Chapter 2

Low Cost Impedance Measurements

2.1 Introduction

The impedance measurement used for the health monitoring technique contains values of impedance for a range of frequencies. Typically these measurements are made using an impedance analyzer such as the HP 4194A. Unfortunately, not all projects that the impedance method could be applied to have access to an impedance analyzer. Typical impedance analyzers cost approximately $40,000 new (compared to PZT transducers which are very inexpensive on the order of $1/sensor). In addition to the expense, this type of analyzer is bulky as well as very heavy. The impedance technique uses a very small subset of the capabilities of this instrument. Finally the large analyzers would not be not useful for self diagnostic systems where the philosophy would be to imbed all electronics, computing and sensing into a system in an unobtrusive way. By developing a lost-cost miniaturized impedance-measuring device, an on-line system would be more portable and more easily used by maintenance technicians. This chapter presents a new technique of measuring impedance that will broaden its availability to the health monitoring community as well as miniaturize the equipment needed to use the impedance method.

2.2 Conventional Impedance Measurements

The most common method of making impedance measurements uses a HP 4194A Impedance/Gain-Phase Analyzer. Other analyzers, such as the HP 4192, have similar functionality, but lack characteristics desired for the impedance based health monitoring technique, such as a frequency sweep mode or graphical display unit. The HP 4194A simultaneously measures 2 independent, complimentary impedance parameters. The combination of these parameters represents both resistive and reactive characteristics of electrical impedance. 15 sets of measurement parameters are available, however only one, the *R-X* function, is generally used for health monitoring. *R* represents the real component of impedance in ohms and *X*, the imaginary component in ohms. In an equivalent series circuit this impedance is equal to $R+jX$. The absolute impedance, *Z*, and phase angle, θ, can be calculated as follows:

$$Z = \sqrt{R^2 + X^2} \tag{2.1}$$

and

$$\theta = \tan^{-1}\left(\frac{X}{R}\right). \tag{2.2}$$

Instead of using magnitude (Z) and phase (theta), the component *R* is generally employed for structural health monitoring. This is due to the fact that *R* is more reactive to damage or changes in structural integrity, while *X* changes more due to temperature, loading or wire length (Raju 1998).

Other devices have been suggested for making impedance measurements for health monitoring, but are not commonly used. Raju suggested using a laptop connected to the HP 4192A analyzer via a PCMCIA-GPIB data bus to remotely control the analyzer and simulate a sweep function with a Visual Basic for Applications software package developed by himself. This is submitted as a less expensive and more portable alternative to the 4194A. Unfortunately, it still requires a user to purchase equipment that is not common in many structural engineering labs and is still a far cry from the desired self contained monitoring system.

The impedance method represents just one technique for developing a self-sensing technology. Another self-sensing method using a RC-bridge circuit with a signal generator and sensor signal pickup has been presented by Pardo de Vera and Guemes

(1997). The bridge circuit is the circuit used to make a self-sensing actuator presented by Dosch et al. (1992) as seen in figure 2.1.

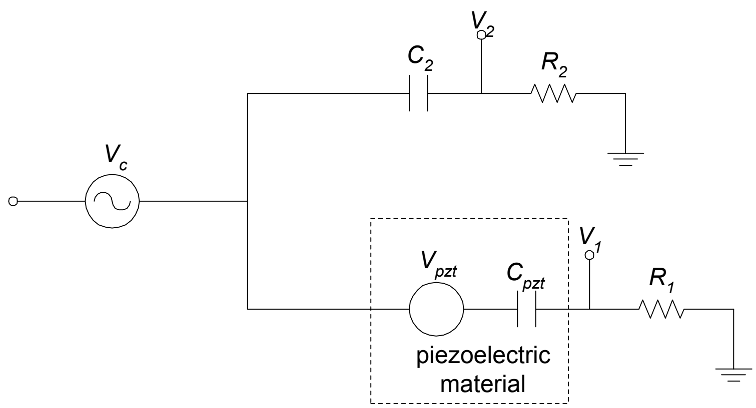

Figure 2.1 Self-sensing actuator circuit (rate of strain sensor)

In the diagram V_c represents the controlling voltage, and the output voltage is V_1-V_2. It is important that the circuit be precisely balanced ($R_1C_{pzt} = R_2C_{pzt}$) to prevent the excitation signal from contaminating the output. An initial attempt at balancing can be made by using a reference PZT similar in dimensions to the sensor, yet not attached to the structure. Also with additional processing it is possible to obtain real impedance versus frequency data.

Giurgiutiu and Rogers (1998) suggested the simplified use of the core electronics from the HP 4194A for impedance measurements. This contains sections for signal generation, an auto-balancing bridge section and for taking a vector ratio. The signal generation and bridge section would be similar to Pardo de Vera and Guemes's device. The vector ratio detector determines the impedance by taking the ratio of voltage to current. Issues with this method include that the design may be patented by Hewlett Packard and the design is more complex than needed since it contains functions that are not used in the health monitoring technique.

2.3 Alternative Impedance Measuring Circuits

To address the issues of prohibitive cost and portability, a new method of generating impedance measurements utilizing an FFT analyzer and small current measuring circuit has been developed. FFT analyzers, such as those used in modal analysis, are much more common and less expensive than impedance analyzers. They also often have the benefit of being portable and may be implemented on a computer chip the size of a postage stamp, thus moving in the direction of creating a self contained, unobtrusive monitoring system.

The electrical impedance of the bonded PZT is equal to the voltage applied to the PZT divided by the current through the PZT. An approximation of the impedance is generated by taking the ratio with the FFT analyzer of the voltage supplied to the circuit, V_i, to the voltage, V_o, across a sensing resistor, R_s, in series with the PZT as seen in figure 2.2.

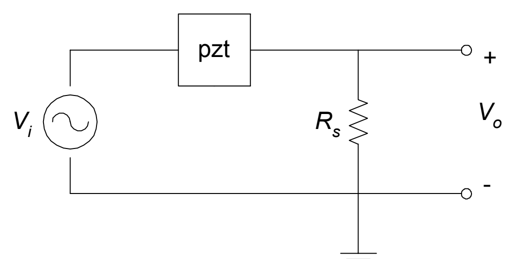

Figure 2.2 Circuit for approximating PZT impedance

This circuit can be recognized a voltage divider. The output voltage is proportional to the current through the sensing resistor, which, if the sensing resistor is small, is approximately the current through the PZT if the sensing resistor was not included (as when measuring with a normal impedance analyzer). The circuit is described by the following equations:

$$I = \frac{V_o}{R_s} \tag{2.3}$$

where I is the current through the sensing resistor. The approximated impedance (Z) is:

$$Z = \frac{V_i}{I} = \frac{V_o}{V_i / R_s} \tag{2.4}$$

Since PZT's are a capacitive element the current through them increases with frequency. Conversely, at low frequencies the circuit has a very high impedance. In this case an inverting amplification circuit can be used to provide a larger output voltage. The size of the sensing resistor could be increased, however, this reduces the voltage applied to the PZT (a larger voltage drop occurs on the sensing resistor). The circuit for approximating the impedance along with the amplification circuit is shown in figure 2.3.

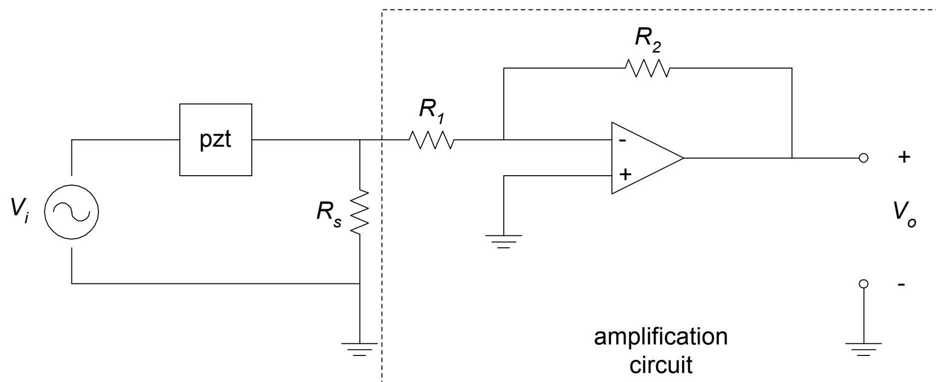

Figure 2.3 Impedance approximating circuit with amplification

The gain, G, provided by the amplification circuit is shown in the following equation:

$$G = -\frac{R_2}{R_1}. \tag{2.5}$$

Since an inverting amplifier is shown, the gain is negative.

At high frequencies (approximately 100 kHz for a gain of 20 dB with a 741 op-amp) the op-amp becomes ineffective due to roll-off of the output signal. The following picture shows an FFT analyzer (HP 35665A dynamic signal analyzer) and current measuring circuit device. The large size of the circuit box was determined by the various connection pieces as well as the batteries used to run the op-amp.

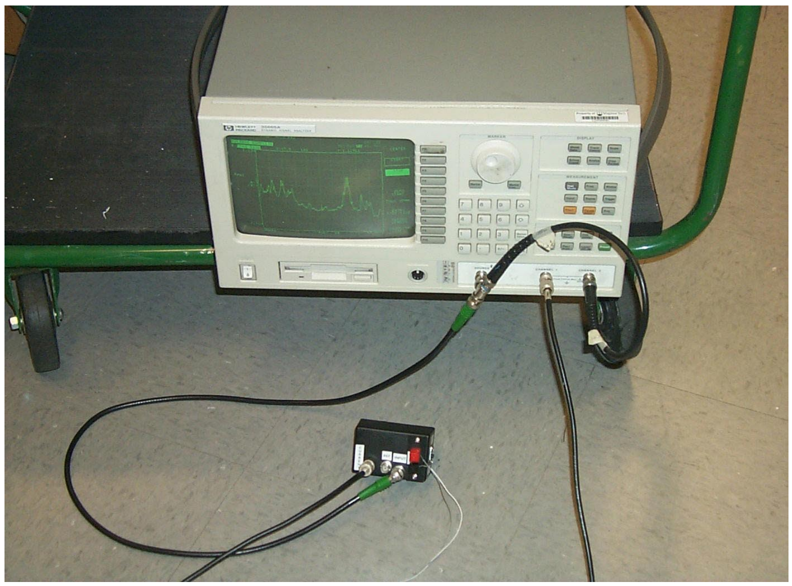

Figure 2.4 FFT Analyzer and current measuring circuit

Advantages of the new impedance method include its low cost, greater accessibility and smaller size. The price of the parts required to make one test device was less than $10. It can be assume that the cost would be reduced even more if the parts were ordered in bulk. The new method requires the use of a digital signal analyzer with an FFT function, which is a common piece of equipment in most labs. The circuit is also very small. When combined with digital signal analyzers, which can as small as a postage stamp, the device will be relatively unobtrusive. Other advantages include the possibilities of varying the driving voltage up to the limit of the DSA (10 V for the SigLab analyzer) and combining the technique with wireless communication devices.

2.4 Proof-of-Concept Experiments

In order to demonstrate the effectiveness of the new method of taking impedance measurements three experiments were performed using the new technique. The first compared the new technique to the traditional technique on a bolted joint. The second tested a relatively large pipeline structure and compares the damage metric. The third tested a composite beam for damage.

2.4.1 Bolted Joint Experiment

The loosening mode of failure of bolted joints is a common form of failure in many structures. Real-time condition monitoring and active control of critical joints will improve the reliability and safety of many structures where bolted joints are used. A test specimen was constructed using two 1/4 x 2 x 9 inch sections with an overlap of 3 inches. The joint was fastened using a 3/4-inch bolt with washers. Six 7/8 x 3/4-inch PZT sensors, cut from 0.01 inch thick sheets were bonded to the beam. Three were located 0.5, 2.75 and 5 inches from one free end of the beam and three were similarly placed from the other free end of the beam. In the actual implementation of a self-monitoring system only one PZT would be needed, however, more were bonded to the beam for use in additional experiments. The beam was suspended vertically from one loop of fishing line to simulate a free-free boundary condition. A schematic of the beam is shown in Figure 2.5.

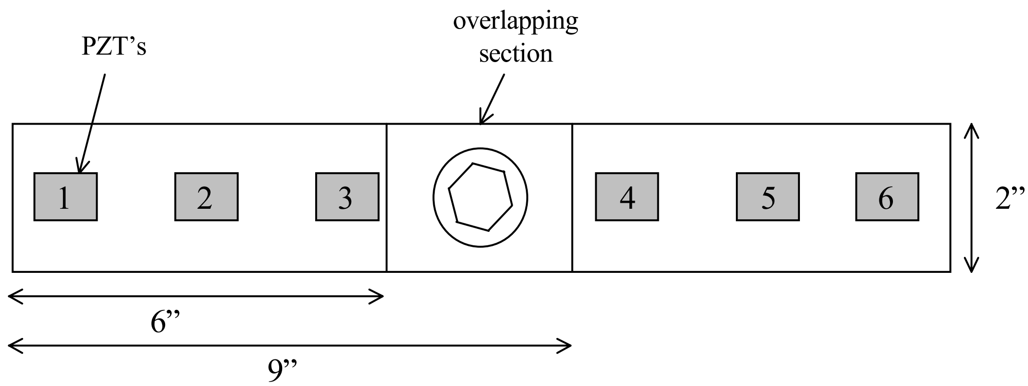

Figure 2.5 Bolted beam schematic

In order to verify that the new, low cost measuring method and traditional method using an HP 4194A impedance analyzer would give the same results, the joint was tested using both methods. For the low cost method a 1 V peak chirp signal was applied using a DSPT SigLab™ 20-42 dynamic signal analyzer and an approximately 20 ohm sensing resistor used without the amplification circuit. Ten runs were averaged. The resulting impedance measurements are shown in Figure 2.6.

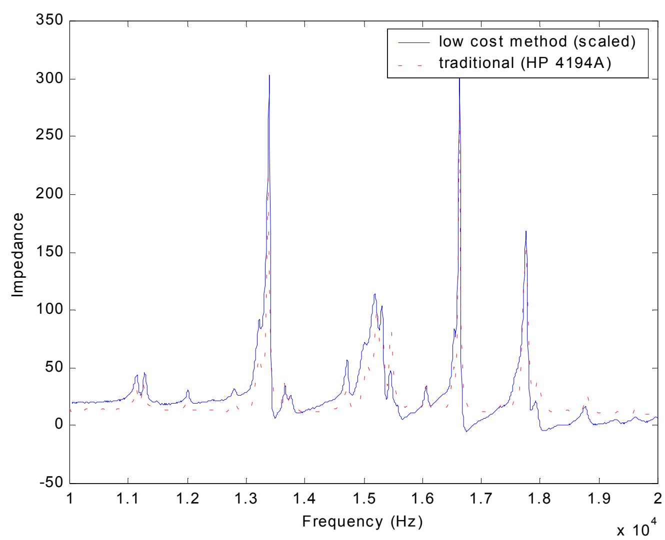

Figure 2.6 Impedance method measurement comparison

The peaks in the response are exactly the same, indicating that the measurements are the same even though small differences are seen. These differences could be as a result of differences in the windowing, A/D conversion, sampling frequency and excitation. Even though the shapes of the two measurements are nearly identical it is important to remember that the impedance method works by comparing a change in impedance from one measurement to another. However, as long as the same method is used to make the two measurements being compared it is irrelevant if the measurements using different methods are different.

The bolt was also loosened from 20 ft-lbs and the change in impedance compared between the two methods. As can be seen in the following two figures, the change in impedance was also approximately the same for each method.

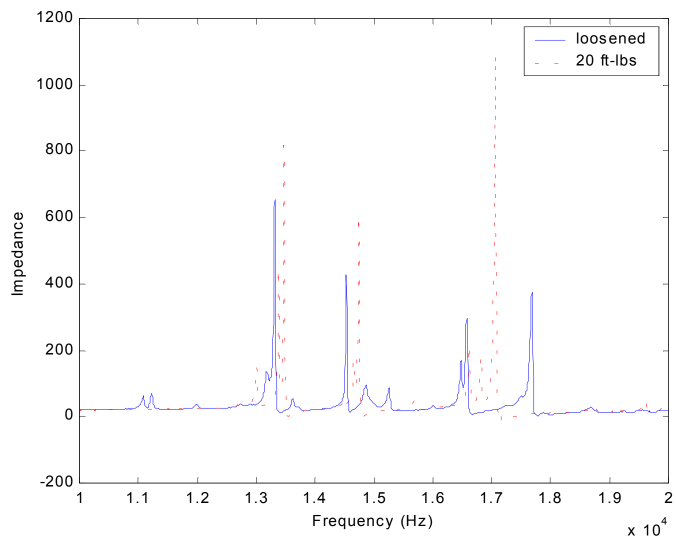

Figure 2.7 Low cost response to simulated damage

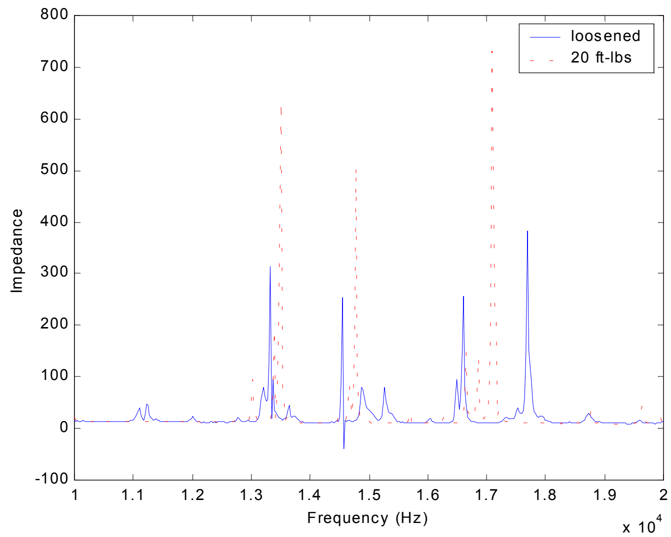

Figure 2.8 Traditional response to simulated damage

The shift in the three largest resonant peaks for the new method were 1.16%, 1.40%, and 2.85% compared to 1.30%, 1.50% and 2.92% for the traditional method giving a maximum difference of 0.14 % shift. This again confirms that the new method gives the same results as the traditional method.

2.4.2 Pipeline Experiment

Another area where the impedance method would be particularly useful is the monitoring of pipes in civil structures. Pipelines convey natural gas, oil, and water, and some pipelines contain communication and power cables, all of which are very important to maintain functional residential and industrial facilities. Pipelines are also required for economic and community recovery after natural disasters. However, pipelines are severely damaged by shaking, liquefaction, and landslides during earthquakes (O'Rourke and Palmer 1996; Koseki et al. 1998) and the immediate assessment of pipeline facilities is critical to prevent fires, explosions, and pollution from broken gas or sewage lines.

A model of a pipeline with bolted joints was tested. This model consists of segmented pipes (d-40 mm), flanges, elbows, and joints connected by more than 100 bolts. The size of this structure is 2 m wide and 1.3 m tall. The critical source of failure in pipelines has been determined to be the bolted joints (Eidinger 1999). One PZT sensor/actuator (15 x 15 x 0.2 mm) is bonded on each of a large (relative to previous experiment) model pipeline as can be seen in figures 2.9 and 2.10.

Figure 2.9 Portion of pipeline structure

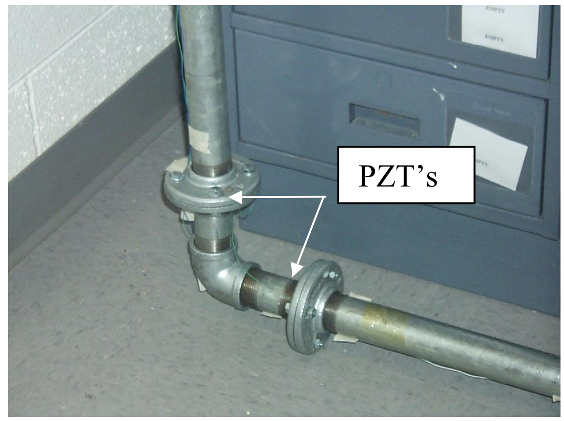

Figure 2.10 Close up of joint showing location of PZT's

For this experiment one PZT located at the bottom flange of the joint in figure 2.10 was monitored. A 35-47.8 kHz, 1 V peak, chirp signal was applied to the PZT and sensing resistor circuit using an HP 35665A DSA. A 100 ohm sensing resistor was used. Twenty runs were averaged. After two measurements in the undamaged state were taken, one of the four bolts on the joint was completely loosened (first damage state) and the measurements repeated. 4 more damaged states were tested consisting of: 2) two bolts loose, 3) three bolts loose, 4) 3 of the 4 bolts loose on the primary joint plus one bolt loose on the adjacent joint and finally 5) a second bolt loose on the adjacent joint. The measurements were corrected for slight upward shifts due to temperature variation. Selected measurements are shown in figure 2.11 comparing the traditional method to low cost method. It can be seen that both methods show the same shape and follow the same trend when damage is introduced.

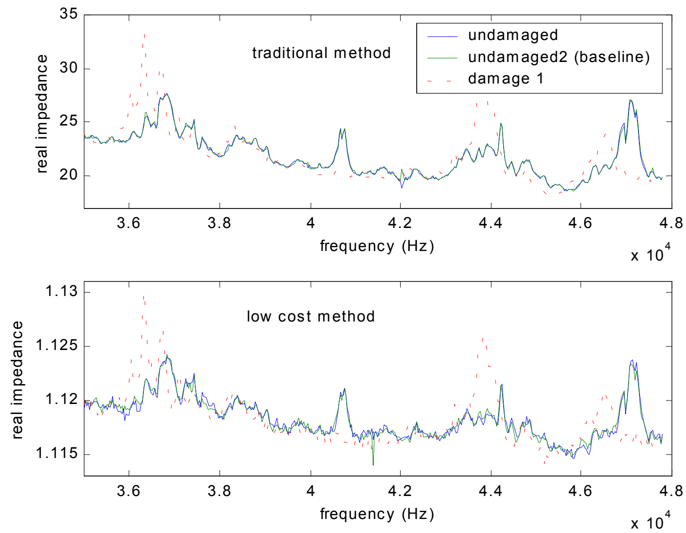

Figure 2.11 Comparison of low cost to traditional method on pipeline structure

Further comparisons were made using the damage metric defined as in the first chapter

$$M = \sum_{i=1}^{n} \left[\mathrm{Re}(Y_{i,1}) - \mathrm{Re}(Y_{i,2}) \right]^2 , \tag{2.6}$$

where M represents the damage metric, $Y_{i,1}$, is the impedance of the PZT when measured at healthy conditions, $Y_{i,2}$ is the impedance of the structure for the comparison with the base line measurement at frequency interval i. The damage metric for each method was calculated and then scaled for comparison by the damage metric at the first damage case. Differences of 0.0287, 0 (since the metric was scaled by this case) and 0.0247 for the undamaged case and first and second damage cases, respectively, were found. The results are shown in figure 2.12.

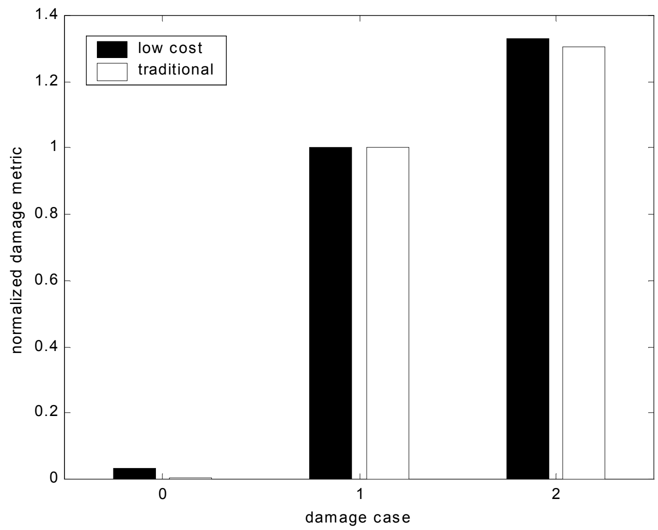

Figure 2.12 Damage metric for traditional and low cost impedance

The larger damage metric for the low cost undamaged case compared to the tradition undamaged case indicates more variability in the low cost measurement as a result of an increased noise level. The damage metric for the damage cases is approximately the same for both methods. This indicates that not only are the original impedance measurements the same, but that the change in the shapes with damage is also the same.

2.4.3 Detecting Damage in a Composite Beam

An experiment was performed with the low cost impedance method to detect damage in a sample C-Channel fiberglass beam. The beam was approximately 3 inches wide with a 7/8 in. sidewall and length of 12 in. The thickness was 1/16 in. A 1.44 in. x 1.44 in. PZT patch was attached 1 3/8 in. from one end. The beam is shown in Figure 2.13.

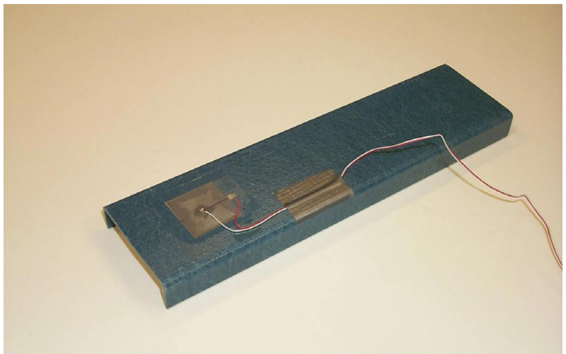

Figure 2.13 Undamaged composite beam with PZT attached

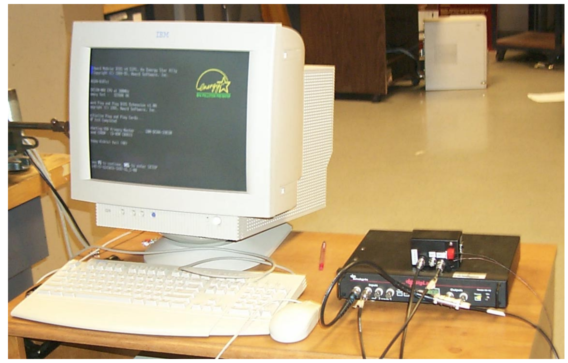

Figure 2.14 Low-cost impedance box, SigLab Analyzer and PC

An initial impedance measurement using the low cost method was made of the undamaged beam using the SigLab™ 20-42 DSA (figure 2.14). An approximately 1.5 in. wide by 2.0 in. deep cut was made parallel to the width at the far end of the beam to simulate delamination. Some cracking at the surface was present. Figure 2.15 shows the damage. An impedance measurement was recorded. Finally, a similar cut, measuring 1.0 in. wide, by 1.0 in. deep, was made at the end of the beam near the PZT (figure 2.16).

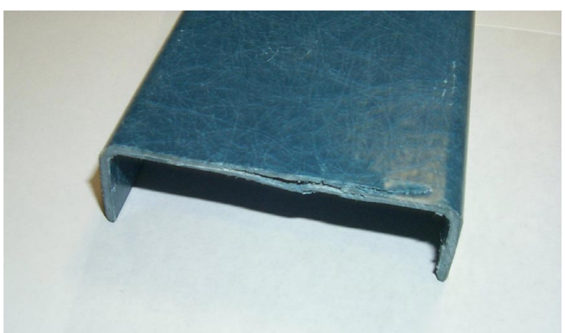

Figure 2.15 Damage at far end of beam

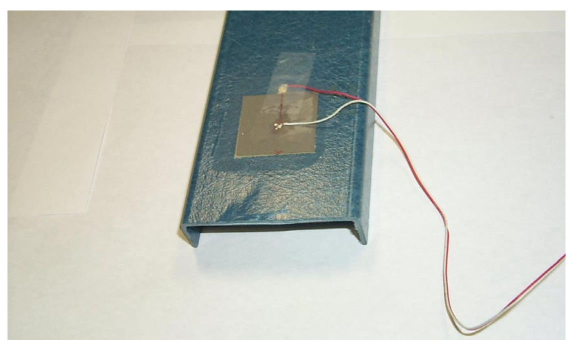

Figure 2.16 Damage at end near PZT

Figure 2.17 shows the impedance measurements for the undamaged case and two damaged cases.

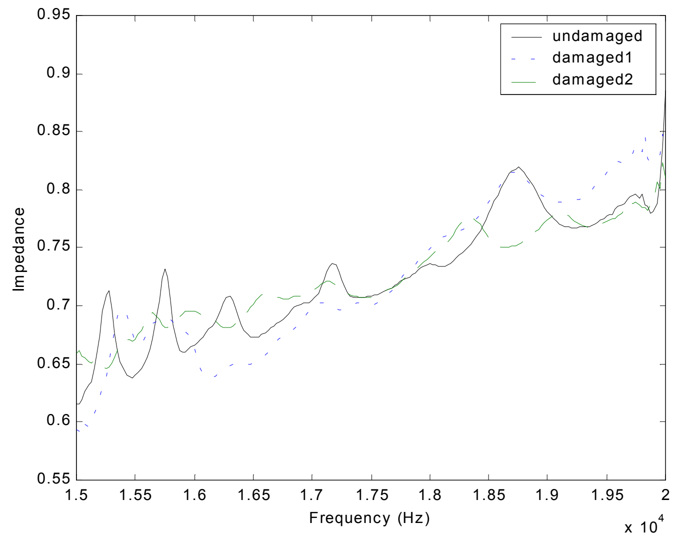

Figure 2.17 Impedance measurements with accumulating damage

The shape of the impedance measurements differs significantly from the previous two experiments because of the higher level of damping exhibited by composite structures. However, the damage can clearly be seen by the changes in the impedance measurements. This demonstrates that the impedance method can detect damage even with turnkey devices.

2.5 Conclusions

A more practical method of making measurements for the impedance method has been developed and tested to allow greater accessibility to the technology. A voltage divider circuit combined with an amplification circuit and FFT analyzer provides an accurate alternative to measure impedance for the health monitoring method. The experimental investigations of low cost impedance-based health monitoring techniques on various components were presented showing that the turnkey device is as effective as a traditional impedance analyzer in making impedance measurements for health monitoring. The device developed in this chapter has already been provided the University of Sheffield for their health monitoring applications using the impedance approach. By making the impedance measurements substantially easier, miniaturized, and inexpensive, the impedance methods can now be readily applicable to the wide variety of real-life field applications. Furthermore, the outcome of this research points to a completely stand-alone, miniaturized impedance measuring device by combining the device with a FFT chip, postage stamp sized DSA or micro-controller and wireless communication technology.