Chapter 5: EFFECTS OF BOUNDARY CONDITIONS AND AMBIENCE ON HEALTH MONITORING

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.

5.1 INTRODUCTION

The purpose 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. It does not attempt to confront all the questions that arise; instead it tries to provide an in-depth view, through experimental analysis, and hence generate the questions and issues that would arise and need to be dealt with if this health monitoring technique is to be successfully used in practical applications. The focus is more on examining the issues at hand than providing solutions.

In almost all practical field applications, the structure that is being monitored is constantly undergoing change due to external boundary conditions and the surrounding ambience. This change, in most cases, is considered to be normal and a part of the everyday use of the structure. Examples of the factors that lead to this change are loading of the structure, vibration of the structure or parts connected to it and change in the ambient temperature. These factors not only effect the structure but also the equipment that is used to monitor its integrity. For example, temperature changes not only affect the structure in question, but also the piezoelectrics (PZT’s) mounted on the structure.
The effect of these factors on the impedance signature of the structure and the capability of the technique to distinguish and determine damage, are the main issues that are dealt with. The external variations are artificially induced and measurements are taken over 7 days. The measurements are repeated over 7 days for two reasons:

1. Repeating the measurements and examining them over a long time period allows for the experimental analysis to approach the actual solution.
2. The measurements are repeated on separate days in order to simulate real-life conditions and hence obtain a more in-depth view. Variation of the impedance signature over time could then be examined.

The external conditions that are simulated are the addition of weight to the structure, vibration and increase in ambient temperature. These conditions are imposed on the structure when it is ‘undamaged’ as well as when it is ‘damaged’. This was done in order to determine if the technique could detect and distinguish change in the structure due to ‘damage’ as opposed to ‘normal’ variations in the environment.

All analysis and inferences are based on the behavior of the impedance signature. Hence this chapter relies largely on frequency response graphs to arrive at any suggestions. Measurements are compared to each other based on the issue at hand.

5.2 EXPERIMENTAL SET-UP

An aluminum truss structure was used as the test rig (same test structure described in Chapter 4). The structure is a combination of cylindrical members connected to each other by Derlin balls. The rig has 4 levels with 4 Derlin balls (nodes) at the corner of each level. Each Derlin ball has a PZT bonded onto its surface. For this experiment, the second level was considered and the PZT’s on the 4 Derlin balls at this level were interrogated.

Damage in the structure is induced by loosening a diagonal member that connects to a Derlin ball. For example, if damage is to be induced in Derlin ball #1 (bearing PZT
#1), the diagonal member that connects to this ball is loosened. Derlin balls in the second level of the structure bear numbers 1, 2, 3 and 4. The PZT’s bonded onto each of these balls also have the same numbering sequence: PZT 1, 2, 3 and 4. Figure 5.1 shows a photograph of the test rig.

Figure 5.1: Photographs (2 angles) of the aluminum test rig. The 4 levels that constitute the structure can be seen. Derlin balls at the 4 corners of each level can also be seen. For this experiment, the second level was considered. Damage in the structure is induced by loosening one of the diagonal members that connect to a Derlin ball. The numbering sequence for the PZT’s bonded onto the balls is shown.
The HP 4192A impedance analyzer is used to interrogate the PZT’s. The frequency range employed was 40 – 45 kHz. This range was found to have sufficient dynamic interaction for the structure in question. The ‘R – X’ function was used to obtain the frequency response.

The following 5 ambient conditions are imposed on the structure in an attempt to simulate real-life variations:

1. ‘Baseline’: This term is used to refer to the condition of the structure in the absence of any of the below stated 4 conditions.

2. ‘Weight 1’: This term is used to refer to the case when a load of 15 lbs. is added to the structure. The weight (in the form of circular calibrated disks) is hung on the flat member at the first level as shown in figure 5.1.

3. ‘Weight 2’: This term is used to refer to the case when a load of 15 lbs. is added to the structure. The weight is hung on the flat member at the second level as shown in figure 5.1.

4. ‘Vibration’: This term is used to refer to the case when the structure is manually shaken while the measurements are being taken.

5. ‘Heat’: This term is used to refer to the case when the temperature of the area surrounding the PZT’s is increased. This is done by holding a hair-dryer at a distance of 2.5 inches directly above the PZT that was to be interrogated. The hot air from the dryer was used to heat the PZT and the structure in its immediate vicinity, for 60 seconds. The measurement from the PZT was made after the heating was completed.

The order of the experiments was as follows:

The ‘Baseline’ readings are taken from all 4 PZT’s. ‘Weight 1’ is then added at the first level and the next set of readings are taken. ‘Weight 1’ is removed and ‘Weight 2’ is then added at the second level and readings are taken again. ‘Weight 2’ is removed and the structure is manually shaken, and readings are taken while the Vibration is being
imposed on the structure. Each PZT is then heated in turn using the hair dryer, and readings are taken after 60 seconds of heating. This set of 5 readings from the 4 PZT’s (amounting to a total of 20 measurements per day) are repeated over 7 days. For the first 4 days, the structure is maintained in an ‘undamaged’ condition, i.e., all diagonal members that connect to the Derlin ball at the second level are fully tight. At the end of the fourth day, the four diagonal members at the second level of the truss, are loosened by a one-fourth turn. This is done to induce ‘damage’ in the structure. Hence, for the final 3 days, the structure is analyzed in a ‘damaged’ state. The 5 conditions stated previously are imposed in the exact same way on all 7 days; the only difference is that the first 3 days the structure is ‘undamaged’ and the last 4 days the structure is ‘damaged’. A summary of the entire series of experiments is provided in table 5.1. The terminology used in the table is used throughout the analysis and in all the graphs presented.

Table 5.1: Summary of the readings taken from the 4 PZT’s over the 7 days. The term ‘5 readings’ stands for: 1. Baseline, 2. Weight 1, 3. Weight 2, 4. Vibration and 5. Heat. It can be seen that a total of 20 readings are taken on each day.

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<th>Day 1 (Truss is in an undamaged state)</th>
<th>Day 2 (Truss is in an undamaged state)</th>
<th>Day 3 (Truss is in an undamaged state)</th>
<th>Day 4 (Truss is in an undamaged state)</th>
<th>Day 5 (Truss is in a damaged state)</th>
<th>Day 6 (Truss is in a damaged state)</th>
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<td>PZT 4</td>
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5.3 RESULTS AND ANALYSIS

The results from the various test cases were analyzed using frequency response plots. Damage metric charts, based off the frequency charts are used to quantify the analysis.

While the frequency response charts provide a qualitative approach to the analysis, the damage metric charts quantify and summarize the information. The formulation used to arrive at the damage metric charts is ‘1 – Correlation’. The range of values is 0 to 2.0. The greater the damage the greater the numerical value of the damage metric.

Since this chapter is largely reliant on the frequency response plots, the analysis is done by presenting a series of plots; any derived observations are based on these charts. Comparisons among the measurements in the data set are done depending on the issue at hand.

It was found that the ‘R’ portion of the frequency response was more reactive than the ‘X’ part (it had a larger number of peaks and valleys in the frequency range considered); hence, only the ‘R vs. Frequency’ plots are presented. The damage metric charts also are based off these plots.

5.3.1 OBSERVATION 1: VARIATION OF IMPEDANCE SIGNATURES ON A GIVEN DAY

The ‘R vs. Frequency’ plot for all 4 PZT’s are presented. To prevent cluttering of data, results from Day 1 only are shown. Each plot shows the variation of the impedance signature with the 5 ambient conditions imposed on the structure. It must be noted that
measurements on Day 1 are taken with the structure in an ‘undamaged’ state. Figures 5.2 a-d show the ‘R vs. Frequency’ plots for PZT 1 through 4 on Day 1.

Figure 5.2 a: ‘R vs. Frequency’ plot for PZT 1, Day 1.

Figure 5.2 b: ‘R vs. Frequency’ plot for PZT 2, Day 1.
Figure 5.2 c: ‘R vs. Frequency’ plot for PZT 3, Day 1.

Figure 5.2 d: ‘R vs. Frequency’ plot for PZT 4, Day 1.
On analyzing figures 5.2 a to d, it was noticed that in the case of PZT’s 2 and 3, the impedance signature remained essentially the same, except in the case when ‘Heat’ is applied. When ‘Heat’ is applied, the impedance signature shows a vertical downward shift, while still retaining the same pattern as the remaining cases. In the case of ‘Weight 1’, ‘Weight 2’ and ‘Vibration’, there are small variations along the signature, but the essential pattern remains the same as that of the ‘Baseline’. It can however be seen that the signature in the ‘Vibration’ case has random peaks and variations. This is expected as the structure is being manually shaken while the reading is being taken and hence, the impedance signature varies accordingly. In the case of PZT 4, the curve in the ‘Heat’ case does not display the vertical shift mentioned previously. There is a relatively large change in the pattern of the curve when compared to the remaining cases. No definite pattern could be traced in the case of PZT 1.

5.3.2 OBSERVATION 2: COMPARISON OF EXTENT OF DAMAGE USING DAMAGE METRIC CHARTS

Damage metric charts, using the ‘1-Correlation’ formulation and based off the ‘R vs. Frequency’ plots are presented. Figure 5.3 a shows the damage metrics for PZT 2 for the measurements taken over the 7 days. The method used to arrive at the metrics is: The ‘Weight 1’, ‘Weight 2’, ‘Vibration’ and ‘Heat’ curves on a given day are compared to the ‘Baseline’ curve on the same day, and the correlation metric is calculated for each of these curves. This calculation is done for all 7 days. The chart shown is for PZT 2 only to prevent cluttering of data.
It can be seen from figure 5.3 a, that on any given day, the metrics generally show an increase in value in the following order: ‘Weight 1’, ‘Weight 2’, ‘Vibration’ and ‘Heat’. The metrics in the case of ‘Heat’ have the highest values. It can also be seen that the metrics in the case of Days 5 to 7 (when the structure is damaged) generally have larger values than those in the case of Days 1 to 4 (when the structure is undamaged).

Figure 5.3 b, presents the same damage metric chart as shown in figure 5.3 a except that the metrics are mathematically averaged. The ‘Weight 1’ metric values (refer figure 5.3 a) from Days 1 to 4 (when the structure is undamaged) are added and the obtained value is divided by 4. This gives the first column in figure 5.3 b. The process is repeated for the next three columns as well. The ‘Weight 1’ metric values (from figure 5.3 a) from Days 5 to 7 (when the structure is damaged) are added and the obtained value
is divided by 3. This gives the fifth column in \textit{figure 5.3 b}. The process is repeated for the next three columns as well. \textit{Figure 5.3 b} serves to draw a comparison of the metric values between the ‘damaged’ and ‘undamaged’ cases for PZT 2.

\textit{Figure 5.3 b}: Damage metric chart for PZT 2. The metric values are averaged (from \textit{figure 5.3 a}) and serve as a comparison of the ‘damaged’ versus the ‘undamaged’ case.

It can be seen from \textit{figure 5.3 b}, that when the metric values are averaged over the first 4 days (for the undamaged structure) and the next 3 days (or the damaged structure), there is a definite pattern in their values. There is an increase in metric value with the ambient conditions. The metrics for the ‘Heat’ case have the highest value. It can also be seen that the metrics have larger absolute values when the structure is ‘Damaged’ as compared to those from the ‘Undamaged’ structure.
Figure 5.3 b displayed the averaged damage metrics for PZT 2 only. Figure 5.3 c shows the averaged damage metrics for all 4 PZT’s. The metric values in this chart are calculated in the same way as in figure 5.3 b.

![Damage Metric for individual PZT's](image)

*Figure 5.3 c: Damage metric values for all 4 PZT’s, with the values averaged over the first 4 days (structure undamaged) and the last 3 days (structure damaged).*

There is a lack of consistency in the metric values for the 4 PZT’s shown in figure 5.3 c. Hence, in an attempt to simplify and summarize the information from this figure, the metric values are averaged as explained below.

The metric values from the 4 PZT’s are averaged and the results are presented in figure 5.3 d. The method used to arrive at the metrics is:

The ‘Weight 1’ metric (refer figure 5.3 c) for PZT’s 1 through 4, in the ‘undamaged’ case are added and the obtained value is divided by 4. This gives the first column in figure 5.3 d. This calculation is repeated for the next three columns as well. The fourth column is obtained by adding the ‘Weight 1’ metric values (from figure 5.3 d) for PZT’s
1 through 4, in the ‘damaged’ case and dividing the obtained value by 4. The last three columns are arrived at in the same way. Figure 5.3 d serves to provide an overall comparison (by averaging the metric values over time and over the 4 PZT’s) of the ‘undamaged’ versus the ‘damaged’ case.

Figure 5.3 d: Damage metric chart, with the metrics averaged for all 4 PZT’s over the first 4 days (‘Undamaged’) and the last three days (‘Damaged’).

It can be seen from figure 5.3 d that on averaging the information from PZT’s 1 through 4, a pattern evolves. There is a general increase in metric values with the ambient conditions imposed. The values from the ‘Heat’ case have the highest absolute value. It can also be seen that the metrics in the ‘Damaged’ case have larger absolute values when compared to those from the ‘Undamaged’ case.
5.3.3 OBSERVATION 3: FREQUENCY RESPONSE PLOTS SHOWING VARIATION WITH TIME

‘R vs. Frequency’ plots, with each plot showing curves for any one of the 5 ambient conditions, over all 7 days are shown. To prevent cluttering of data, plots from PZT 2 only are considered. The 5 plots are:

Figure 5.4 a: ‘R vs. Frequency’ plot, PZT 2, ‘Baseline’ curves from Days 1 to 7.
Figure 5.4 b: ‘R vs. Frequency’ plot, PZT 2, ‘Weight 1’ curves from Days 1 to 7.
Figure 5.4 c: ‘R vs. Frequency’ plot, PZT 2, ‘Weight 2’ curves from Days 1 to 7.
Figure 5.4 d: ‘R vs. Frequency’ plot, PZT 2, ‘Vibration’ curves from Days 1 to 7.
Figure 5.4 e: ‘R vs. Frequency’ plot, PZT 2, ‘Heat’ curves from Days 1 to 7.

These plots are presented in order to examine the trend of the impedance signature over time.

![Figure 5.4 a: ‘R vs. Frequency’ plot for PZT 2. ‘Baseline’ readings on the 7 days are shown.](image-url)
Figure 5.4 b: ‘R vs. Frequency’ plot for PZT 2. ‘Weight 1’ readings on the 7 days are shown.

Figure 5.4 c: ‘R vs. Frequency’ plot for PZT 2. ‘Weight 2’ readings on the 7 days are shown.
Figure 5.4 d: ‘R vs. Frequency’ plot for PZT 2. ‘Vibration’ readings on the 7 days are shown.

Figure 5.4 e: ‘R vs. Frequency’ plot for PZT 2. ‘Heat’ readings on the 7 days are shown.
It can be seen from figures 5.4 a to e that the essential pattern of the impedance signatures remains the same over time. However, there are small random variations along the curves with progress in days. Though this result is not conclusive in itself, it does provide an indication towards the repeatability of the measurements. There is a certain degree of change with time, but it is small and can be attributed to random and uncontrollable ambience variations. The next section attempts to quantify this variation and examine the data to see if the damage metrics have a large value when they are calculated over time.

5.3.4 OBSERVATION 4: DAMAGE METRIC CHART FOR VARIATION WITH TIME

A damage metric chart, with the metrics calculated over time, is presented. The method used to arrive at the metrics is discussed below:

All readings taken on Day 1 (that is, ‘Baseline’, ‘Weight 1’, ‘Weight 2’, ‘Vibration’ and ‘Heat’ readings, for PZT 2, Day1) are considered as the baseline. Readings taken on the next 6 days are compared to corresponding readings taken on Day 1 to arrive at the metrics. The ‘Baseline’ reading from Day 2 is compared to the ‘Baseline’ reading from Day 1, and the metric that is yielded gives the first column in figure 5.5. The ‘Baseline’ reading from Day 3, is compared to the ‘Baseline’ reading from Day 1 and the metric yielded gives the second column in the chart. This is continued for Days 4, 5, 6 and 7, which in turn give the next four columns in the chart.

The ‘Weight 1’ reading from Day 2 is compared to the ‘Weight 1’ reading from Day 1, and the metric that is yielded gives the seventh column in figure 5.5. The ‘Weight 1’ reading from Day 3, is compared to the ‘Weight 1’ reading from Day 1 and the metric yielded gives the eighth column in the chart. This is continued for Days 4, 5, 6 and 7, which in turn give the next four columns in the chart.
This procedure is repeated for the ‘Weight 2’, ‘Vibration’ and the ‘Heat’ cases. *Figure 5.5* serves to draw a comparison of the extent of damage (or variation) when measurements are repeated over time.

![Diagram](image.png)

*Figure 5.5*: Damage metric for PZT 2. Metric values are calculated over time to determine the extent of damage (or variation) with time.

It can be seen from *figure 5.5* that the largest metric has a value of 0.11; when this is compared to any of the previous damage metric charts, it is observed that the value is relatively very small. This in itself proves that though there is variation of the measurements with time, this variation, which is due to random uncontrollable effects, is small compared to a case when the structure is damaged.

When the metric blocks for the ‘Baseline’, ‘Weight 1’ and ‘Weight 2’ cases are observed, the first 3 columns (Days 2, 3 and 4; structure undamaged) have smaller absolute values than the last 3 columns (Days 5, 6 and 7; structure damaged). Hence, the
technique is able to determine ‘damage’ over time. The same pattern was not established in the case of ‘Vibration’ and ‘Heat’. This could be attributed to the crude method used to shake and heat the structure. In the first 3 cases, the conditions are constant over time (The weight, in lbs., and the position it is suspended from, remains the same, on all days. The extent of vibration or heat imparted to the structure however, could not be maintained the same on all 7 days).

Consider the metrics to be separated into two sets:
Set 1: Metrics from Days 2, 3 and 4 (when the structure is undamaged); the first 3 columns in each block.
Set 2: Metrics from Days 5, 6 and 7 (when the structure is damaged); the last 3 columns in each block.
When the columns within each set are compared to each other, there is very little variation. For example, consider the first 3 columns in the chart. The largest difference between any two of them is 0.04 (0.05 – 0.01 = 0.04) and this value is negligible.

Hence, it can be concluded that the extent of variation of the measurements when taken over time, is negligible. There is a variation in the signature pattern. But when this variation is quantified, and the values compared to a case when the structure is damaged, these values turn out to be negligible. The damage metric charts, coupled with the frequency response plots, establish the repeatability of the measurements. This proves the capability of the impedance technique to monitor the integrity of complex structures over time.

5.4 SUMMARY
A relatively complex truss structure is 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 at two separate points on the structure, vibration of the structure and application of heat.
Four PZT’s are used to procure the impedance signature of the structure. Measurements are made over a period of 7 days; for the first four days the structure is maintained in an ‘undamaged’ state and the last three days, the structure is analyzed in a ‘damaged’ state. The ‘R – X’ function is used to obtain the frequency response. Various comparisons are made with the acquired data.

A comparison of the impedance signatures on any one given day, with the ambient conditions imposed, is made. A general trend is noted in the charts presented: for the conditions of ‘Weight 1’, ‘Weight 2’ and ‘Vibration’, minor variations are seen along the original (‘Baseline’) impedance curve. The essential signature pattern remains the same. In the ‘Vibration’ case, random peaks and valleys were observed; this is expected, since the structure is being manually shaken while the measurements are being made. In the ‘Heat’ case, a vertical shift in the curve is seen; the essential signature pattern however, remains the same.

When damage metric charts are plotted for the above variations, no definite trend is observed when individual measurements are considered. Hence, the metric values from various cases are averaged and an overall damage metric chart is presented (figure 5.3 d). It was noted that there is an increase in damage metric values with variation in the ambient conditions. The metric for the ‘Heat’ case has the largest metric. Also, the metrics in the ‘damaged’ case have larger values than those in the ‘undamaged’ case.

Next, a comparison of measurements is made to observe the trend of the signatures with time. This is also done to check the repeatability of the measurements over time. Frequency response plots for PZT 2, depicting the variation of individual measurements over the 7 day period are presented. It was seen that there are minor variations in the impedance signature over time. However, when damage metric charts are calculated for this case, the values were seen to be small, and hence, negligible. It was concluded that though there is degree of variation, the measurements are repeatable. The
damage metric charts also proved that the impedance technique could determine damage over time; when the baseline reading is taken at some point of time, and damage was inflicted to the structure at a much later time, the technique could be used to detect and determine this damage. The technique is able to distinguish ‘damage’ from normal, everyday structural and ambient variations, to an extent.

In conclusion, it can be stated that external ambient conditions, do cause variations in the impedance signature. However, the impedance technique is able to distinguish and detect damage, within limits. A more complete understanding of the variation of the impedance signatures (with factors such as temperature), and application of signal processing methods would aid towards a more effective damage detection technique. It was also concluded that the measurements do vary over time, but the variation is relatively small (with reasonably small ambient variations); the measurements were found to be repeatable.