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SENSORS LOCATION EFFECT ON THE DYNAMIC BEHAVIOUR OF THE COMPOSITE STRUCTURE WITH FLAW DETECTION

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ABSTRACT

In this paper presents an experimental and numerical investigation of the natural frequency of composite material cantilever plates. The stacking sequence of the composite plate is Quasi-isotropic laminated plate is $[2(0^{\circ})/\pm 45^{\circ}/2(90^{\circ})]_s$. The plate was subjected to incremental cuts and tests to determine changes in new modal properties. The study included white noise and sinusoidal dynamic testing techniques and a virtual instrument dynamic analyzer. In this study also, determining the resonant frequencies of the undamaged and damaged plate, and evaluating the capabilities of piezoelectric ceramics (PZT's) for fault detection based on their sensitivity and accuracy changes in modal parameters. Numerical results are obtained using finite element software for the composite materials plates.

The experimental and numerical results are very good agreement for the composite material cantilever plates with and without damage.

INTRODUCTION

In general, modal analysis is the study of the structural dynamic characteristics of a mechanical structure. By applying the nondestructive testing techniques of modal analysis, modal parameters of a structure can be determined. Modal parameters are believed to be global characteristics of a structure and therefore, any changes to the system changes the modal parameter. Piezoelectricity is a property of certain classes of crystalline materials. Mechanical pressure applied to a crystalline structure produces a voltage proportional to the pressure. A poling field can be applied so that a ceramic exhibits piezoelectric

responses in various directions. A voltage with the same polarity results from a compressive force applied parallel to the poling axis or from a tensile force applied perpendicular to the poling axis. A voltage with the opposite polarity results from a tensile force applied parallel to the poling axis, or from a compressive force applied perpendicular to the poling axis. (Refs. [4-5]). Piezoelectric ceramics can be manufactured in various sizes, shapes, and the thickness, which allow them to be surface mounted or embedded into a structure. In general, small piezoelectric sensors produce strong clear signals without the need for amplification or conditioning.

Wafer thin piezoelectric ceramics mounted on the surface of a structure are subjected to the same bending and torsion stresses as the structure. In a previous study (Ref. [1]) conducted as a Joint Research Interchange between California Polytechnic State University and NASA, it was shown possible to detect modes of vibration using surface mounted piezoelectric sensors. In a second study (Ref. [2]) also conducted as a Joint Research Interchange between California Polytechnic and NASA, structural flaws were detected using changes in resonant frequencies.

The objective of this study was to combine findings obtained in the above research efforts and investigate the potential of surface mounted piezoelectric ceramics for flaw detection. Tasks included constructing a carbon fiber plate test specimen, mounting six piezoelectric sensors, determining the natural frequencies and amplitude of the undamaged and damaged plate, and evaluating the capabilities of piezoelectric ceramics for fault detection.

EXPERIMENTAL PROCEDURE AND TESTING

The composite plates test specimens were composed of 8 plies of the fiberite carbon fiber pre-impregnated with epoxy 977-2. The fiber orientation is $[0^{o}/\pm45^{o}/90^{o}]_{S}$ and symmetric about the natural axis. An 8"x9" composite air press was used to cure the plates (Ref. [3]) and a diamond blade radio saw sized it to approximately 4"x9". Sensors were cut to size from 2"x1"x0.01" lead zirconate titanate piezoceramic wafers and secured on the surface of the cantilever plates.

Damage to the plate involved using a 2.0" mini radial saw mounted in a milling machine to make incremental edge cuts. The lengths and locations of the cuts depended on the tests.

The data acquisition system consisted of a 486DX2-66 Weston PC compatible computer with 16MB of RAM, a National Instruments AT-MIO-16 F-5 Data Acquisition (DAQ) card, a CB-50 connector block, and Labview for Windows Network Analyzer virtual instrument software.

The carbon fiber plates were cantilevers mounted onto a shake table powered by a MB Electronics amplifier. Input signals to the table originated from either the Network Analyzer the Hewlett-Packard function generator depending on the type of test. A Tektronix oscilloscope monitored input signals into the shake table to ensure correct amplitude.

The experimental procedure for the study consisted of three steps. The first step was the construction of the cantilever plates. The second step involved hardware and software implementation on the PC based data acquisition system. The third step was to identify natural frequencies using techniques to obtain experimental data, which correlated changes in frequency and amplitude to changes in the amount of damage inflicted on the cantilever plates.

Two 1"x4"x0.25" aluminum bars secured with two bolts sandwich clamped one edge of the plate. A third hole, placed in the center of the aluminum bars, secured the cantilever

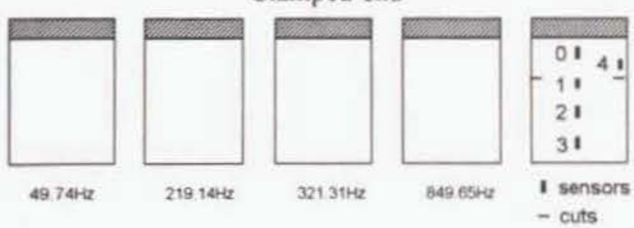
test specimen to the shake table. Damage sets were introduced using thin edge cuts made by a small mini radial saw. The cuts increased along the y-axis parallel to the clamped edge toward the centerline of the plate. That is, a cut of length 2a was composed of two a length cuts positioned symmetrically on both sides of the plate. Damage set 1 was comprised of cuts which began at x=2.2" and increased by 0.30" until the total length equaled 1.2". The frequency band examined for natural frequencies ranged between 0Hz and 1100 Hz.

A total of six sensors were attached to the plate, four along the center axis equal distant apart (identified as 0, 1, 2 and 3), one at the edge (4), and one centered on the bottom surface of the plate (5). The first five sensors were cut to the size of 0.5"x0/5"x0.01" while sensor 5 was cut to the size of 0.7"x0.7"x0.0095". Conductive epoxy secured the negative pole of each sensor to the cantilever plate surface. Utilizing the conductive property of carbon fiber, the plate surface was the common ground of the four sensors. Lead wires soldered from the positive pole of the ceramic to a 10-pin plug, which connected the sensors to the PC data acquisition system.

RESULTS AND DISCUSSION

Figures 1 a) - d) below show node lines determined using sugar traces for the frequencies 49.74Hz, 219.14Hz, 321.31Hz, and 849.65Hz. Node lines for resonant frequencies higher than 849.65 were audible but could not be accurately distinguished using sugar traces.

Clamped end



a) b) c) d) e)

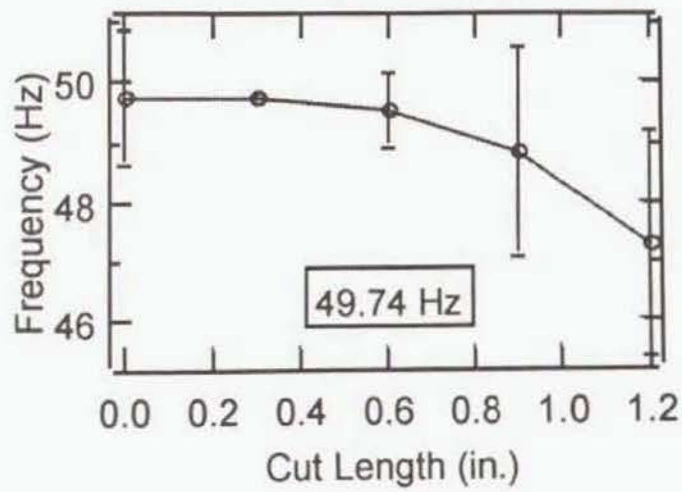
Figure 1 - Node lines identified using sugar traces.

Figures 1a) and b) were believed to be the first bending mode and torsion mode, respectively, Figure 1c) possibly the second bending mode, and Figure 1d) some combination of bending and torsion modes. Figure 1e) indicates the sensor and damage locations.

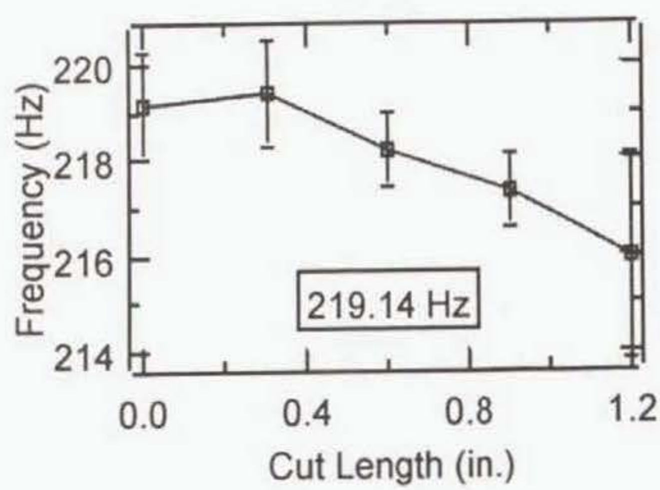
The frequency verses cut length graphs in Figure 2 a) - g) show how the resonant frequencies of the carbon fiber plate changed as the length of the cut increased. The curves were generated using the average of the Frequency Response Functions (FRF 's) peak frequency values acquired from the six sensors. The frequency outlined in the lower center portion of each graph is the value obtained for the undamaged plate. Error bars are the ± standard deviations associated with each test and were derived using values obtained from the six sensors for each peak frequency. Standard deviations averaged approximately ±1.0Hz with a minimum value of 0.0Hz and a maximum value of ±1.45Hz.

Tests conducted for cut lengths equaled to 0.9" and 1.2" showed higher than expected rises and drops in frequencies. The cause of this slight shift was unknown, but because it effected all the data points associated with a particular test, it was suspected that the removal of the carbon fiber plate, in order to damage it may have caused variations in the boundary conditions.

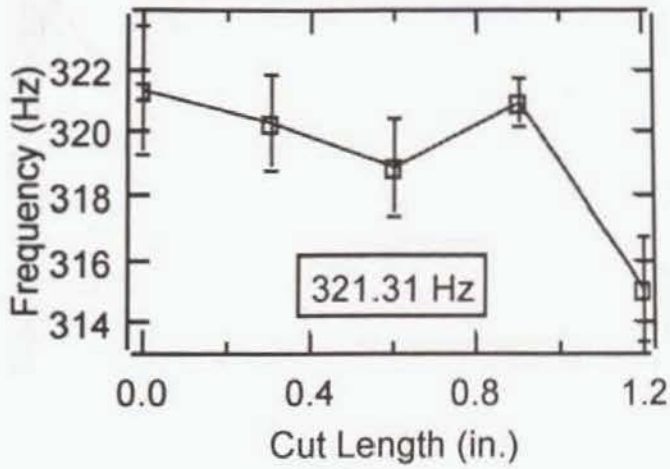
In general, Figures 2 a) - g) show resonant frequencies dropped as the amount of damage increased, and higher resonant frequencies were effected more than lower resonant frequencies. Visually verified as the carbon plate's first bending mode, Figure 2a) shows that the resonant frequency decreased 2.47Hz from 49.74Hz when the plate was undamaged, to 47.28Hz when the plate damage reached 1.2". No conclusions were made about the amount of damage to the plate based on changes in frequency of the first mode due to overlapping standard deviation bandwidths. Standard deviation overlap is apparent in the resonant frequencies of 49.74, 219.14, 321.31, and 533.72 shown in Figures 2 a), b), c), and d), respectively. For the same change in damage, the peak frequency of 849.65 (Figure 2e)) decreased 36.99Hz to 812.01Hz with very little standard deviation overlap. A conservative estimation of the smallest cut length detectable using PR-noise techniques was 0.6".



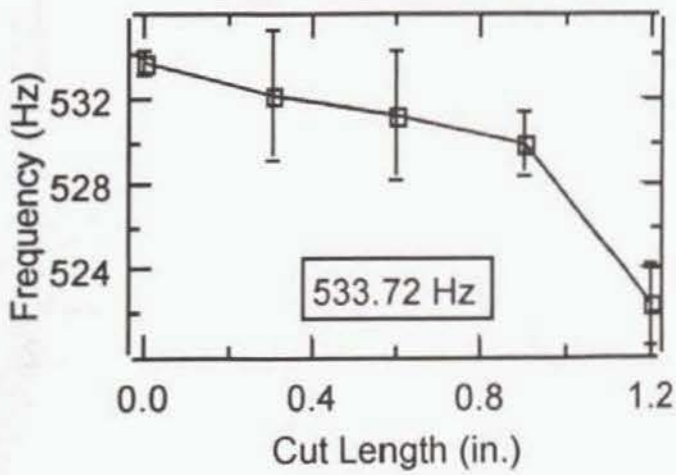
a)



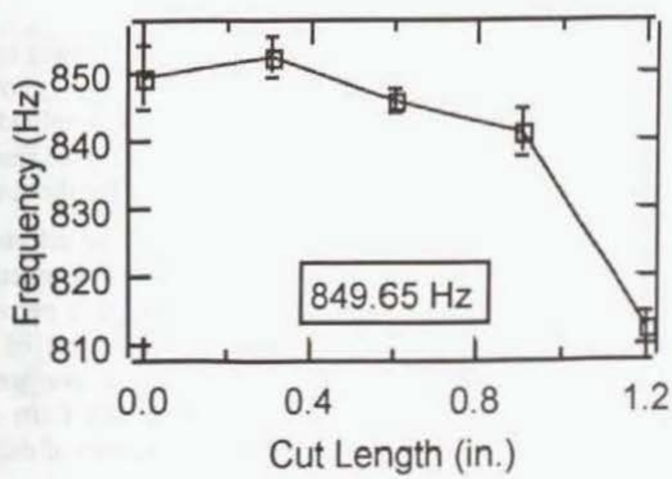
b)


Frequency (Hz)
322
320
318
316
314
321.31 Hz
0.0
0.4
0.8
1.2
Cut Length (in.)

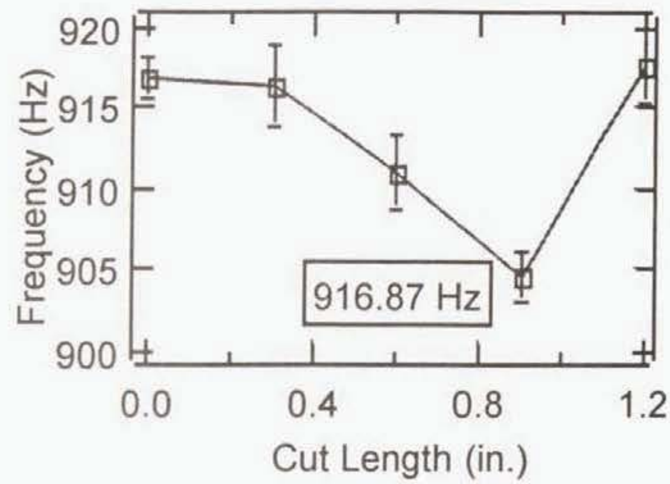
c)


Frequency (Hz)
532
528
524
533.72 Hz
0.0
0.4
0.8
1.2
Cut Length (in.)

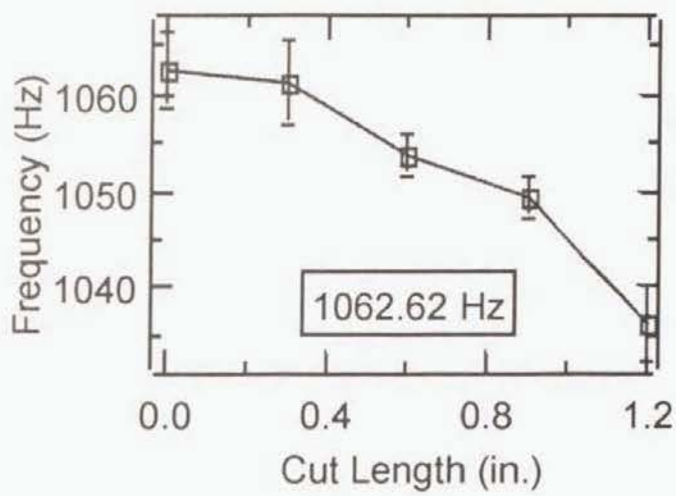
d)


Frequency (Hz)
850
840
830
820
810
849.65 Hz
0.0
0.4
0.8
1.2
Cut Length (in.)

e)



f)

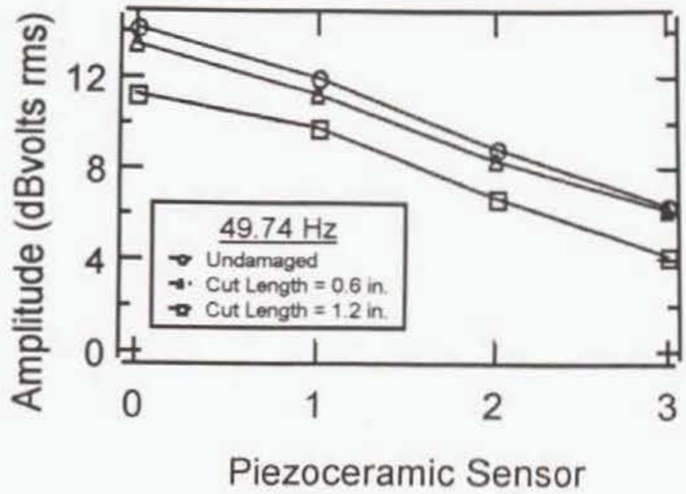


g)

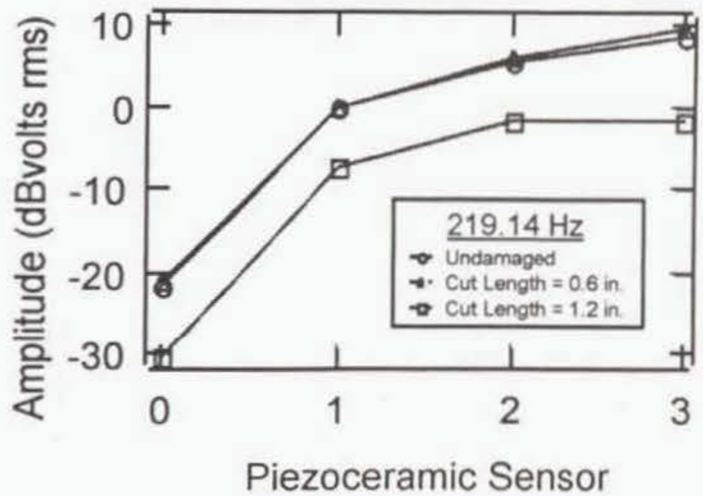
Figure 2 – PR-noise results.

Sinusoidal test results supported evidence of peak frequency changes indicated by PR-noise tests. Amplitude verses sensor graphs shown in Figures 3 a) - g) corresponded well with those shown in Figure 2 a) - g). The graphs exemplify how amplitudes of sensors 0, 1, 2, and 3 diminished as the plate became out of tune with the original resonant frequency due to an increase in damage. Sensors 4 and 5 were not utilized for the sinusoidal tests.

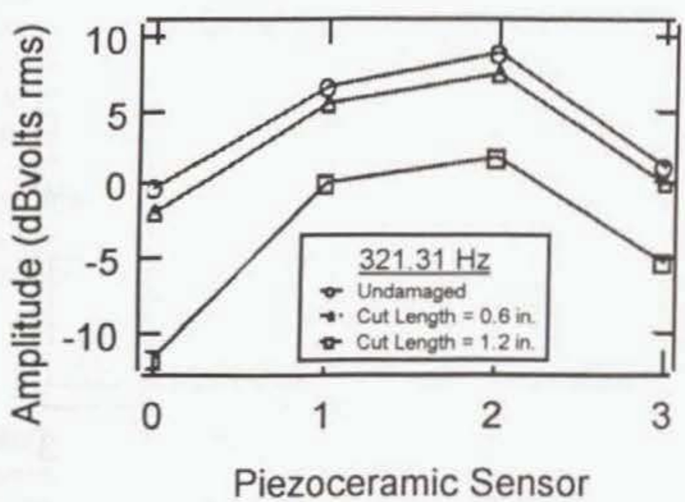
Figures 3 a) -g) also indicated resonant amplitudes tended to be effected more by the second two 0.3" cuts than the first two 0.3" cuts. This suggested that resonant frequencies are more dependent on the total length of a cut, as a percent of the plate length, than to the number of cuts in the plate. The total effect of damage is not necessarily the sum of it parts. Sinusoidal test data was not averaged therefore no standard deviation was applied. Tests proved susceptible to data shifts similar to those mentioned in the PR-noise tests. Figures 3 b) and 3f) are examples of data shifts for 0.6" cut length and 1.2" cut length, respectively.


49.74 Hz
Undamaged
Cut Length = 0.6 in.
Cut Length = 1.2 in.
Amplitude (dBvolts rms)
Piezoceramic Sensor
0
4
8
12
0
1
2
3

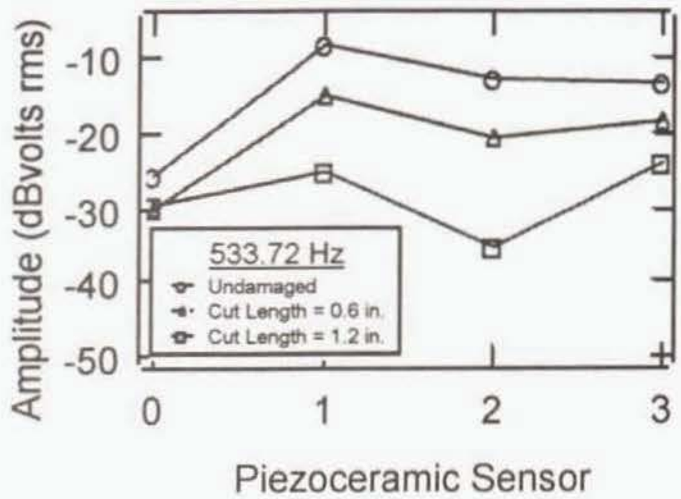
a)


219.14 Hz
Undamaged
Cut Length = 0.6 in.
Cut Length = 1.2 in.
Amplitude (dBvolts rms)
Piezoceramic Sensor
10
0
-10
-20
-30
0
1
2
3

b)

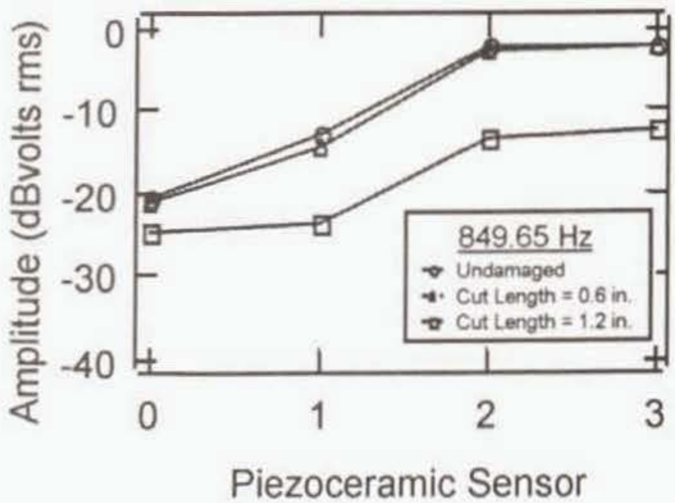

321.31 Hz
Undamaged
Cut Length = 0.6 in.
Cut Length = 1.2 in.
Amplitude (dBvolts rms)
Piezoceramic Sensor
10
5
0
-5
-10
0
1
2
3

c)



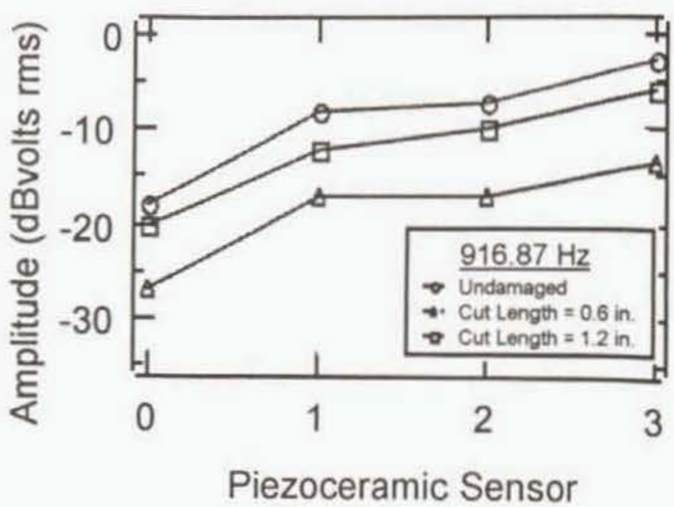
533.72 Hz
Undamaged
Cut Length = 0.6 in.
Cut Length = 1.2 in.
Amplitude (dBvolts rms)
-10
-20
-30
-40
-50
0
1
2
3
Piezoceramic Sensor

d)



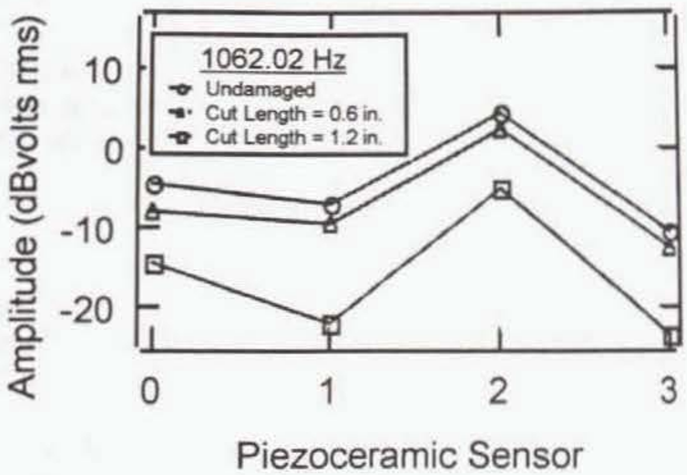
849.65 Hz
Undamaged
Cut Length = 0.6 in.
Cut Length = 1.2 in.
Amplitude (dBvolts rms)
0
-10
-20
-30
-40
0
1
2
3
Piezoceramic Sensor

e)



916.87 Hz
Undamaged
Cut Length = 0.6 in.
Cut Length = 1.2 in.
Amplitude (dBvolts rms)
0
-10
-20
-30
0
1
2
3
Piezoceramic Sensor

f)



g)

Figure 3 - Sinusoidal results.

Dynamic tests indicated that there was correlation between a sensor's ability to detect resonant frequencies and its location. Table 1 below summarizes the best sensor for detecting resonant frequencies.

Table 1 - Best sensors for detecting resonant frequencies.

	Resonant Frequency	Best Sensor	Node line
1	49.74	0	1 a)
2	219.14	3	1 b)
3	321.31	5	1 c)
4	849.65	2,3	1 d)

Relating the resonant frequencies, identified node lines (Figure 1 a) - d)), and sensor locations yielded interesting observations. For example, the resonant frequency of 49.74Hz was identified as the plates first bending mode. Sensor 0, located nearest the cantilever edge, was the most sensitive to the first mode of vibration. Similarly, sensors 2 and 3, located within close proximity of the two node lines associated with the resonant frequency 849.65Hz, were also the best sensors. Sensor 3, located near the free edge of the plate, was subjected to the maximum changes in bending stresses between the two node lines of the resonant frequency 219.14Hz. Sensor 4 located within close proximity of damage was not the best sensor for detecting any of the resonant frequencies which suggested that sensor location was important in relation to node lines but not damage.

CONCLUSIONS

Results from both the PR-noise tests and Sinusoidal tests provided frequency and amplitude evidence, respectively, which allowed damage as small as a 0.6" cut to be detected. Test results also suggested that resonant frequencies were more dependent on the total length of a cut, as a percent of the plate length, than to the number of cuts in the plate.

PZT 's worked well as sensors and its appeared their sensitivity to a particular resonant frequency was a function of position with respect to corresponding node line(s). The ability of PZT sensors to detect changes in frequency and amplitude was independent of its proximity to damage.

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