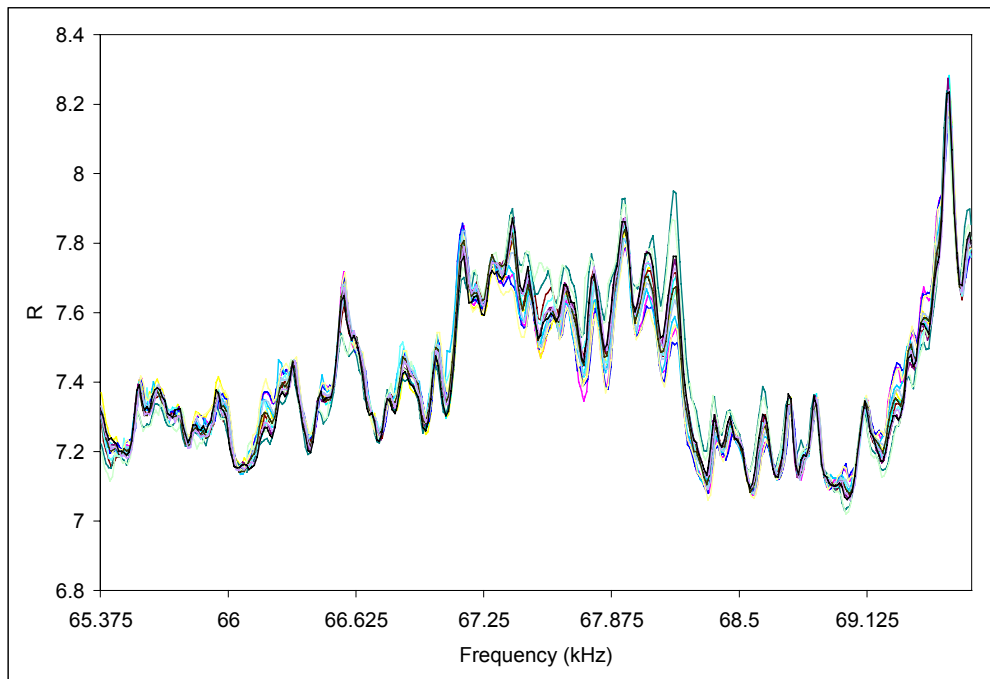


(b) compensated impedance

Figure 3.2 Impedance (real) vs. Frequency plots of PZT 1



(a) uncompensated impedance



(b) compensated impedance

Figure 3.3 Impedance (real) vs. Frequency plots of PZT 2

The damage metric chart is presented in Fig. 3.4. The first fourteen variations are those due to the change in boundary conditions in Fig. 3.2 and 3.3. The most pronounced values are those values due to the vibration. As depicted, the values are very small and hence, negligible. The location of damage 1, 2 and 3 are shown in Fig. 3.1. Damage is simulated by loosening a bolt (1/8 turn). The exact sensing range of each PZT sensor was difficult to predict, since a large number of bolts were presented in this structure. Consistent with the results of others (Esteban, 1996; Lovell and Pines, 1998), the bolted joints are the major contributors of energy dissipation in the structures.

Damage 1 is believed to be well out of sensing range of both PZT 1 and PZT 2. Hence, only a small increase in damage metric is shown for both PZTs. However, PZT 2 shows an increase in damage metric value over that of any of the increase caused by the normal variations. This small increase cannot be used to signal the presence of damage, however does provide evidence of the sensitivity of this method in the relatively large ranges. Damage 2 is located closed to the PZT 2 and Damage 3 is within sensing region of the PZT 1, hence the increase in damage metric values are the highest for both PZTs. Note that the effect of loosening single bolt on the entire structure is minor, thus damage can be detected in its early stage.

The impedance measurements of PZT 2 for the case of both damage 2 and damage 3 are shown in Fig. 3.5, for visual comparison. It can be seen that, when damage 2 was introduced, the impedance measurement is significantly different from the pervious readings. However, in the case of damage 3, only a small variation in the impedance measurement was observed, since damage is distant from this PZT.

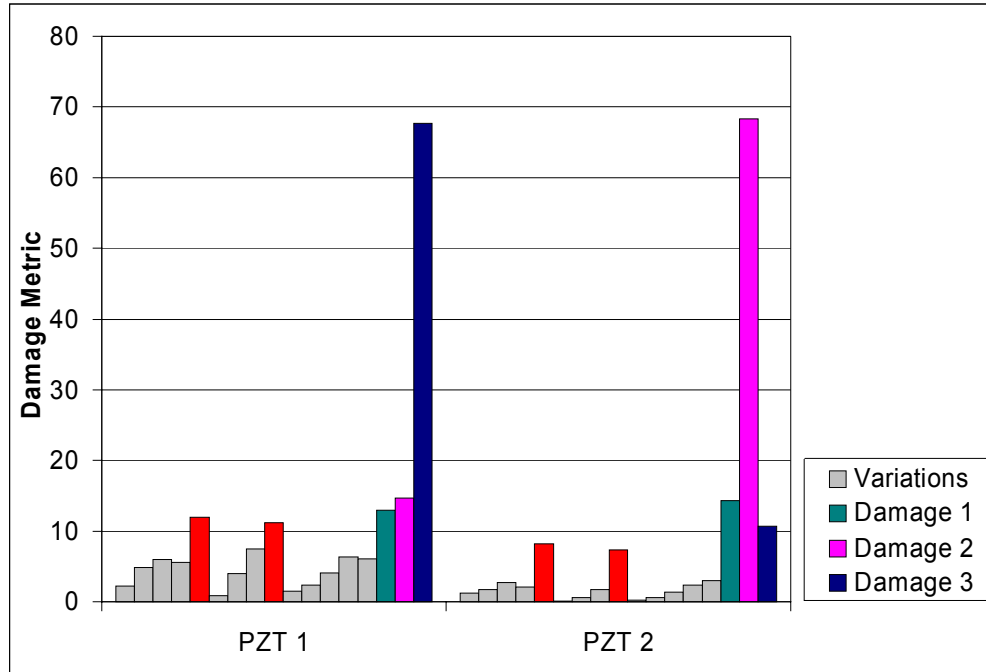


Figure 3.4 Damage metric chart for PZTs. Comparison of metric values with induced damage

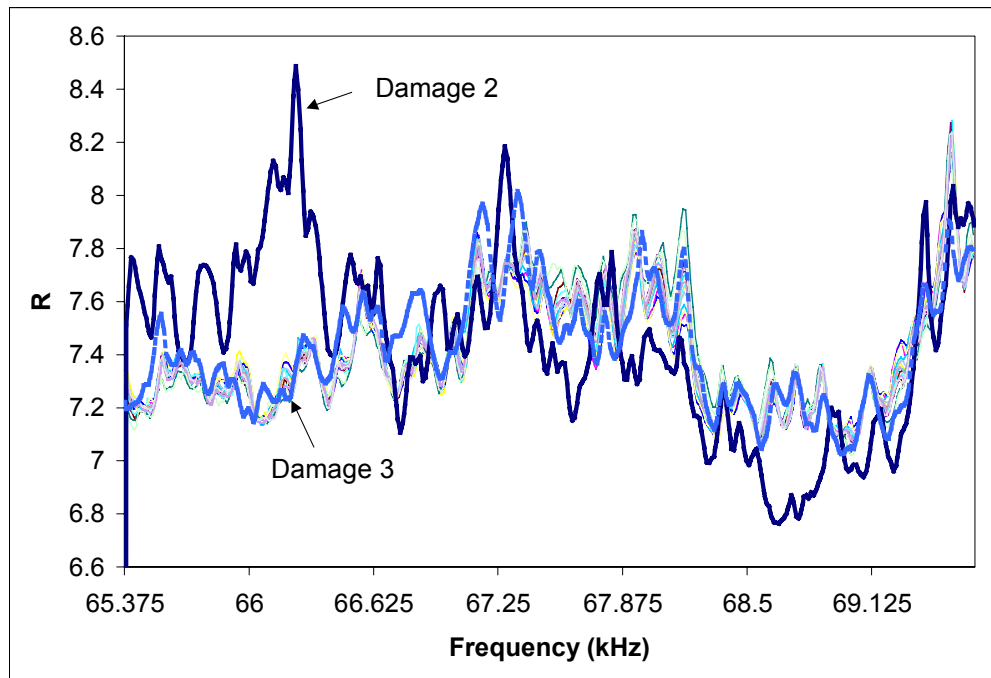


Figure 3.5 Impedance vs. Frequency plots for PZT 2

Bolted and riveted connections are commonly found in civil structures. These connections invariably promote damage growth due to the nature of the geometry and the local stress concentrations. It has been estimated that approximately 70% of all mechanical failure occurs due to fastener failure (Simmons, 1986). These connections are often difficult to inspect due to the geometry and/or the location in the structure. Various types of bolt failure that occur include tensile overload, shear overload, hydrogen embrittlement, and fatigue failure. Although only the changes in joint stiffness are used to simulate real-time damage, the results of this experiment support the effectiveness of the impedance-based technique in monitoring the condition of various civil applications, which are subjected to either adverse environments that can degrade the connections, or strenuous loading cycles causing bolt cracking and fatigue damage.

The change in measured data due to the environmental effects makes it difficult to detect and locate structural damage. Further problems with the large-scale civil structures are that they possess very low natural frequencies and are difficult to excite, leading to difficulties in picking up very small frequency changes for damage detection techniques based on low frequency vibration data. (Friswell and Penny, 1997). As demonstrated in this example, the impedance-based structural health monitoring technique can be easily applied to the relatively large civil structures under the presence of certain environmental changes.

3.3 A Massive Cylinder Header

The possibility of implementing the impedance-based structural health monitoring technique to detect damage on large, dense structures was also investigated. The ability to detect damage on massive, dense structures had not yet been tested. The primary objective of this research was to experimentally investigate the ability of the impedance-based technique in a large, dense and an electrically continuous object. The preliminary sets of experiments were conducted on the header section (Raju, 1998). A clear variation in the impedance measurements due to the induced damage could be observed. It was concluded however, that

these variations were found to be within the limits of the normal variations due to the boundary condition changes.

Therefore, extensive experiments and analysis were performed on the header section to seek answers to the following issues; i) the range of the impedance variations due to the boundary condition changes, ii) the extent of damage that could be detected over the boundary condition changes, iii) the sensing range of the PZT actuator/sensors on the header section.

The test structure, obtained from the Electric Power Research Institute (EPRI) nondestructive evaluation center in Charlotte, NC., is shown in Fig 3.6. It has an outside diameter of 430 mm, a thickness of 50 mm, and a length of 83 mm. Three 2.5 x 2.5 x 0.2 mm PZT actuator/sensors (labeled red, white, and green) were bonded 30° apart to the cross section of the header. Damage was induced at a randomly chosen position by drilling a hole and then further deepening it. A baseline reading is taken before damage or any variation is induced. The HP 4194 impedance analyzer is used to interrogate each PZT.

First, the effects of external boundary conditions, ambience and other structural variations on the header section were considered. The following three ambient conditions were imposed on the structure in an attempt to simulate real-life variations;

- repeatability - variation of the signal over a given time period (2 weeks) is monitored,
- orientation change- variation of the impedance signature with different orientations (vertical and horizontal) of the header is investigated,
- vibration - header is manually hammered while the measurements are being taken.

The impedance measurements were made over the 44-45 kHz and 147-150 kHz frequency ranges.

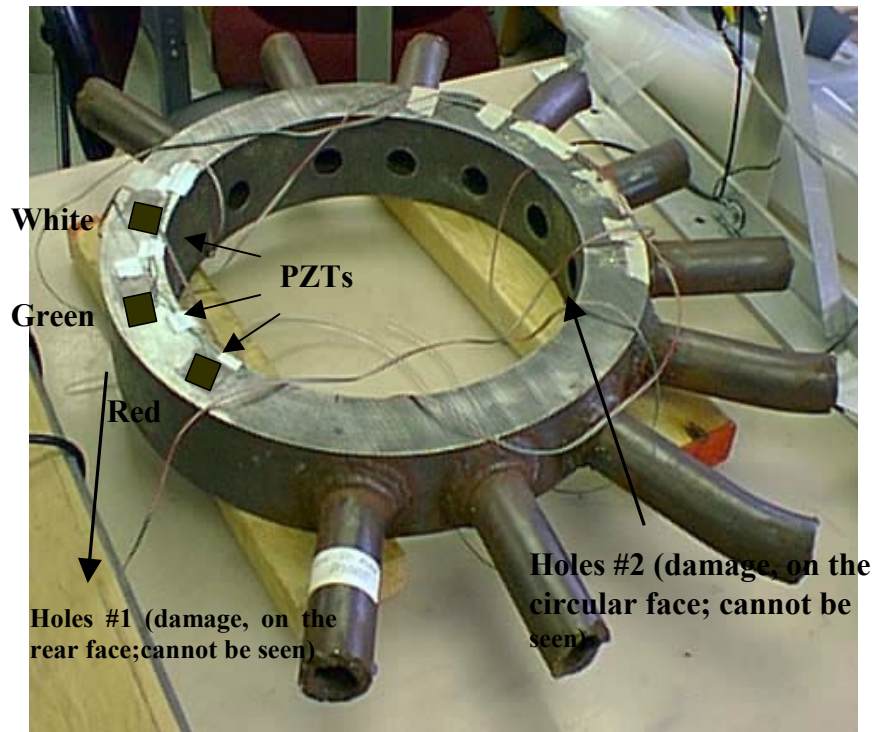
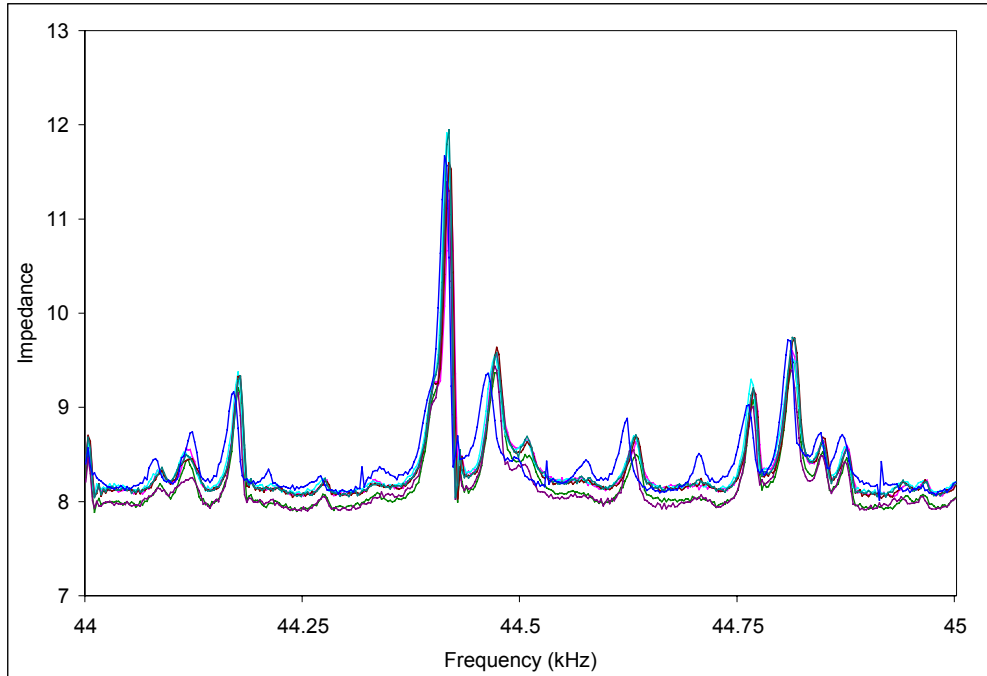
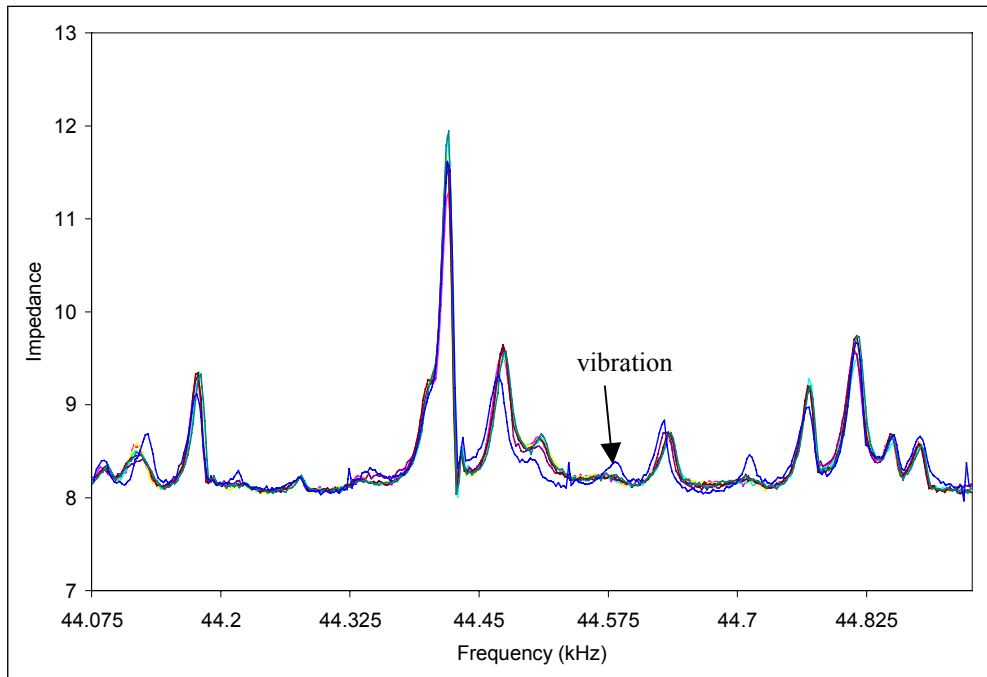


Figure 3.6 Three PZT actuator/sensors were used to find damage in the header section

As can be seen at Fig. 3.7 and 3.8, boundary condition changes cause a variation in the impedance signature. The variations were significantly reduced by the compensation procedure. The essential signature pattern remains and the measurements were found to be repeatable. Low frequency ranges show relatively small variations compared to the higher frequency ranges. ‘Vibration’ produces the largest damage metric, thus this value is considered to be a maximum value of that produced by the boundary condition changes.

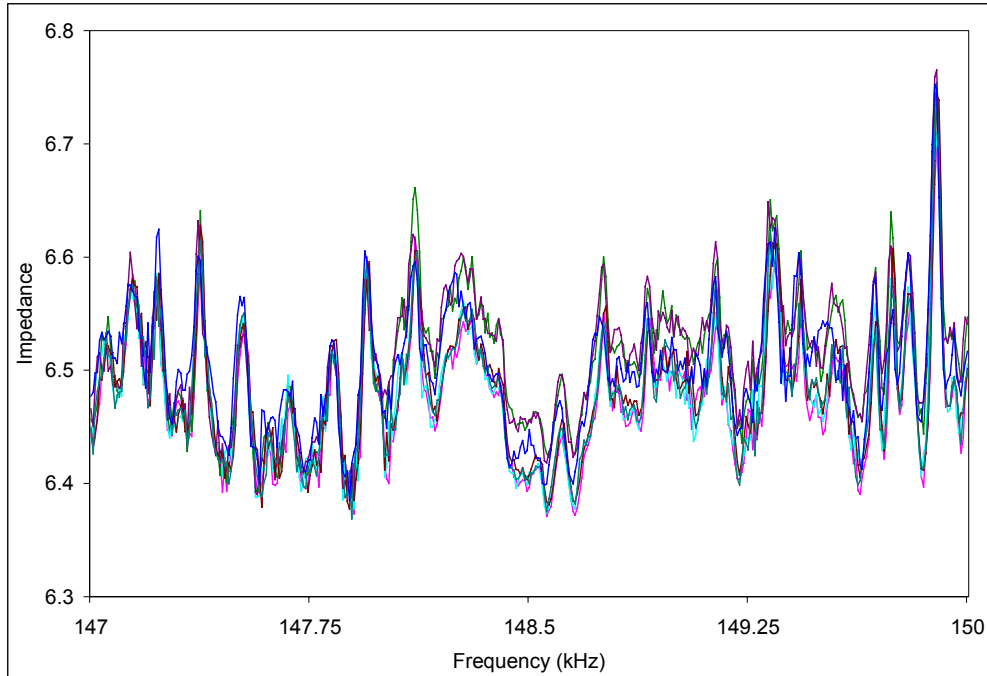


(a) uncompensated impedance

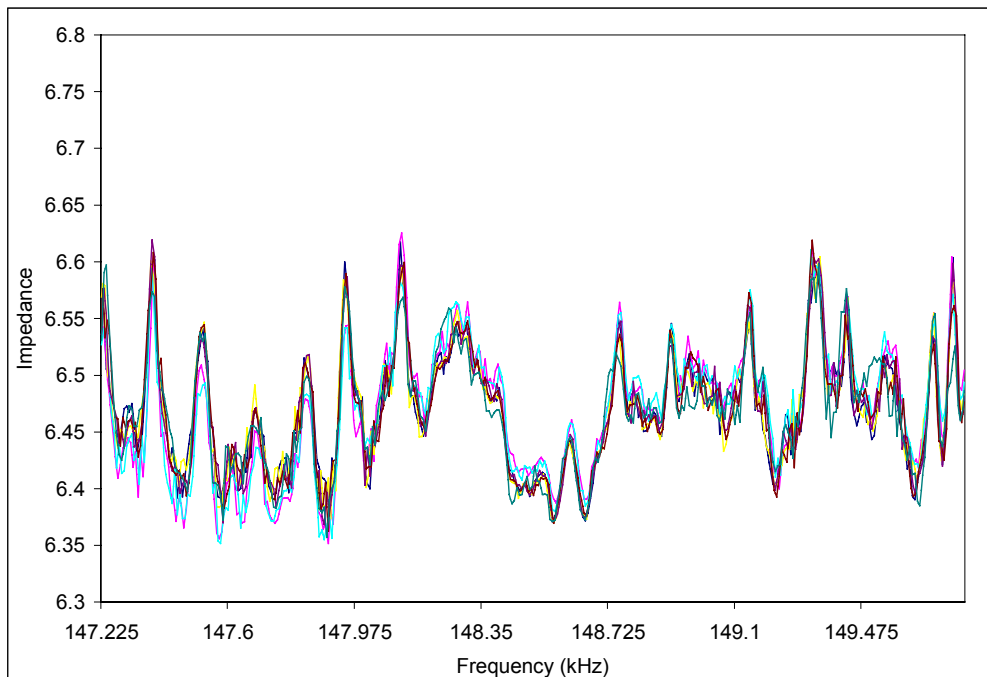


(b) compensated impedance

Figure 3.7 The variation in the real impedance measurements shows that vibration gives the largest change.



(a) uncompensated impedance

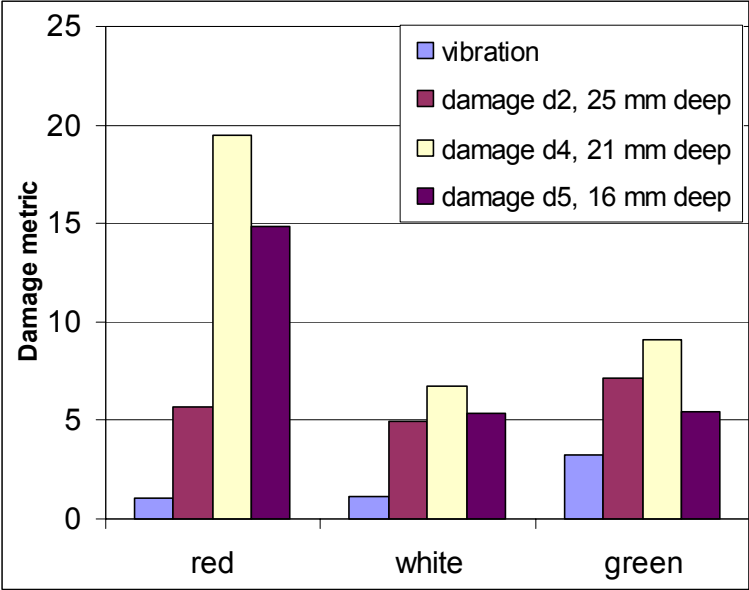


(b) compensated impedance

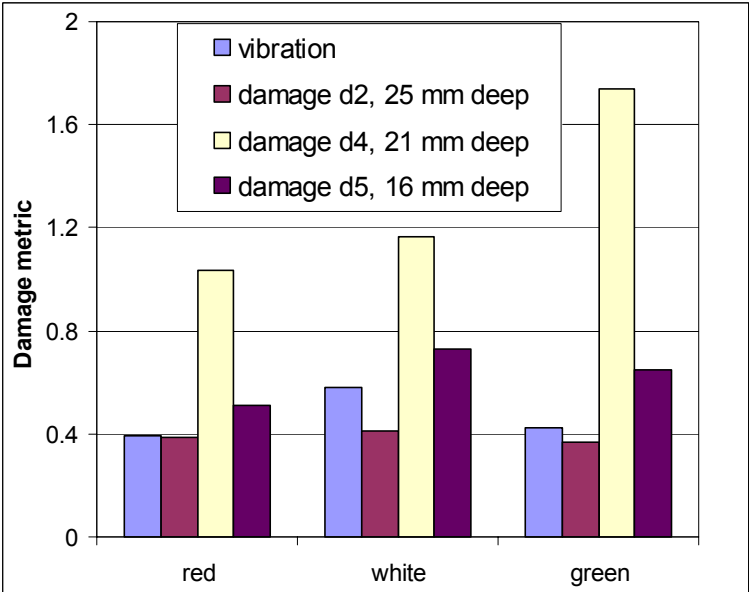
Figure 3.8 The variation in the real impedance measurements shows that higher frequency ranges are more sensitive than the lower frequency range

After identifying the range of the impedance signature variation due to the boundary condition changes, damage was induced in the vicinity of the PZT sensor/actuator (as holes #1 in Figure 3.6) to increasing levels. The diameter of the holes drilled was 2, 4, 5 mm and deepened until a clear change of the damage metric due to the induced damage could be observed over the boundary condition changes. The ability to detect the levels of damage was studied using the damage metric chart as can be seen from Figure 3.9.

From the analysis of the metric charts, the sensitivity of the impedance-based technique is confirmed at 2 mm diameter x 25 mm deep, 4 mm x 21 mm and 5 mm x 16 mm, if damage is located in the vicinity of the PZT sensors. This damage corresponds to the mass loss of 0.002 % of an entire structure. The measurements of frequency response functions were made using an attached accelerometer before and after the damage, however, by this incipient-type of damage, no noticeable change in vibrational response was observed. Although, no conclusion could be reached about the optimal frequency range, there is a general trend that low frequency range is more reactive to the presence of the damage over the high frequency range. However, it is suggested that interrogating with several different frequency ranges would give more accurate results. Note that 2x25 mm hole could not be detected at the 147-150 kHz frequency range.



(a) Frequency Range 44-45 kHz



(b) Frequency Range 147-150 kHz

Figure 3.9 The damage metric to identify the extent of damage that could be detected over the boundary condition changes in the header

After identifying the ability to detect the level of damage in the header section, the next step is to determine the sensing area of the PZT sensors. Damage was induced at opposite location of the PZT sensors (as holes #2 in Figure 3.6), by drilling the hole 5 mm diameter with 20 mm deep. Figure 3.10 shows the damage metric with the number of holes made. As can be seen in the figure, the impedance-based technique can detect 3 holes (5x20 mm) located at 180 degree away from the PZT sensor. Therefore, it could be concluded that if the minimum threshold value of the damage is assumed to be 0.002% of mass loss (5x20 mm hole), as a minimum, three sensors can detect damage at any locations in this specific structure. If the threshold value is three times larger than that, only a single PZT sensor can cover the entire structure.

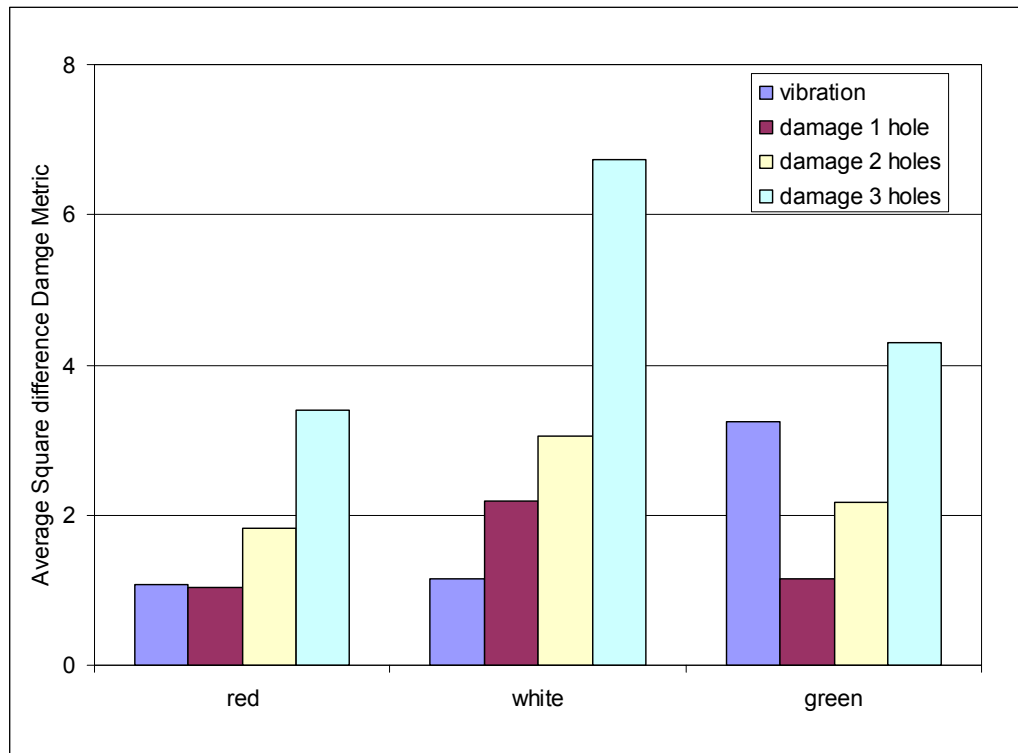


Figure 3.10. The damage metric for the 44-45 kHz frequency range. Damage metric induced by 3 holes gives significant value over that produced by vibration

3.4 Summary

Relatively complex and massive structures are experimentally analyzed to determine the effects of external boundary conditions, ambience and other structural variations on the impedance-based health monitoring technique. The ambient conditions imposed are the addition of weight on the structure, vibration, and the orientation change of the structure.

A comparison of the impedance signatures, with the ambient conditions imposed, was made. Although, the essential signature pattern remains, random peaks and valleys were observed with the ‘vibration’ and large line drifts of impedance curves were observed with the progress in time, possibly caused by small temperature changes. However, the variations could be reduced and be considered as minor changes with the aid of the compensation technique, described in chapter 2. The measurements were found to be repeatable and no noticeable degradation was observed. When damage was introduced close to the PZT sensors, the impedance measurement is significantly different from the previous readings and able to detect imminent damage, even in its early stage.

In summary, by integrating the technique with a signal processing procedure to minimize variations due to the boundary condition and temperature changes, the impedance-based structural health monitoring technique has extended its capability to detect incipient type damage in large-scale civil structures under the uncontrolled environmental conditions.