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Detection of Cracks in Single-Crystalline Silicon Wafers Using Impact Testing

Christina Hilmersson
University of South Florida

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by

Christina Hilmersson

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Department of Mechanical Engineering
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University of South Florida

Major Professor: Daniel P. Hess, Ph.D.
Autar Kaw, Ph.D.
Craig Lusk, Ph.D.
Sergei Ostapenko, Ph.D.

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ABSTRACT

This thesis is about detection of cracks in single-crystalline silicon wafers by using a vibration method in the form of an impact test. The goal to detect cracks from vibration measurements introduced by striking the silicon wafer with an impact hammer. Such a method would reduce costs in the production of solar cells. It is an inexpensive, relatively simple method which if commercialized could be used as an efficient in-line production quality test.

A hammer is used as the actuator and a microphone as the response sensor. A signal analyzer is used to collect the data and to compute frequency response. Parameters of interest are audible natural frequencies, peak magnitudes, damping ratio and coherence.

The data reveals that there are differences in frequency between the cracked silicon wafers and the non-cracked silicon wafers. The resonant peaks in the defective wafers were not as sharp (i.e., lightly damped) and occurred at lower frequencies (i.e., lower stiffness) with a lower magnitude and a higher damping ratio. These differences could be used to detect damaged product in a solar cell production line.

Chapter 1: Introduction and Background

1.1 Overview

The renewable energy market is growing and so are the photovoltaic industries. The thought of using the sun's power for generation of electricity is not new. The concept dates back to the industrial revolution [1].

Crystalline Silicon is the most common material used in the photovoltaic market with over 95% market share [2]. The reason that the photovoltaic cell is not more widespread is cost, particularly cost of cell production. During crystal growth and processing of silicon wafers, imperfections (such as cracks, residual stresses and sub-surface damage) are introduced. Breakage during production due to defects is currently 6-15%, but the industry wants to get this down to 1% [2], the method used in this thesis to detect the cracks could help facilitate this goal. There is a need for fast in-line mechanical quality control methods to detect these imperfections during the production of silicon solar cells. This could reduce the further processing of defective products and reduce overall costs. This thesis focuses on vibration impact testing of wafers for crack detection.

1.2 Background

During the production of the silicon cells, it is not uncommon that cracks and residual stresses are introduced. There currently exist some methods to detect residual stresses. These are X-ray diffraction, transmission electron microscopy (TEM), micro-Raman spectroscopy [3], scanning infrared polariscopy [4], resonance ultrasonic vibrations (RUV) [5] and audible vibration [6].

The cracks introduced are on a cleavage plane are almost closed and are not visible with the human eye. The critical lengths of such cracks is about 1 cm. At 1 cm or more, they propagate in processing from handling etc.

The methods that have been used to detect cracks are scanning acoustic microscopy (SAM), ultrasound lock-in thermography, and millimeter wave [7]. More recently, resonance ultrasonic vibration (RUV) has been investigated to assess the presence or lack of cracks. Ultrasonic vibrations are applied to the wafers and the frequency spectra analyzed [8].

The SAM method of determining the presence of cracks is not feasible during mass production of photovoltaic cells since the time required to scan a 100 mm by 100 mm wafer is between 10 to 15 minutes. Additionally, the wafer has to be submerged in a water bath or covered with a water droplet. The SAM method, however, does allow for cracks as small as 5 to 10 microns to be detected.

Ultrasound Lock-in Thermography can detect cracks with lengths as small as 100 microns. It takes 5-10 seconds to inspect a 100 mm by 100 mm wafer. The major disadvantage is still the time required to test the wafer.

The Millimeter Wave method can be used to inspect a 100 mm by 100 mm wafer in as little as 3 to 5 seconds, but can only be employed for wafers before the metallization process. The crack length that can be detected is 400 microns and larger [7].

The foundation behind the approach taken in this thesis is that impact on a cracked surface sounds different than impact on a non-cracked surface. An easy physical experiment is to tap a glass with a spoon and compare it to a glass which has a crack. One can hear the difference with a human ear. The same demonstration can be performed on silicon wafers. One can hear with the human ear which wafers are significantly cracked. These cracks are obviously large enough to be seen with your eye as well. It would be desirable to detect cracks that are not visible with the eye. In this thesis, an impact hammer is used to tap numerous silicon wafer specimens and the vibratory response is recorded by a microphone.

The silicon wafers of interest are single crystalline silicon wafers grown by the Czochralski method [9]. This thesis assesses the use of an impact test method to detect cracks. This could be a relatively fast, inexpensive and non-destructive method that could be used for in-line quality testing.

1.3 Outline

This thesis presents two different types of data: data from crack-free wafers and data from cracked wafers. In Chapter 2, a description of the setup as well as a description of each instrument used is given. The makeup of the test matrix is covered in Chapter 3. This includes wafer number, type of crack, crack length, wafer thickness and picture number. In Chapter 4, the results obtained are given. Finally, Chapter 5 presents the conclusion and future recommendations.

Chapter 2: Experimental Setup

2.1 Introduction

This chapter presents the experimental setup and describes the sensors and the analyzer used. The specimens used are single-crystalline Czochralski (Cz) silicon wafers. Since the purpose is to detect cracks in wafers there are different types of specimens tested. In this research, the cracked specimens have been deliberately damaged with a diamond pin. In all, thirty different cracked specimens were made and tested.

2.2 Sensors

An impact hammer and a sound level meter are the two sensors used in this experiment. The impact hammer, model PCB 084A17, is made by PCB Piezotronics Inc. The sensitivity of the impact hammer is 22.5 mV/N. The hammer's weight is 2.9 grams and the aluminum handle is 101.6 mm long, the hammer has a stainless steel head with a diameter of 6.3 mm and a red vinyl tip with a 2.5 mm diameter. The hammer is connected by a 0.18G10 coaxial cable, which is 3 m long, with a 5-44 connector terminating in a 10-32 connector that is connected with a BNC to the SigLab dynamic analyzer.

The sound level meter used is a model 2900 manufactured from Quest Technologies. The meter is set to measure sound pressure in the range of 60-120 dB. The sensitivity of the sound level meter is 5V/120 dB. The sound level meter and the SigLab dynamic analyzer are connected from the ac output of the meter with a 6 ft shielded cable 1/8” plug to an RCA plug. The RCA plug is connected with a gold plated RCA to BNC adapter and connected with the female BNC connection of the analyzer.

2.3 Analyzer

The analyzer is SigLab model 20-42 and is manufactured by DSP Technology Division. The SigLab has 4 input channels and 2 output channels. The impact hammer is connected to input channel 1 and the sound level meter is connected to input channel 3. The analyzer calculates the frequency response with the impact force as the input and the sound pressure as the output. A laptop is connected to the SigLab with a Slim SCSI PC card, the PC runs the SigLab software which is written in MatLab R12. In the SigLab software, the bandwidth is set to 1.0 kHz and the record length is 8192, which gives a delta frequency of 0.313 Hz and a record time of 0.3 seconds. Also, the sensitivity of the hammer and the sensitivity of the sound level meter are included in the analyzer setup. The hammer sensitivity is set to 44.4 N/V for channel 1 and the sound pressure level sensitivity is set to 24 dB/V for channel 3.

2.4 Frequency response

The frequency response is computed with the impact force, F, (in units of Newtons) applied from the hammer as the input and the sound pressure level, S, (in units of dB) from sound meter as the output. Time trace measurements of the input and output are obtained. The measurements are windowed (i.e., box window for the input and exponential window for the response) and the Fast Fourier Transforms of the windowed time traces are computed. The measurements are repeated eight times,n, and then averaged. Power spectra (P_{FF}(f),P_{SS}(f)) and cross spectra (P_{SF}(f)) are computed as [10,11]

$$P_{FF}(f) = \sum \frac{F(f)F(f)^*}{n} \tag{1a}$$

$$P_{SS}(f) = \sum \frac{S(f)S(f)^*}{n} \tag{1b}$$

$$P_{SF}(f) = \sum \frac{F(f)S(f)^*}{n} \tag{1c}$$

where *F(f)* is the Fourier transform of *F*, *S(f)* is the Fourier transform of *S* and the * is the complex conjugate. The frequency response is then computed as

$$FR(f) = \frac{P_{SF}(f)}{P_{FF}(f)} \tag{2}$$

An m-file was written in Matlab to graph the magnitude (in units of dB/N), phase (in units of degrees) and coherence (non-dimensional) versus frequency (Hertz). The coherence, $\gamma^2(f)$, is a function of frequency and is computed as

$$\gamma^2(f) = \frac{P_{SF}(f)P_{SF}(f)^*}{P_{FF}(f)P_{SS}(f)} \tag{3}$$

Coherence is a number between 0 and 1, where 1 means that all the output is caused by the input whereas a number of 0 means that none of the output is caused by the input.

2.5 Test specimens

The test specimens are single crystalline (100) Czochralski (Cz) silicon wafers. They are pseudo square (see specimen corners in Figure 2.1) with dimensions 127 x 127 mm. The thickness of the wafers were find by weighing each wafers and knowing that the density of the wafer is 2.329 g/cm^3. Some of the specimens are crack-free and some of the specimens have cracks introduced in different orientations. The crack-free wafers are scanned in a Scanning Acoustic Microscopy (SAM) before and after testing to ensure that the wafers had not been damaged during the impact testing.

Cracks are introduced in the wafers using a diamond pin and pressing carefully on the edge of the wafers with a light force (equivalent to the force used in writing). By doing this, the human ear can hear the wafer crack. To quantify the cracks, the wafers are scanned in the SAM before and after the impact testing.

Since the cracks are not visible using optical methods the cracks images were created in the SAM. The wafers were placed under a water bath. A transducer (work as a transmitter and receiver) moves above the wafer and produced sound waves. These sound waves are at high frequencies and that is the reason why the wafer is in the water bath since the high frequencies do not propagate through air.

Three different types of sets are presented in this thesis: the large crack wafer set, the miscellaneous crack wafer set and the small crack wafer set. First the small crack wafer set was investigated. Since the small crack wafer did not show significant differences, larger cracks were made. These exploratory larger cracks are presented in the miscellaneous wafer set. After analyzing the miscellaneous wafers, the larger crack set was made and are presented as the large crack wafer set.

2.5.1 Large crack wafer set

The large cracks have crack lengths varying from 38 mm to 55 mm. Some of the cracks begin at the center of an edge of the specimen, others are offset from the center of the edge. Some have segmented cracks (meaning the cracks are not continuous; instead they have small cracks in sequence). If zooming in on the crack and use high resolution of the SAM image one can see that wafer numbers 39, 32, 36, 40, 6, 8 and 41 has segmented crack. Wafer numbers 48 and 33 are also segmented but the initial crack from the edge is longer than the others. Wafer number 27 initially had segmented crack but during the tests it became continuous and wafer numbers 31 and 35 have continuous cracks.

The large center cracks are cracked in the center of an edge of the specimen and are numbered 39, 31, 35, 48. These crack lengths vary between 38.6 to 52.7 mm and are shown in Figures 2.1-2.4. The large offset cracks are cracked offset from the center of an edge of the wafer are numbered 32, 40, 36, 27 (see Figures 2.5-2.12). The length of these cracks are 41.8-54.8 mm.

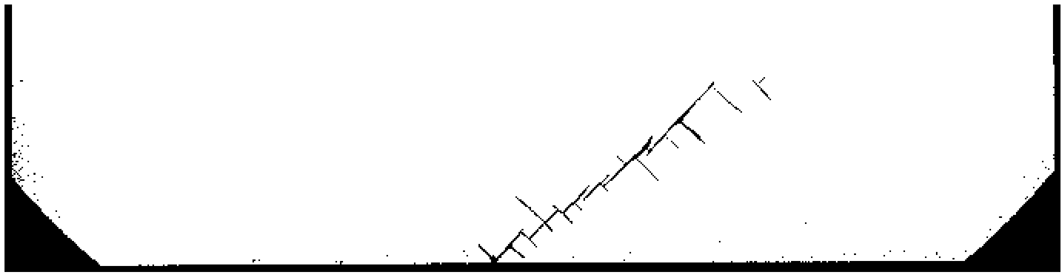

Figure 2.1 Large center crack wafer number 39

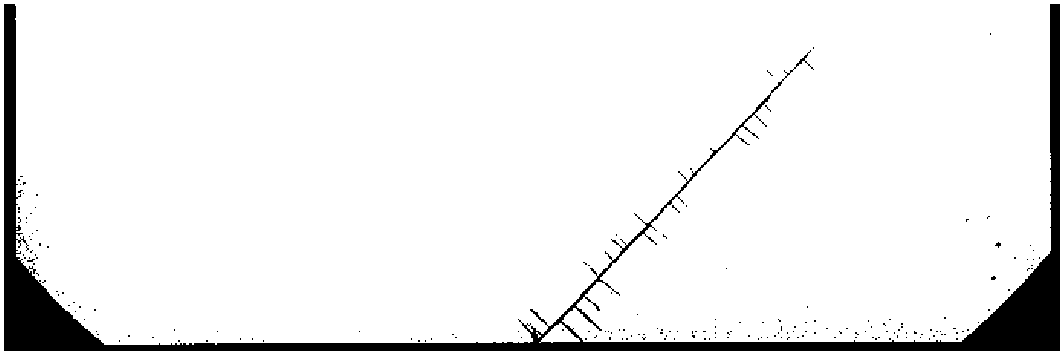

Figure 2.2 Large center crack wafer number 31

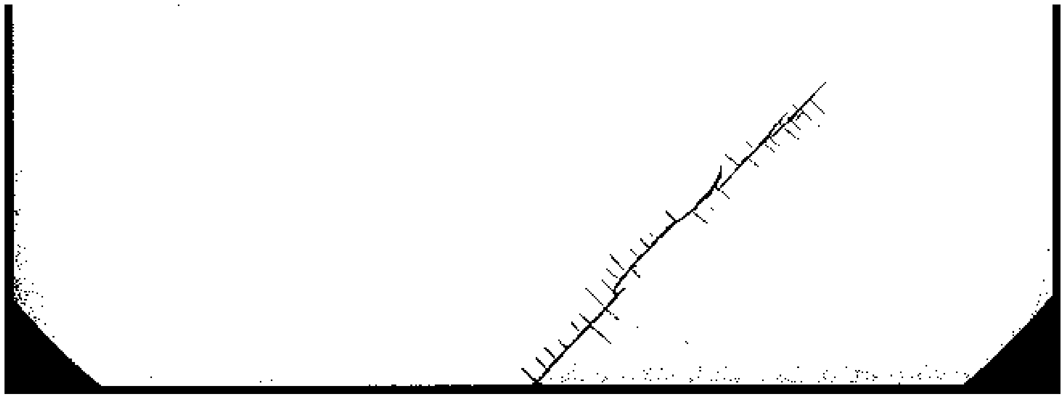

Figure 2.3 Large center crack wafer number 35

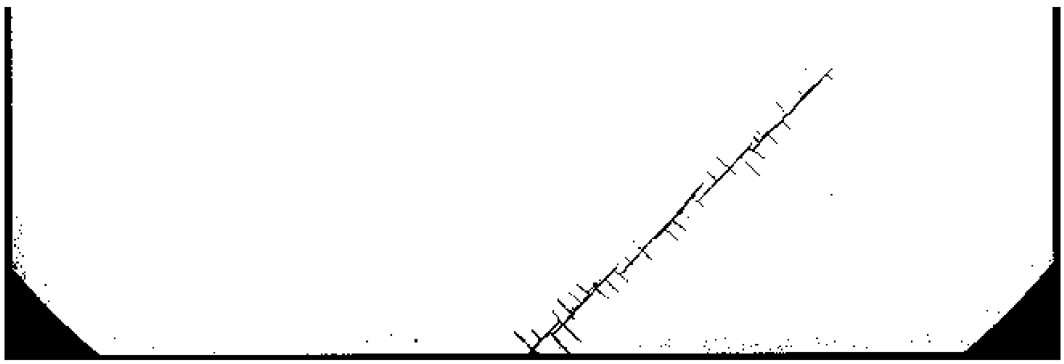

Figure 2.4 Large center crack wafer number 48

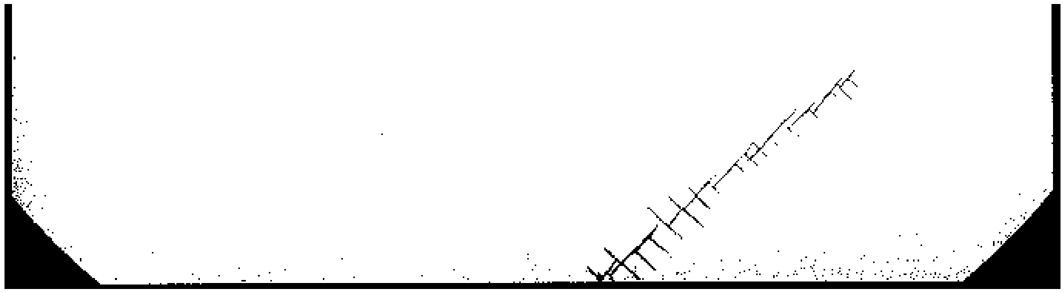

Figure 2.5 Large offset crack wafer number 32

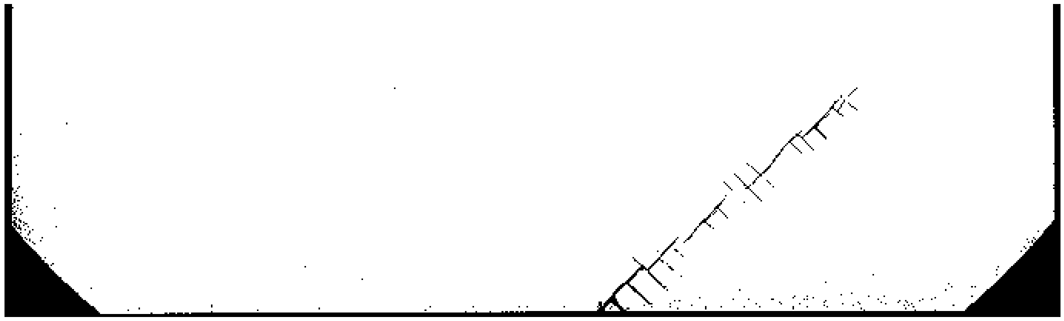

Figure 2.6 Large offset crack wafer number 40

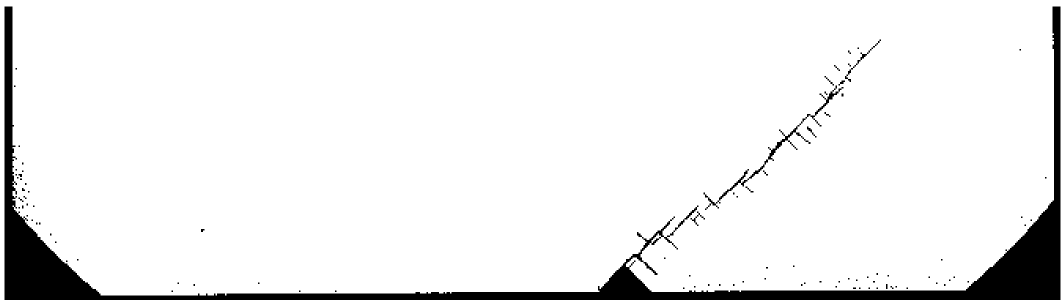

Figure 2.7 Large offset crack wafer number 36

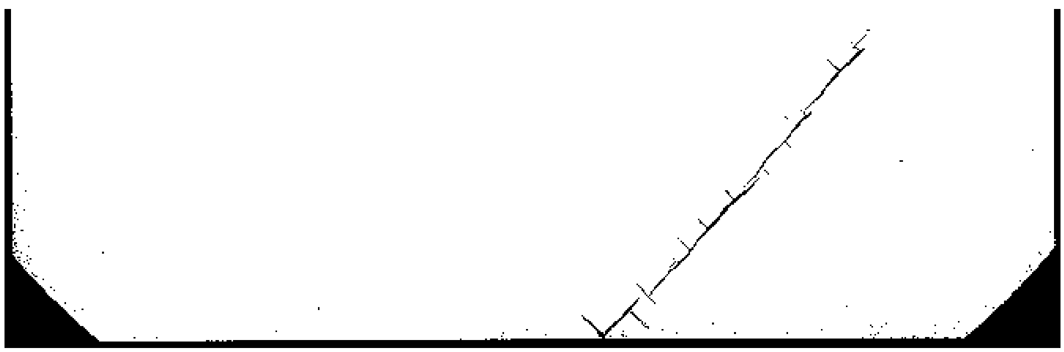

Figure 2.8 Large offset crack wafer number 27

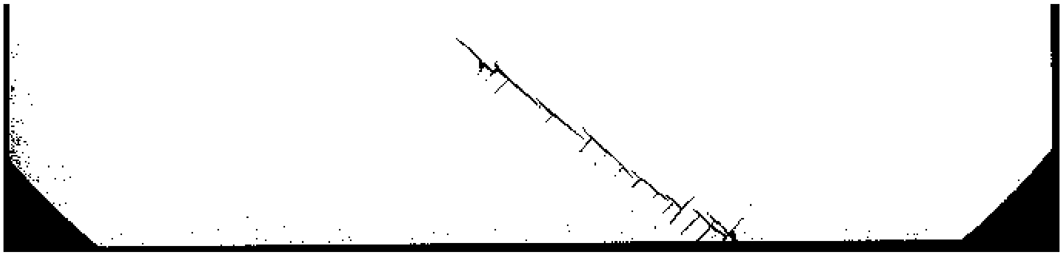

Figure 2.9 Large crack other direction wafer number 8

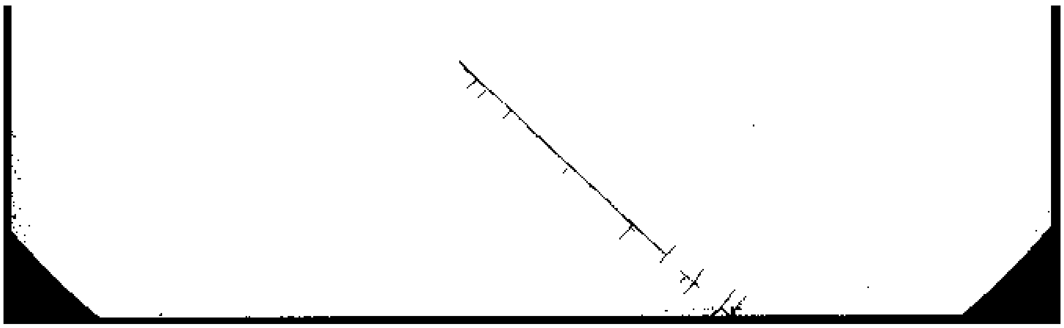

Figure 2.10 Large crack other direction wafer number 6

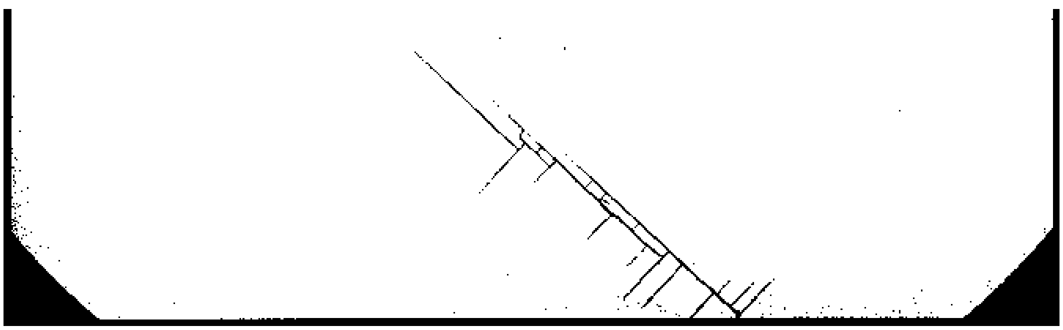

Figure 2.11 Large crack other direction wafer number 33

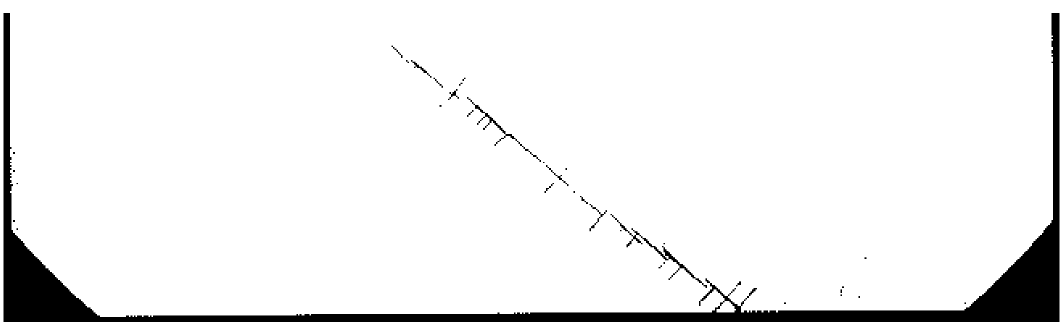

Figure 2.12 Large crack other direction wafer number 41

2.5.2 Miscellaneous wafer set

The miscellaneous cracks were made to explore larger cracks so the cracks starts at different location of the edge of the wafers. The cracks are made in different directions and have various crack lengths. The crack lengths vary from 18.5 mm to 52.7 mm. Wafer numbers 45, 46, and 7 have segmented cracks (meaning the cracks are not continuous instead they have small cracks in sequence). Wafer number 11 is smaller than the other, wafer number 23, 25, 47, 8 have continued cracks. The SAM images of the miscellaneous wafers are shown in Figures 2.13-2.20.

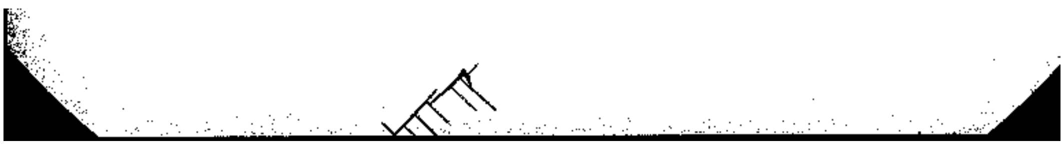

Figure 2.13 Miscellaneous wafer number 11

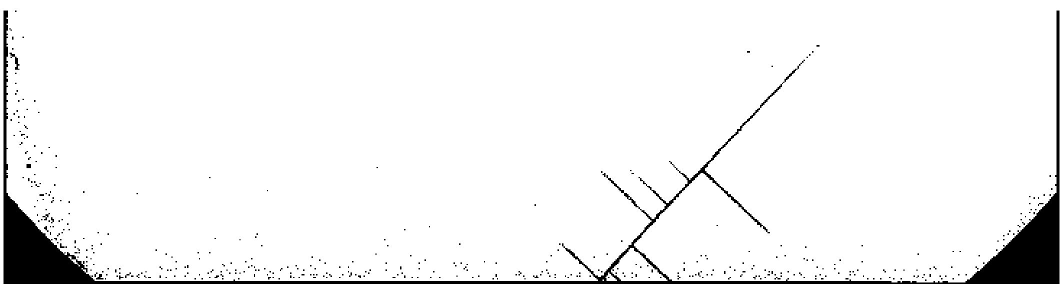

Figure 2.14 Miscellaneous wafer number 23

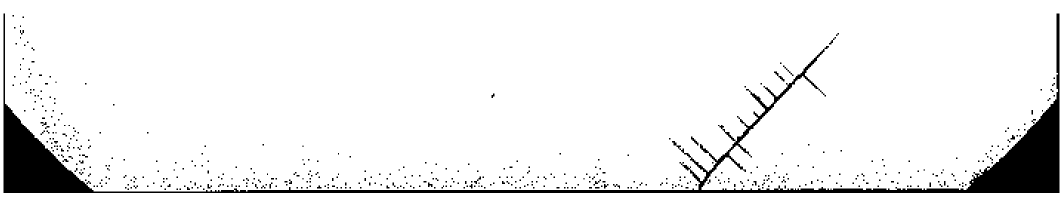

Figure 2.15 Miscellaneous wafer number 25

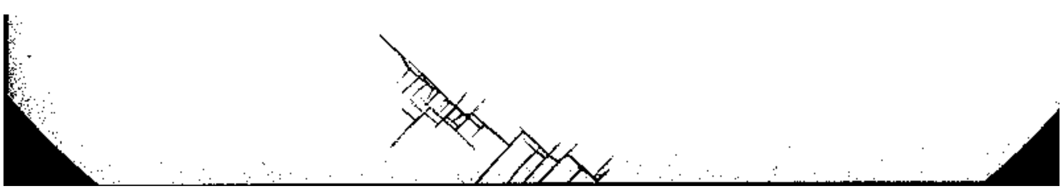

Figure 2.16 Miscellaneous wafer number 45

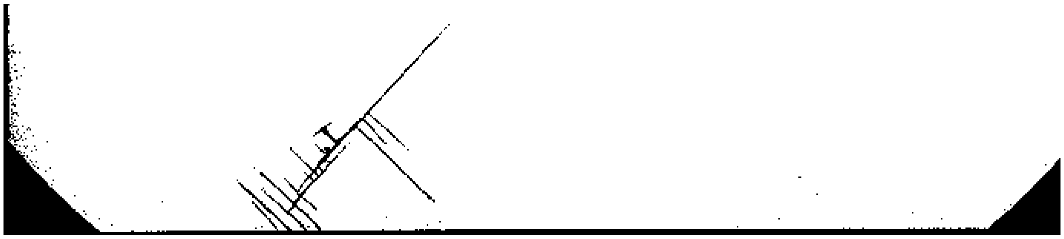

Figure 2.17 Miscellaneous wafer number 46

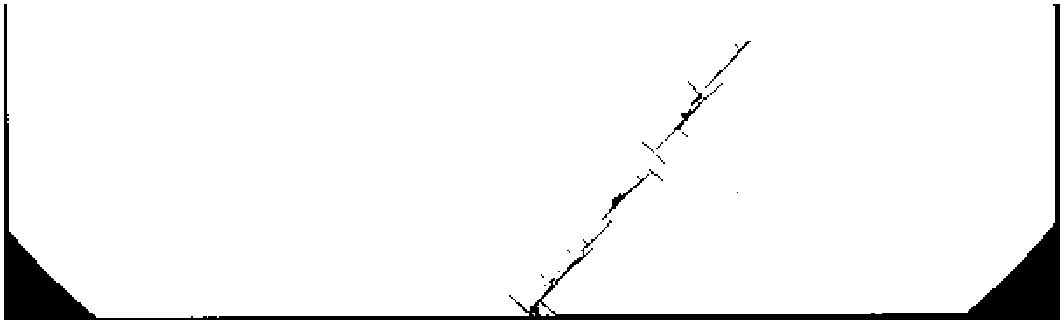

Figure 2.18 Miscellaneous wafer number 7

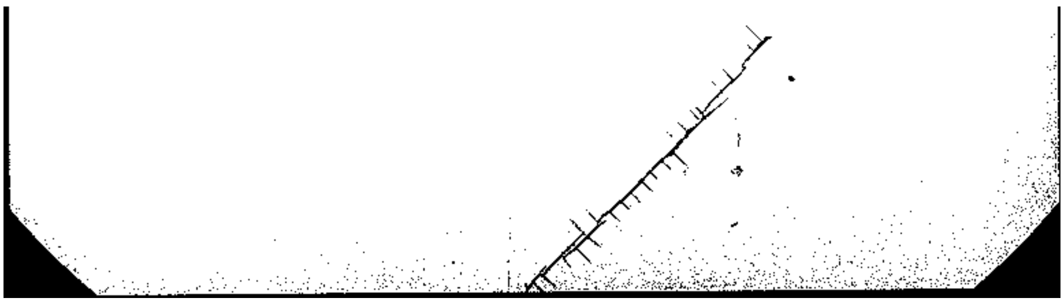

Figure 2.19 Miscellaneous wafer number 47

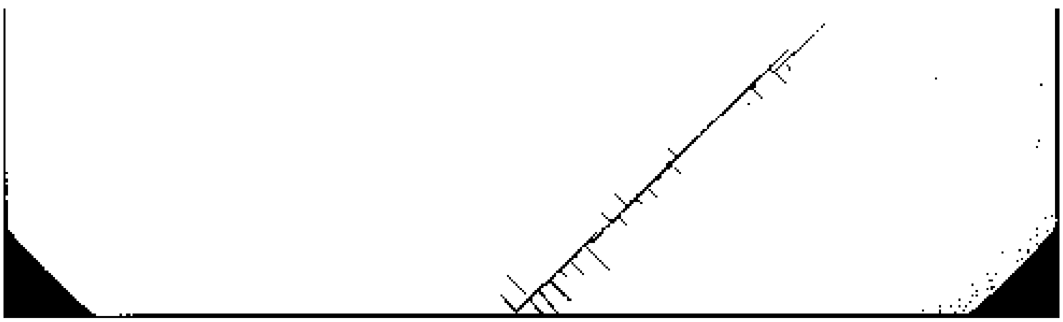

Figure 2.20 Miscellaneous wafer number 8

2.5.3 Small crack wafer set

The small cracks have crack lengths from 2.3 to 7.6 mm. Some of the cracks are a single crack and others have a V-shape. Note that all cracks in this work initiate at an edge of the wafer. For the V-shape cracks, the point of the V is at the wafer edge. The location of the small cracks are arbitrary. All the small crack specimens are shown in Figures 2.21 – Figure 2.30.

Figure 2.21 Small crack wafer number 21

Figure 2.22 Small crack wafer number 22

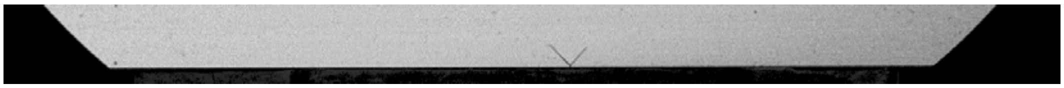

Figure 2.23 Small crack wafer number 23

Figure 2.24 Small crack wafer number 25

Figure 2.25 Small crack wafer number 26

Figure 2.26 Small crack wafer number 27

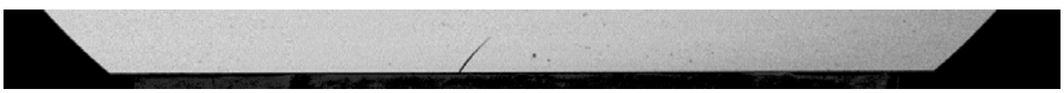

Figure 2.27 Small crack wafer number 29

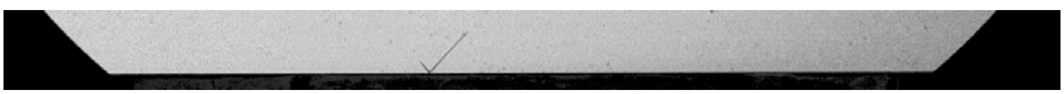

Figure 2.28 Small crack wafer number 30

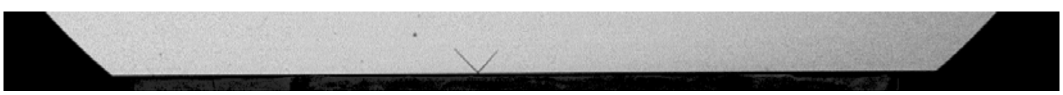

Figure 2.29 Small crack wafer number 31

Figure 2.30 Small crack wafer number 32

2.6 Setup

The test setup is shown in Figure 2.31 The specimen is set on a piece of convoluted foam of dimensions 7 x 33 x 26.5 cm. The sound level meter is attached to a rigid fixture and the microphone is set at 1.2 cm above the specimen. The microphone is set perpendicular to the wafer. The impact hammer is connected to channel 1 of the SigLab analyzer and the sound level meter is connected to channel 3 of the SigLab analyzer.

Figure 2.31 Picture of the set up

2.6.1 Position of hammer and microphone

The horizontal position of the hammer and the sound level meter with respect to the specimen is shown in Figure 2.32.

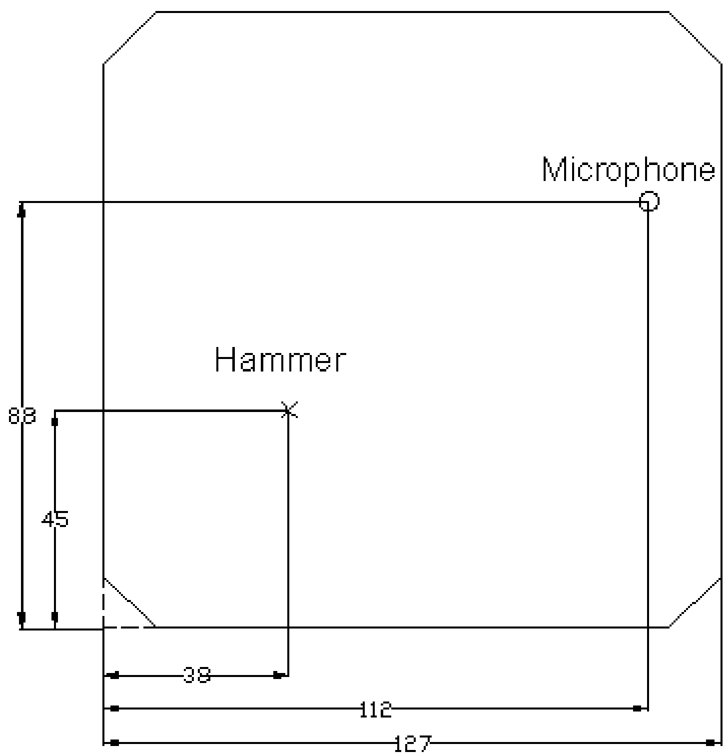

Figure 2.32 Position of hammer and microphone relative to wafer all the units are in mm

The decision on were to locate the hammer and microphone with respect to the wafer was made by keeping the hammer in the same place and moving the microphone, and then moving the hammer while keeping the microphone in the same location. Figures 2.33-35 show the frequency response with the microphone located in the same position as Figure 2.32 and the hammer is changing position. Figure 2.33 shows one dominate audible mode at 600 Hz,

Figure 2.34 and Figure 2.34 show 4 dominated modes with different peak magnitudes. The hammer and microphone locations used and shown in Figure 2.32 gave the most response (magnitudes) for the four audible modes.

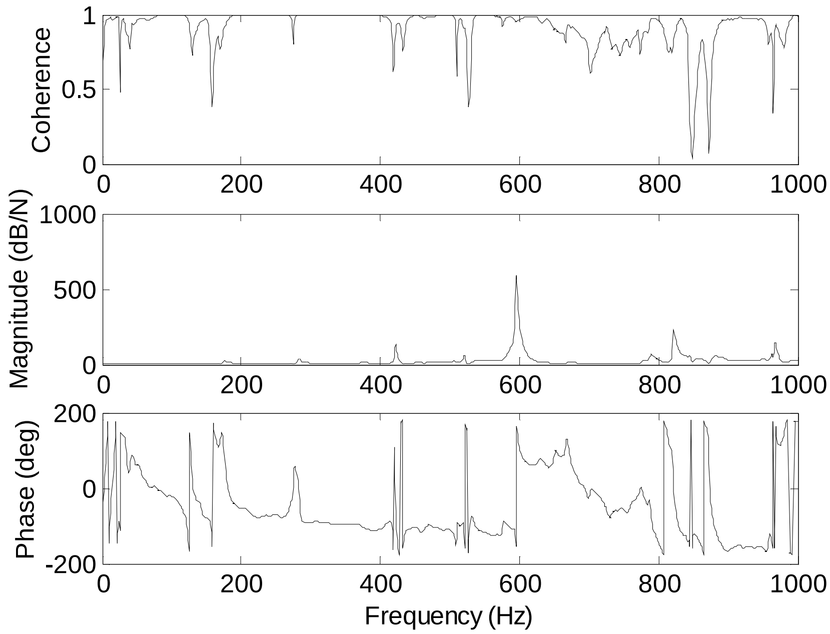

Figure 2.33 Hammer (x=83 mm, y=48 mm)

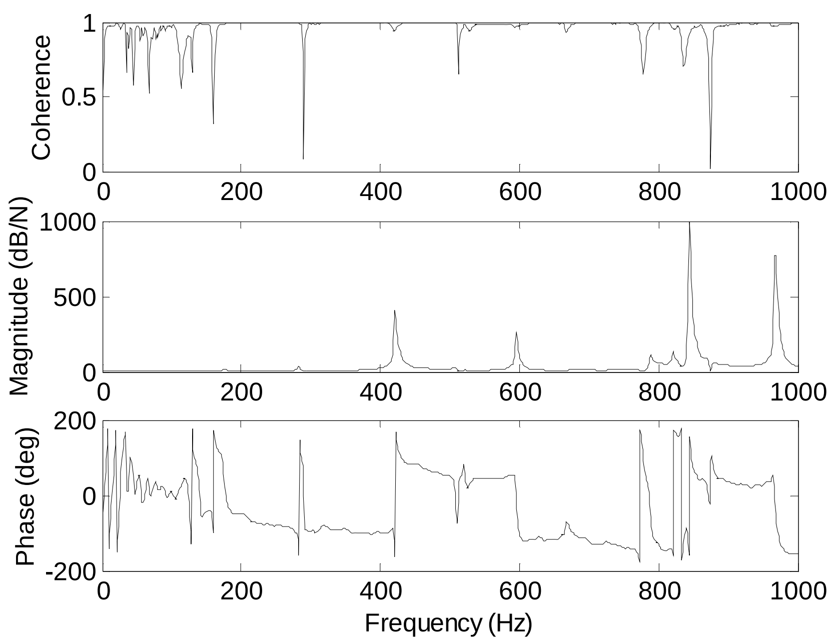

Figure 2.34 Hammer (x=39 mm, y=60 mm)

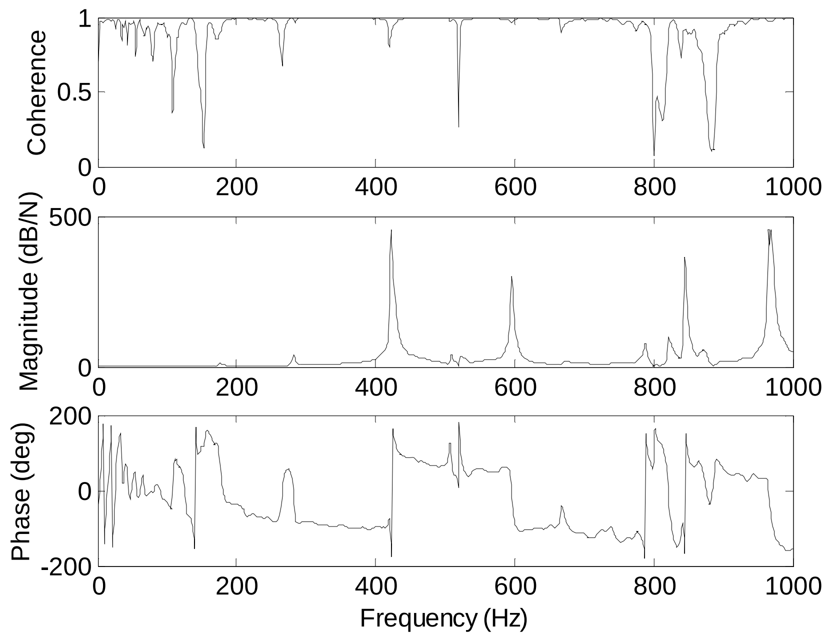

Figure 2.35 Hammer (x=53 mm, y=48 mm)

After deciding the location of the hammer and microphone as shown in Figure 2.32 both the hammer and the microphone were moved $\pm$ 5 mm. These results show small variations in magnitude (see Appendix F, Figure F.1-F.4).

Chapter 3: Test Matrix

3.1 Introduction

This chapter lists all the wafers that were tested in this study and how the run order was determined. Three different groups of cracked wafers are listed: large crack wafer group, small crack wafer group and miscellaneous wafer group. This miscellaneous wafer group was not tested as a set, but is included because it was used to explore larger cracks.

3.2 Randomization

The order of the tests was randomized to eliminate bias error. All the wafers were tested three times each (8 impacts per test) and the test order is shown in Table 3.1 (for small crack tests see Table A.1). A table with the wafer number and test number (three tests per wafer) is also shown in Table 3.2 (for small crack tests see Table A.2). This table was used to define the random run order. The test order was determined by assigning each test a random number and sorting the random numbers.

Table 3.1 Run order for the large crack wafer set

Run order	Wafer number	Test number	Random Number in ascending order
1	8	38	48
2	32	26	49
3	38	7	75
4	40	30	111
5	8	37	137
6	40	28	148
7	31	16	149
8	47	11	176
9	39	15	207
10	33	45	218
11	34	6	253
12	39	13	275
13	32	25	286
14	34	5	298
15	27	35	302
16	36	33	347
17	36	32	350
18	40	29	352
19	6	42	382
20	38	9	492
21	33	43	497
22	6	40	498
23	32	27	503
24	29	1	512
25	36	31	524
26	47	10	525
27	27	36	562
28	41	48	565
29	47	12	597
30	29	2	623
31	39	14	641
32	35	21	643
33	29	3	650
34	6	41	690
35	27	34	691
36	48	24	741
37	35	20	750
38	8	39	752
39	33	44	753
40	31	17	757
41	41	46	784
42	38	8	786
43	34	4	799
44	31	18	805
45	48	22	854
46	41	47	860
47	48	23	879
48	35	19	928

Table 3.2 Test number for the large crack wafer set

Wafer number	Test Number		
29	1	2	3
34	4	5	6
38	7	8	9
47	10	11	12
39	13	14	15
31	16	17	18
35	19	20	21
48	22	23	24
32	25	26	27
40	28	29	30
36	31	32	33
27	34	35	36
8	37	38	39
6	40	41	42
33	43	44	45
41	46	47	48

3.3 Test with large cracks

The large crack test set contains 16 specimens from which 12 specimens are cracked and the other 4 are crack-free. Table 3.3 shows the wafer number, type of crack, if segmented or continuous, the length of the crack, the thickness of the wafer and the figure number of the image.

Table 3.3 Large crack wafers

Wafer number	Type of crack	Segmented	Crack length [mm]	Wafer thickness [μm]	Photo Figure number
29	Crack Free	Crack Free	0	305	N/A
34	Crack Free	Crack Free	0	305	N/A
38	Crack Free	Crack Free	0	306	N/A
47	Crack Free	Crack Free	0	306	N/A
39	Center Crack	Yes	38.6	306	2.1
31	Center Crack	No	51.4	305	2.2
35	Center Crack	No	52.7	305	2.3
48	Center Crack	Yes	51.9	306	2.4
32	Offset Crack	Yes	41.8	305	2.5
40	Offset Crack	Yes	42.5	307	2.6
36	Offset Crack	Yes	47.5	306	2.7
27	Offset Crack	No	48.5	305	2.8
8	Offset Crack	Yes	43.3	305	2.9
6	Offset Crack	Yes	47.2	305	2.10
33	Offset Crack	Yes	52.9	306	2.11
41	Offset Crack	Yes	54.8	306	2.12

3.4 Test with small cracks

Thirty small crack wafers were tested. Twenty wafers were crack-free and ten wafers had cracks introduced to the wafers. Table 3.4 shows the wafer number, type of crack, the length of the crack, the thickness of the wafer and the figure number of the image.

Table 3.4 Small crack wafers

Wafer number	Type of crack	Crack length [mm]	Wafer thickness [μm]	Photo Figure number
11	Crack Free	0	294	N/A
12	Crack Free	0	294	N/A
13	Crack Free	0	294	N/A
14	Crack Free	0	292	N/A
15	Crack Free	0	291	N/A
18	Crack Free	0	291	N/A
19	Crack Free	0	291	N/A
20	Crack Free	0	292	N/A
33	Crack Free	0	294	N/A
34	Crack Free	0	294	N/A
35	Crack Free	0	294	N/A
36	Crack Free	0	294	N/A
37	Crack Free	0	294	N/A
38	Crack Free	0	293	N/A
39	Crack Free	0	294	N/A
40	Crack Free	0	294	N/A
41	Crack Free	0	294	N/A
42	Crack Free	0	293	N/A
43	Crack Free	0	294	N/A
44	Crack Free	0	293	N/A
21	V-shape	4.3 - 4.5	291	2.21
22	Single	7.4	291	2.22
23	V-shape	4.1 - 7.7	291	2.23
25	V-shape	4.6 – 6.3	291	2.24
26	V-shape	4.1 - 4.4	293	2.25
27	V-shape	4.2 - 4.9	292	2.26
29	Single	6.3	295	2.27
30	V-shape	2.3 - 7.0	293	2.28
31	V-shape	4.0 - 4.6	294	2.29
32	Single	7.6	294	2.30

3.5 Tests of miscellaneous cracks

The tests from the miscellaneous cracks set were not performed in a totally randomized manner. The wafers were tested at different periods of time.

However, these tests are grouped put together for presentation. This set includes twelve wafers total: four are crack-free and eight wafers are cracked. Table 3.5 shows the wafer number, type of crack, if segmented or continuous, the length of the crack, the thickness of the wafer and the figure number of the image.

Table 3.5 Miscellaneous wafers

Wafer number	Type of crack	Segmented	Crack length [mm]	Wafer thickness [μm]	Photo Figure number
20	Crack free	Crack Free	0	305.6	N/A
42	Crack free	Crack Free	0	293.0	N/A
49	Crack free	Crack Free	0	293.8	N/A
2	Crack free	Crack Free	0	295.2	N/A
11	Cracked	No	9	305.1	2.13
23	Cracked	No	41.5	305.8	2.14
25	Cracked	No	25.7	305.5	2.15
45	Cracked	Yes	18.5	306.0	2.16
46	Cracked	Yes	25.8	305.6	2.17
7	Cracked	Yes	43.8	294.0	2.18
47	Cracked	No	43.3	293.3	2.19
8	Cracked	No	52.7	294.3	2.20

Chapter 4: Test Results

4.1 Introduction

This chapter presents the test data and results. This includes frequency response data with four audible modes. The following parameters are extracted from these 4 modes: natural frequencies, peak magnitudes, damping ratios and coherence.

4.2 Sample frequency response data

Typical frequency response data from a crack-free wafer is shown in Figure 4.1. The graph shows a range of frequencies from 0-1000 Hz for coherence, magnitude and phase. Four dominant modes are found at the following frequencies: 420 Hz, 590 Hz, 840 Hz and 960 Hz.

By comparing the frequency response data of a non-cracked wafer with a wafer with a large crack, as shown in Figure 4.2, one can still see four different modes but the frequencies are lower, the damping is larger (peaks not as sharp) and the peak magnitudes are lower. In the next section, these parameters are extracted from the frequency response data.

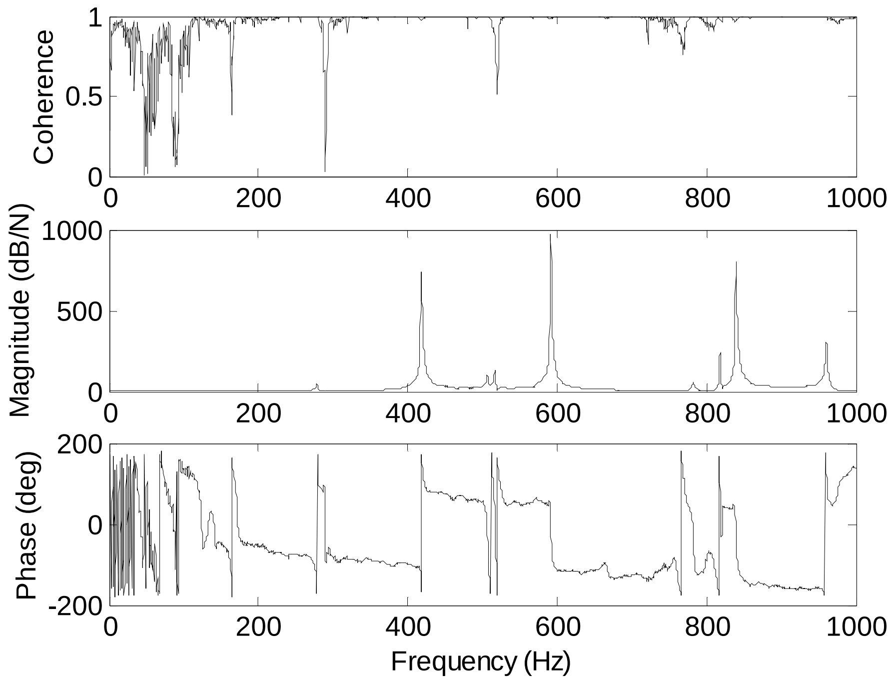

Figure 4.1 Frequency response of crack-free wafer number 29

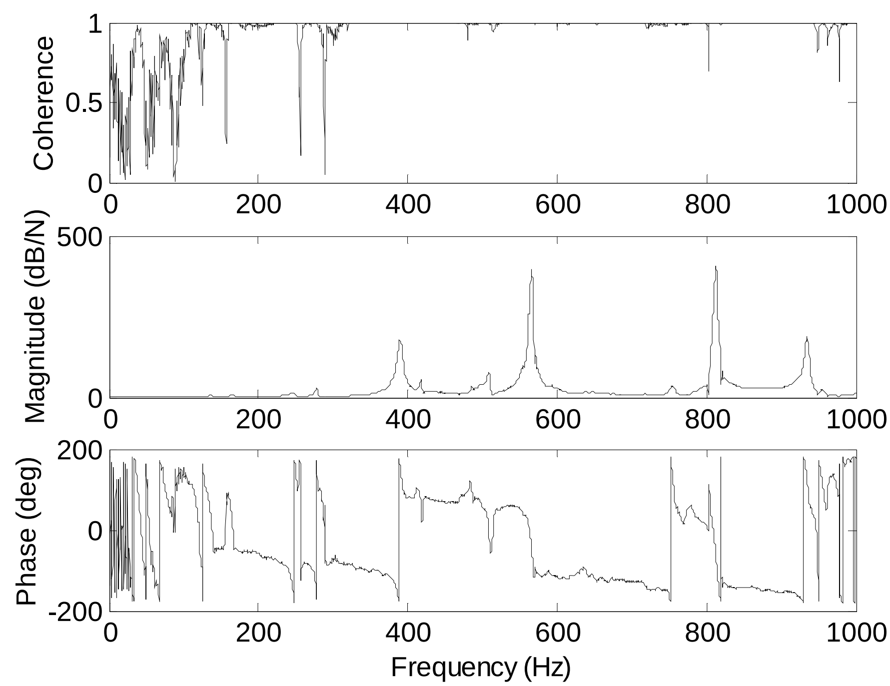

Figure 4.2 Frequency response of large crack wafer number 35

The coherence ranges between 0 and 1, and it measures the amount of output that is caused by the input. A coherence value of 1 means that 100% of the output is caused by the input. In Figure 4.1 and Figure 4.2 the coherence versus frequency is plotted. From these figures, one can see that the coherence is close to one around the four dominant modes. All the frequency response data from the large crack wafer set are presented in Figures B.1-B.20. The lowest coherence at some peaks is 0.9.

The small crack wafer set is not included, since they did not show any change compared to the crack-free wafers when the cracks are less than 8 mm. However, the data was collected and the extracted parameters are presented in the next section and may be compared with the large crack wafer set and the miscellaneous wafer set.

4.3 Extracted parameters

The following parameters are extracted from the four dominant modes in the frequency response data: natural frequencies, peak magnitudes and damping ratio. The data from the large-crack wafer set are shown in Tables C.1-C.16 and Figures C.1-C.16, the miscellaneous wafer set in Tables D.1-D.16 and Figures D.1-D.16, and the small crack wafer set in Figures E.1-E.16.

4.4 Natural frequencies

4.4.1 Large crack wafer set

The data from the second mode frequencies of the large crack wafer set are most representative and are shown in Table 4.1 (as well as in Appendix C). The first 4 specimens in the table are the crack-free wafers and the following 12 specimens have cracks as defined in Table 3.3 and shown in Figures 2.1-2.12.

In the crack-free wafers, the second mode frequency ranges from 591.6 to 594.1 Hz. For an individual crack-free wafer, the frequency deviation is less than 0.3 Hz, which is the frequency resolution of the measurements. The frequency deviation across all four crack-free wafers is 2.5 Hz.

For the 12 large crack wafers, the second mode frequency ranges from 565.9 to 592.8 Hz and all the wafers are within 26.9 Hz. Six of the cracked wafers have frequencies that fall within the crack-free frequency range, two of the cracked wafers have slightly lower frequencies (590.3-590.9 Hz) and four of the cracked wafers have significantly lower frequencies from 565.9 to 587.8 Hz. These 4 large crack specimens are numbered 31, 35, 48 and 27 and are italicized in Table 4.1. Comparing the "italicized" cracked wafers in Table 4.1 with Table 3.3, one sees that the continuous cracked wafers all show significant changes in frequency.

Table 4.1 Second mode frequency for large specimens

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	591.6	591.6	591.6	591.6
34	592.2	592.2	592.2	592.2
38	592.8	593.1	593.1	593.0
47	594.1	594.1	594.1	594.1
39	592.8	592.8	592.8	592.8
31	*571.9*	*571.9*	*569.7*	*571.1*
35	*565.9*	*565.9*	*566.3*	*566.0*
48	*584.4*	*583.4*	*582.8*	*583.5*
32	590.6	590.9	590.6	590.7
40	592.5	592.8	592.8	592.7
36	591.9	591.9	591.9	591.9
27	*587.8*	*587.8*	*570.9*	*582.2*
8	590.3	590.6	590.6	590.5
6	592.2	592.2	592.2	592.2
33	591.9	591.6	591.9	591.8
41	592.8	592.8	592.8	592.8

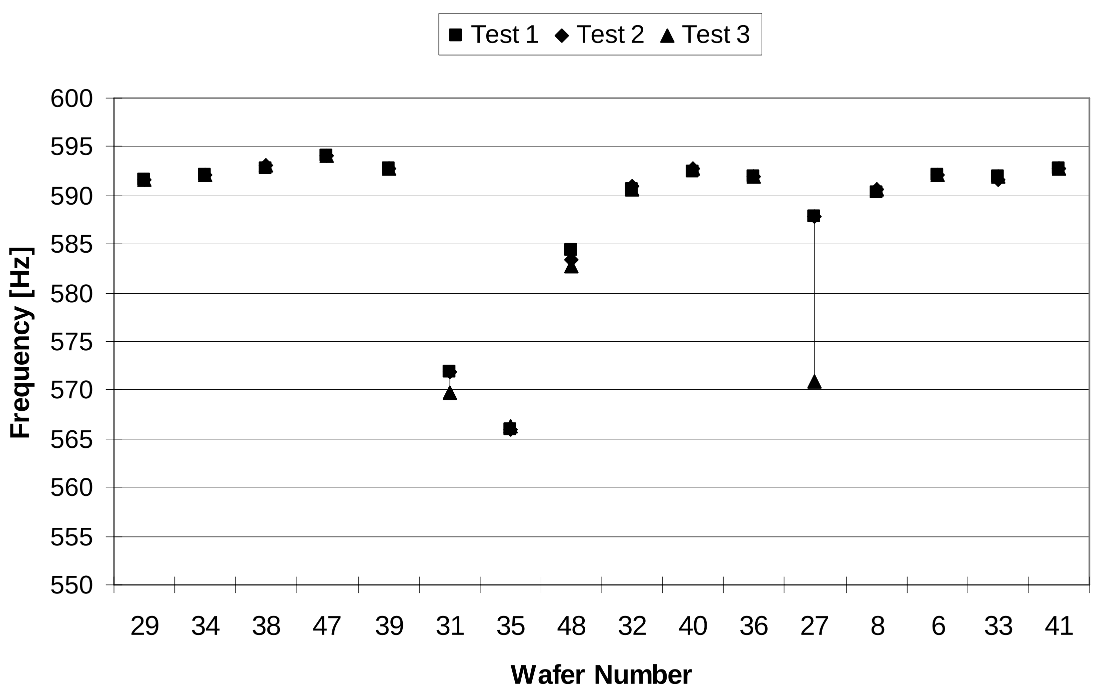

Figure 4.3 Second mode frequency for large specimens

The data in Table 4.1 is graphed in Figure 4.3. As seen in Figure 4.3 all the specimens have a low frequency deviation (less than 0.3 Hz), except large crack wafer numbers 31, 48, and 27. Cracked wafer 31 has a deviation of 2.2 Hz, wafer number 48 has a deviation of 1.6 Hz, and wafer number 27 has a deviation of 16.9 Hz.

By looking at the before and after images for wafer number 27(segmented) and wafer number 31(continuous), one can see that the cracks did elongate with testing (3 tests with 8 impacts each), thus reducing stiffness and frequency; however wafer number 48 (segment) did not show a notable change.

Similar data for the first frequency mode are presented in Table C.1 and Figure C.1 (Appendix C). The crack-free wafers first mode frequency range is 418.1-420 Hz. For an individual crack-free wafer the frequency deviation is less than 0.6 Hz. The frequency deviation across all four crack-free wafers is 1.9 Hz.

For the 12 large crack wafers the first mode frequency range is 389.4-420.9 Hz and all the wafers are within 31.6 Hz. Five of the cracked wafers have frequencies that fall within the crack-free frequency range, four of the cracked wafers have slightly lower frequencies (412.8-416.9 Hz) and three of the cracked wafers have significant lower frequencies from 389.4 to 415.9 Hz. These 3 large crack specimens are numbered 31, 35 and 27.

All the specimens have a frequency deviation of less than 0.6 Hz except large crack wafers numbered 31, 35, 48, and 27. Cracked wafer 31 has a deviation of 4.4 Hz, wafer number 35 has a deviation of 0.9 Hz, wafer number 48 has a deviation of 1.3 Hz, and wafer number 27 has a deviation of 10.6 Hz.

Table C.5 and Figure C.5 shows the third frequency mode. The crack-free wafers third mode frequency range is 839.1-842.8 Hz. For an individual crack-free wafer the frequency deviation is less than 0.3 Hz. The frequency deviation across all four crack-free wafers is 3.8 Hz.

For the 12 large crack wafers the third mode frequency range is 812.5-843.4 Hz and all the wafers are within 30.9 Hz. Eight of the cracked wafers have frequencies that fall within the crack-free frequency range, one of the cracked wafers has slightly lower frequencies (834.1-835 Hz) and three of the cracked wafers have significant lower frequencies from 812.5 to 835 Hz. These three cracked specimens are numbered 31, 35, and 27.

All the specimens have a frequency deviation less than 0.3 Hz except large crack wafers numbered 31, 35, 48, and 27. Cracked wafer 31 has a deviation of 13.4 Hz, wafer number 35 has a deviation of 0.6 Hz, wafer number 48 has a deviation of 0.9 Hz, and wafer number 27 has a deviation of 18.4 Hz.

Table C.7 and Figure C.7 shows mode four. The crack-free wafers fourth mode frequency range is 960.6-964.7 Hz. For an individual crack-free wafer the frequency deviation is less than 0.3 Hz. The frequency deviation across all four crack-free wafers is 4.1 Hz.

For the 12 large crack wafers the fourth mode frequency range is 930.6-962.2 Hz all the wafers are within 31.6 Hz. Five of the cracked wafers have frequencies that fall within the crack-free frequency range, three of the cracked wafers have slightly lower frequencies (958.4-960.3 Hz) and four of the cracked wafers have significant lower frequencies from 930.6-954.1 Hz. These four cracked specimens are numbered 31, 35, 48 and 27.

All the specimens have a frequency deviation less than 0.6 Hz except large crack wafer numbers 48, and 27. Cracked wafer number 48 has a deviation of 2.5 Hz and wafer number 27 has a deviation of 23.4 Hz.

4.4.2 Miscellaneous wafer set

The data from the second mode frequencies of the miscellaneous crack wafer set are shown in Table D.3 and Figure D.3 (Appendix D). The first 4 specimens in the table are the crack-free wafers and the following 8 wafers have cracks as defined in Table 3.5 and shown in Figures 2.13-2.20.

The second mode frequency range for the crack-free wafers is from 569.1 to 592.8 Hz. For an individual crack-free wafer the frequency deviation is less than 0.3 Hz. The frequency deviation across all the crack-free wafers is 23.8 Hz.

For the 8 cracked wafers the second mode frequency ranges from 554.7 to 593.1 Hz, all cracked wafers are within 38.4 Hz and the deviation within a wafer is less than 2.2 Hz.

The deviation across the crack-free wafers are higher than found for the large crack specimens because these miscellaneous wafers have various thickness 293-306μm. This problem will be solved by normalizing in section 4.5. Data for the first mode is also shown in Table D.1 and Figure D.1, for the third mode Table D.5 and Figure D.5, and for the fourth mode in Table D.7 and Figure D.7.

4.4.3 Small crack wafer set

The second mode frequencies for the small crack wafer set are shown in Figure E.3. The first 20 specimens in the Table 3.4 are the crack-free wafers and the following 10 wafers have cracks as defined in Table 3.4 and shown in Figures 2.21-2.30.

The crack-free wafers second mode frequencies range from 564.1 to 571.9 Hz. For an individual crack-free wafer the frequency deviation is less than 0.6 Hz, the frequency deviation across all twenty crack-free wafers is 7.8 Hz.

For the 10 small crack wafers the second frequency mode ranges from 565 to 572.5 Hz and all are within 7.5 Hz. The deviation in an individual wafer is less than 0.3 Hz. Note that the ranges are very similar to the crack-free wafers and that the cracks are small less than 8 mm. Data for the first mode is presented in Figure E.1, for the third mode in Figure E.5, and for the fourth mode in Figure E.7.

4.5 Normalized frequencies

Some of the wafers were found to have slightly different thickness. Since natural frequency is directly proportional to the thickness to the three-halves power, the frequencies are normalized with respect to the thickness of the wafers by

$$f_{norm} = \frac{f}{h^{3/2}} \qquad (4)$$

where f_{norm} is the normalized frequency, f is the measured natural frequency (in Hz) and h is the thickness of the wafer (in μm) [12]. The normalization is necessary for the miscellaneous wafer set since the thickness varied and also to compare the three different type of sets.

4.5.1 Large crack wafer set

The normalized frequencies for the second mode (presented in Table C.4 and Figure C.4) of the large crack wafer set did not show a large difference from section 4.4.1 since the thickness range of these wafers are similar 305-307 μm.

The crack-free wafers second mode normalized frequency ranges from 0.0008 to 0.0010 Hz/ $\mu m^{3/2}$. For an individual crack-free wafer, the frequency deviation is less than 0.0001 Hz/ $\mu m^{3/2}$. The frequency deviation across all four crack-free wafers is 0.0002 Hz/ $\mu m^{3/2}$.

For the 12 large crack wafers, the second mode normalized frequency ranges from 0.1062 to 0.1111 Hz/ $\mu m^{3/2}$ and all the wafers are within 0.0049 Hz/ $\mu m^{3/2}$. Four of the cracked wafers have normalized frequencies that fall within the crack-free normalized frequency range, four of the cracked wafers have slightly lower normalized frequencies (0.1103-0.1108 Hz/ $\mu m^{3/2}$) and four of the cracked wafers have significantly lower normalized frequencies from 0.1062-0.1102 Hz/ $\mu m^{3/2}$. These 4 large crack specimens are numbered 31, 35, 48 and 27. All the specimens have a frequency deviation of less than 0.0001 Hz/ $\mu m^{3/2}$ except large crack wafer numbers 31, 48, and 27.

Cracked wafer 31 has a deviation of 0.0004 Hz/ $\mu m^{3/2}$, wafer number 48 has a deviation of 0.0003 Hz/ $\mu m^{3/2}$, and wafer number 27 has a deviation of 0.0032 Hz/ $\mu m^{3/2}$.

Since the thickness for the large crack wafer set does not vary significantly, the normalization of the first, third and fourth frequency modes are not discussed in this section but are presented in Appendix C for completeness. Data for the first mode in Table C.2 and Figure C.2, for the second mode in Table C.4 and Figure C.4, for the third mode in Table C.6 and Figure C.6, and for the fourth mode in Table C.8 and Figure C.8.

4.5.2 Miscellaneous wafer set

The miscellaneous wafers second mode frequencies are graphed in Figure 4.4 and the normalized second mode frequencies are graphed in Figure 4.5. In Figure 4.4 wafer numbers 42, 49, 2, 23, 7 ,47, 8 had significantly lower frequencies than the other 5 wafers. The reason that the frequencies are lower is not because of any cracks instead it is because the thickness of the wafers varied from 293-306 μm.

The crack-free wafers second mode normalized frequency ranges from 0.1110 to 0.1135 Hz/ $\mu m^{3/2}$. For an individual crack-free wafer, the normalized frequency deviation is less than 0.0001 Hz/ $\mu m^{3/2}$. The normalized frequency deviation across all four crack-free wafers is 0.0025 Hz/ $\mu m^{3/2}$.

For the 12 large crack wafers, the second mode normalized frequency ranges from 0.1043 to 0.1129 Hz/ $\mu m^{3/2}$ and all the wafers are within 0.0086 Hz/ $\mu m^{3/2}$. Three of the cracked wafers have normalized frequencies that fall within the crack-free normalized frequency range, four of the cracked wafers have slightly lower normalized frequencies (0.1099-0.1109 Hz/ $\mu m^{3/2}$) and one (number 23) of the cracked wafers has significantly lower normalized frequencies from 0.1043-0.1047 Hz/ $\mu m^{3/2}$.

All the specimens have a normalized frequency deviation of less than 0.0002 Hz/ $\mu m^{3/2}$ except large crack wafer numbers 23 and 47 they have a deviation of 0.0004 Hz/ $\mu m^{3/2}$. Data for mode 1 are provided in Table D.2 and Figure D.2, for mode 3 in Table D.6 and Figure D.6, and for mode 4 in Table D.8 and Figure D.8.

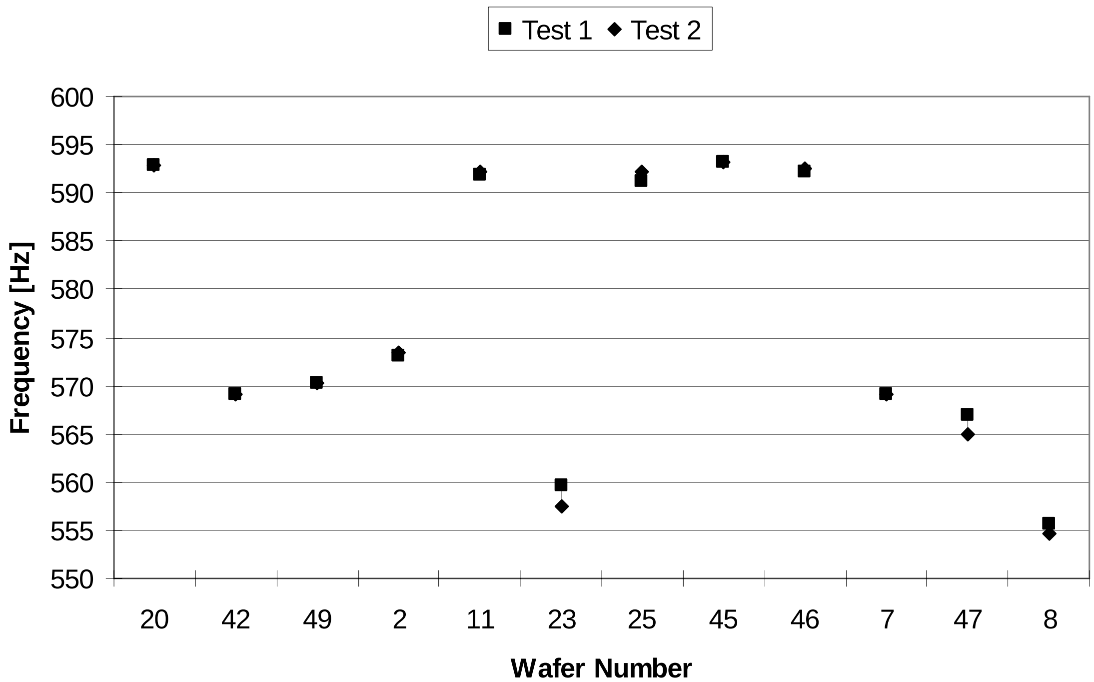

Figure 4.4 Second mode natural frequencies for miscellaneous wafer set

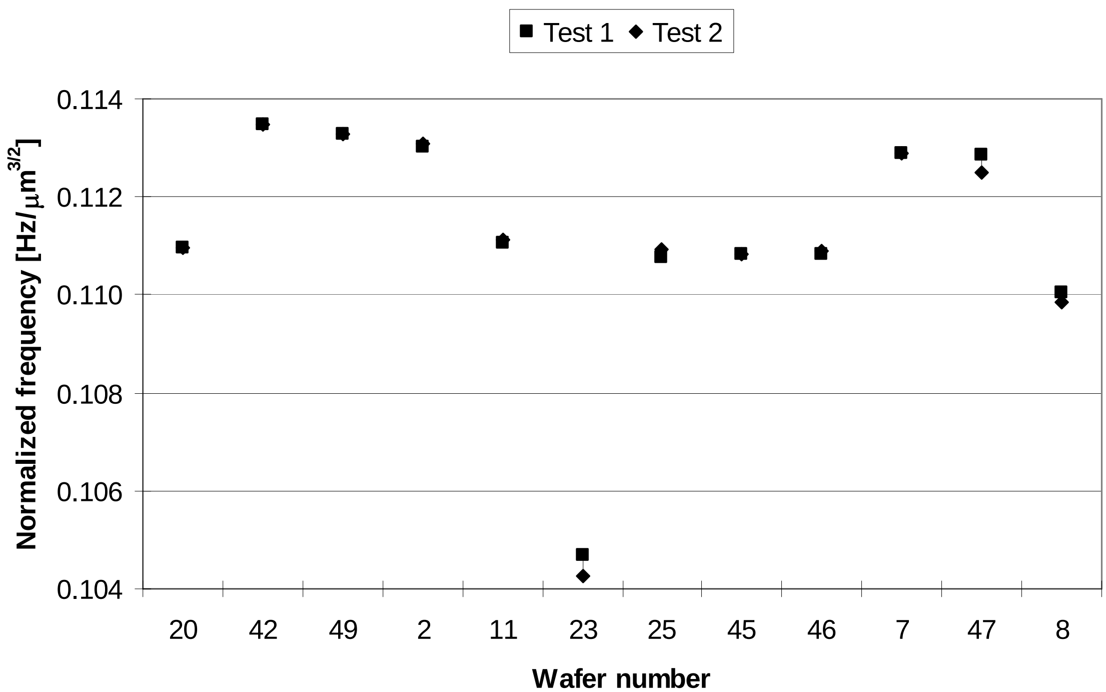

Figure 4.5 Second mode normalized frequencies for miscellaneous wafer set

4.5.3 Small crack wafer set

The second mode normalized frequencies for the small crack wafer set are shown in Figure E.4. Those wafers thickness varies between 291 and 295μm. The twenty crack-free wafers and the ten cracked wafers have the same normalized second mode frequency range from 0.1132 to 0.1138 Hz/ $\mu m^{3/2}$. The deviation for an individual wafer is less than 0.0001 Hz/ $\mu m^{3/2}$ and the deviation across all the wafers are 0.0006 Hz/ $\mu m^{3/2}$. The normalization of the small crack wafer set did improve the second mode frequency data (compare Figure E.3 with E.4). Data for the first mode is provided in Figure E.2, for the third mode in Figure E.6, and for the fourth mode in Figure E.8.

4.6 Peak magnitudes

4.6.1 Large crack wafer set

The data from the second mode peak magnitude of the large crack wafer set are shown in Table 4.2. The first 4 specimens in the table are the crack-free wafers and the following 12 specimens have cracks as defined in Table 3.3 and shown in Figures 2.1-2.12.

The crack-free wafers second mode peak magnitude ranges from 895 to 1025 dB/N. For an individual crack-free wafer, the magnitude deviation is less than 91 dB/N. The magnitude deviation across all four crack-free wafers is 130 dB/N.

For the 12 large crack wafers, the second mode peak magnitude ranges from 397 to 1006 dB/N. All the wafers are within 609 dB/N. Four of the cracked wafers have magnitudes that fall within the crack-free magnitude deviation range, one of the cracked wafers (number 27) was in the crack-free range but during the test, the wafer crack grew and fell outside the crack-free range (591-968 dB/N). Seven of the cracked wafers have significantly lower magnitudes (397-848 dB/N). These 7 large crack specimens are numbered 39, 31, 35, 48, 32, 40, 36, 27 and are italicized in Table 4.2. For all the cracked wafers, the individual deviation is less than 80 dB/N. With the exception of wafer number 39 (a deviation of 126 dB/N), wafer number 48 (a deviation of 134 dB/N), wafer number 27 (a deviation of 377 dB/N) and wafer number 8 (a deviation of 145 dB/N).

Based on this second mode data, the peak magnitude parameter is a better indicator of large crack faults then natural frequency parameter itself. Notice that all the wafers with continuous cracks show a significant change in peak magnitude (see Tables 3.3 and 4.2).

Table 4.2 Second mode peak magnitude for the large crack wafer set

Specimen number	Test 1 [dB/N]	Test 2 [dB/N]	Test 3 [dB/N]	Mean [dB/N]
29	908	992	978	959
34	976	895	960	944
38	1025	944	936	968
47	900	923	991	938
39	848	723	754	775
31	*487*	*468*	*487*	*481*
35	*398*	*397*	*403*	*399*
48	*801*	*731*	*667*	*733*
32	*805*	*736*	*736*	*759*
40	*675*	*710*	*685*	*690*
36	*712*	*718*	*692*	*707*
27	*949*	*968*	*591*	*836*
8	1006	861	919	929
6	923	979	947	950

Table 4.2 (Continued)

33	888	836	871	865
41	903	824	826	851

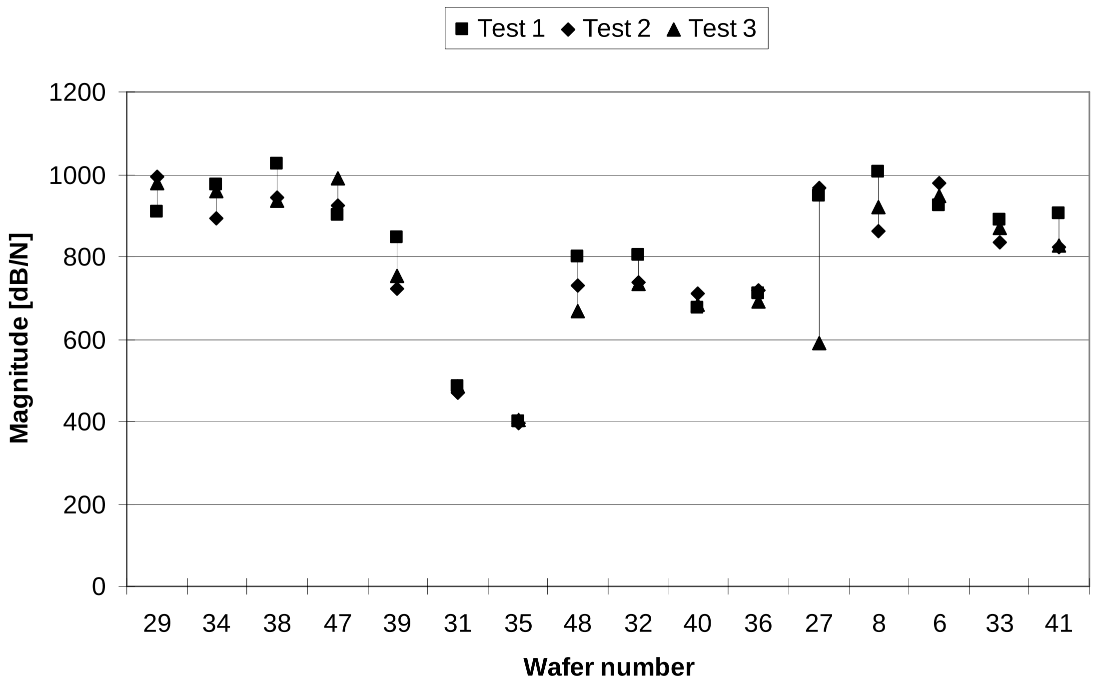

Figure 4.6 Second mode peak magnitude for the large crack wafer set

Note that wafer number 27 did not lower its peak magnitude until the last test since the segmented cracks elongated to a continuous crack during test. Data for mode 1,2,3 and 4 are referenced in Tables C.9-C.12 and Figures C.9-C.12.

4.6.2 Miscellaneous wafer set

The data from the second mode peak magnitude of the miscellaneous crack wafer set are shown in Table D.10. The first 4 specimens in the table are the crack-free wafers and the following 8 specimens have cracks.

The crack-free wafers second mode peak magnitude range from 927 to 1010 dB/N. For an individual crack-free wafer, the magnitude deviation is less than 50 dB/N. The magnitude deviation across all four crack-free wafers is 83 dB/N.

For the 12 large crack wafers the second mode peak magnitudes range from 371-1028 dB/N. All the wafers are within 657 dB/N. Two of the cracked wafers have magnitudes that fall within the crack-free magnitude deviation range. Six of the cracked wafers have significantly lower magnitudes (371-836N). These 6 cracked specimens are numbered 23, 25, 45, 46, 47 and 8. Again, the magnitude parameter is a better indicator of large crack faults than natural frequency parameter itself. Data for modes 1,2,3 and 4 are referenced in Tables D.9-D.12 and Figures D.9-D.12.

4.6.3 Small crack wafer set

The data from the second mode peak magnitude of the small crack wafer set are shown in Figure E.10. The 20 crack-free wafers second mode peak magnitudes range from 760 to 1073 dB/N. For an individual crack-free wafer, the magnitude deviation is less than 153 dB/N. The magnitude deviation across all twenty crack-free wafers is 303 dB/N.

For the 10 small crack wafers, the second mode peak magnitudes range from 811 to 1087 dB/N. All the wafers are within 276 dB/N. Again the crack-free wafers do not deviate from the cracked wafers when the crack size is small. Data for mode 1,2,3 and 4 are referenced in Figures E.9-E.12. Therefore, the vibration impact test used in this thesis does not appear to be suitable for detecting small edge cracks.

4.7 Damping ratio

The damping ratio is found by zooming in on each peak and subtracting 3 dB on each side of the peak and recording the corresponding frequencies. The damping ratio is then calculated by the following equation,

$$\zeta = \frac{(\omega_2 - \omega_1)}{2\omega_n} \quad (5)$$

where ζ is the damping ratio, ω_2 is the frequency 3 dB down on the right side of the peak, ω_1 is the frequency 3 dB down on the left side of the peak and ω_n is the frequency at the peak.

4.7.1 Large crack wafer set

The damping ratio for the second mode frequencies of the large crack wafer set are shown in Table 4.3. The first 4 specimens in the table are the crack-free wafers and the following 12 specimens have cracks.

The crack-free wafers second mode damping ratio range from 0.0014 to 0.0016. For an individual crack-free wafer, the damping ratio deviates less than 0.0002. The damping ratio deviation across all four crack-free wafers is 0.0002.

For the 12 large crack wafers, the second mode damping ratios range from 0.0015 to 0.0054. All the wafers are within 0.0017. Five of the cracked wafers have damping ratios that fall within the crack-free damping ratio range, three of the cracked wafers have a slightly higher damping ratio (0.0017-0.0021), one of the cracked wafers, number 27 (0.0019-0.0036). Three of the cracked wafers have significantly higher damping ratios (from 0.0032 to 0.0054). This shows that the damping ratio parameter can be used to detect large continuous cracks. The other large crack specimens that do not show significant deviation are not continuous. These 3 large crack specimens are numbered 31, 35, 48 and are italicized in Table 4.3. Note that all of the wafers with continuous cracks show significant changes in damping ratio (see Tables 3.3 and 4.3)

Table 4.3 Second mode peak damping ratio for the large crack wafer set

Specimen number	Test 1 [non-dim]	Test 2 [non-dim]	Test 3 [non-dim]	Mean [non-dim]
29	0.0015	0.0014	0.0016	0.0015
34	0.0015	0.0016	0.0015	0.0016
38	0.0015	0.0015	0.0016	0.0015
47	0.0015	0.0016	0.0014	0.0015
39	0.0016	0.0018	0.0016	0.0017
31	*0.0049*	*0.0054*	*0.0052*	*0.0052*
35	*0.0044*	*0.0047*	*0.0046*	*0.0046*
48	*0.0032*	*0.0033*	*0.0036*	*0.0034*
32	0.0015	0.0018	0.0020	0.0018
40	0.0020	0.0019	0.0019	0.0019
36	0.0019	0.0021	0.0021	0.0020
27	*0.0020*	*0.0019*	*0.0036*	*0.0025*
8	0.0015	0.0017	0.0016	0.0016
6	0.0016	0.0015	0.0016	0.0016
33	0.0017	0.0018	0.0018	0.0017
41	0.0015	0.0016	0.0015	0.0015

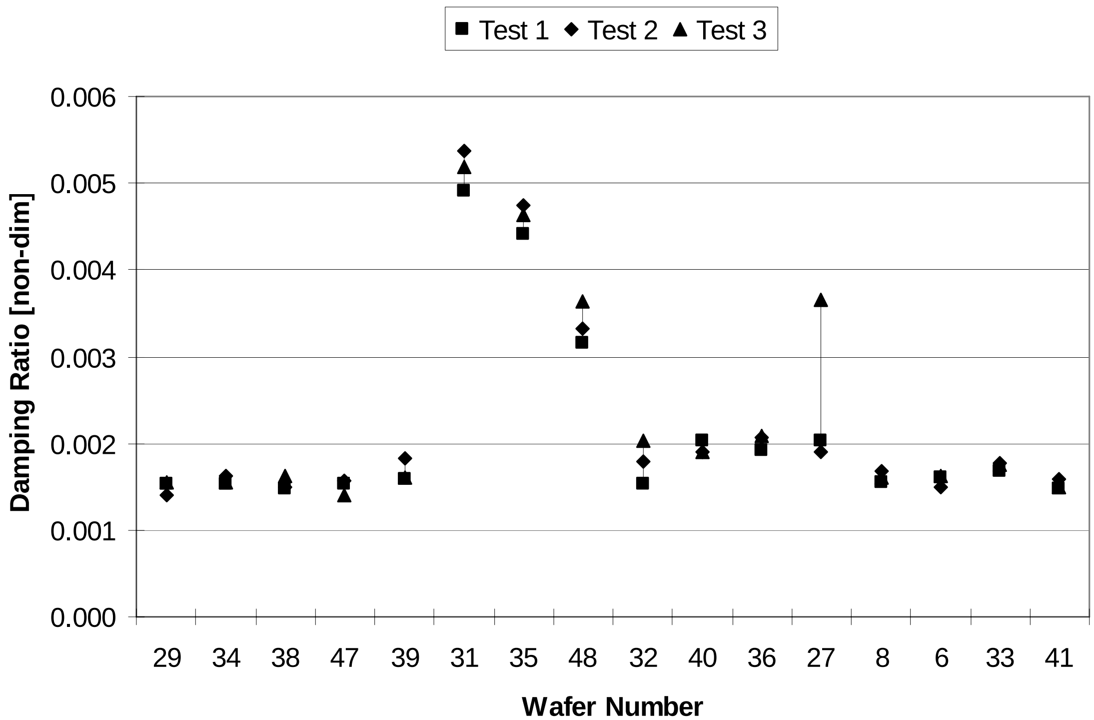

Figure 4.7 Second mode peak damping ratio for the large crack wafer set

Data for mode 1,2,3 and 4 are referenced in Tables C.13-C.16 and Figures C.13-C.16.

4.7.2 Miscellaneous wafer set

The damping ratio for the second mode frequencies of the miscellaneous crack wafer set are shown in Table D.14 and Figure D.14. The first 4 specimens in the table are the crack-free wafers and the following 8 wafers are cracked.

The second mode damping ratio range for the crack-free wafers is from 0.0014-0.0016. For an individual crack-free wafer the damping ratio deviation is less than 0.0001. The damping ratio deviation across all the crack-free wafers is 0.0002.

For the 8 cracked wafers, the second mode damping ratio ranges from 0.0015-0.0041. All cracked wafers are within 0.0027. Four of the cracked wafers have damping ratios that fall within the crack-free damping ratio deviation range, four of the cracked wafers have significantly higher damping ratio from 0.0023-0.0041, those 4 wafers are numbered 23, 25, 47 and 8.

All the specimens have a damping ratio deviation of less than 0.0001 except large crack wafer numbers 23 (a deviation of 0.0014), 25 (a deviation of 0.0007), 47 (a deviation of 0.0007) and wafer number 8 (a deviation of 0.0004). Data for the first mode is shown in Table D.1 and Figure D.1, for the third mode in Table D.5 and Figure D.5, and for the fourth mode in Table D.7 and Figure D.7.

4.7.3 Small crack wafer set

The second mode damping ratio for the small crack wafer set is shown in Figure E.14. For the 20 crack-free wafers, the second mode damping ratios range from 0.0013 to 0.0018 and are shown first, followed by 10 cracked wafers whose second mode damping ratios range 0.0014-0.0017.

For the crack-free wafers and the wafers with a small crack, the deviation of an individual wafer is less than 0.0004, and the range across all the crack-free wafers is 0.0005 and for the cracked wafers the range is 0.0003.

Data for mode 1,2,3 and 4 are referenced in Tables E.9-E.12 and Figures E.13-E.16.

4.8 Discussion

For the large crack wafer set, four wafers (numbered 31,35,48,27) show significant deviation in the natural frequencies for the four modes. For the magnitude peaks, eight wafers (numbered 39, 31, 35, 48, 32, 40, 36, 27) show a significant difference. For the damping ratio, four of the wafers (numbered 31, 35, 48, 27) show a significantly difference. Only four from the twelve large crack wafers set showed significant deviation in frequency, magnitude and damping ratio. These four large crack specimens have continuous cracks as opposed to segmented cracks as in the other 8 large crack specimens.

From the miscellaneous wafer set, wafer numbers 23 and 8 show a difference in the normalized frequency. Looking at the magnitude, six of the cracked wafers show a difference compared to the crack-free wafers. The damping ratio was higher for number 23, 25, 47 and 8. In other words, 50% of the cracked wafers were different from the crack-free data set considering the damping ratio and the magnitude.

The small crack wafer set did not show any notable change in frequency, magnitude nor damping ratio. The crack length of the wafers were to small to detect the cracks using the impact method described in this thesis.

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

The results showed some deviations in the four dominate audible modes that were measured for cracked versus crack-free wafers. A difference in the natural frequencies and in the magnitudes were found by the test. Also, the cracked wafers had higher damping ratios than the crack-free wafers. This is expected due to frictional damping introduced within the crack.

For the large crack wafers considering the second audible mode, 33% of the cracked wafers showed a significant difference in frequency, 67% had a significant difference in peak magnitude, and 33% had a significant difference in damping. Note that only 33% of the large cracked wafers had continuous cracks. Therefore, 100% of the wafers with continuous large cracks showed significant differences in all 3 parameters. For the miscellaneous wafers, 25% of the cracked wafers had a notable difference in frequency, 75% had a notable difference in peak magnitudes and 50% had a notable difference in damping. The small crack wafers did not show any notable difference between the crack-free wafers and the wafers with cracks for the frequency, magnitude, or damping.

Overall, the data showed that the peak magnitude was the most sensitive to cracked wafers, followed next in sensitivity by the damping ratio and the natural frequency.

5.2 Recommendations

For future work, it is recommended to make the impact hammer automated instead of manually hitting the hammer. This would facilitate a quicker repeatable test process possibly suitable for in-line production use. A non-automated impact test takes about 15-30 seconds. If automated this could be reduced to a few seconds.

Different crack lengths should be investigated to establish a quantitative sensitivity limit for the millimeter size cracks. In this thesis, the crack lengths investigated were less than 8 mm or larger than 38-55 mm. Also, explore further tests to different crack locations could be studied.

It is also recommended to develop an endurance test to investigate how many impacts can be applied on the cracked wafer with a critical length of 1 cm before it break. This would represent an endurance “go” or “no-go” test.

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Appendices

Appendix A: Run order

Table A.1 Test number for the small crack wafer set

Wafer number	Test Number		
11	1	2	3
12	4	5	6
13	7	8	9
14	10	11	12
15	13	14	15
18	16	17	18
19	19	20	21
20	22	23	24
33	25	26	27
34	28	29	30
35	31	32	33
36	34	35	36
37	37	38	39
38	40	41	42
39	43	44	45
40	46	47	48
41	49	50	51
42	52	53	54
43	55	56	57
44	58	59	60
21	61	62	63
22	64	65	66
23	67	68	69
25	70	71	72
26	73	74	75
27	76	77	78
29	79	80	81
30	82	83	84
31	85	86	87
32	88	89	90

Table A.2 Run order for the small crack wafer set

Run order	Wafer number	Test number	Random numbers in ascending order
1	20	24	1
2	11	2	2
3	44	60	7
4	27	76	28
5	29	79	43
6	32	89	47
7	33	25	53
8	21	61	66
9	44	59	69
10	33	26	88
11	14	11	116
12	38	40	125
13	35	31	137

Table A.2 (Continued)

14	27	77	148
15	25	71	156
16	31	86	163
17	41	49	169
18	22	64	185
19	43	56	195
20	36	35	229
21	39	45	231
22	40	46	240
23	35	32	262
24	32	90	264
25	40	48	272
26	43	55	289
27	12	4	302
28	42	53	303
29	15	13	309
30	41	50	313
31	29	81	340
32	18	18	352
33	18	17	375
34	11	3	379
35	34	29	397
36	31	85	411
37	13	9	412
38	21	63	417
39	22	65	423
40	37	38	426
41	26	73	433
42	39	44	492
43	18	16	502
44	42	54	503
45	21	62	505
46	11	1	507
47	20	23	519
48	37	39	531
49	20	22	535
50	36	36	542
51	27	78	558
52	33	27	574
53	26	74	592
54	19	21	597
55	42	52	603
56	34	28	608
57	25	72	614
58	37	37	618
59	38	41	629
60	30	84	662
61	31	87	664
62	23	69	687
63	12	5	710
64	43	57	722
65	22	66	732
66	13	8	737

Table A.2 (Continued)

67	19	19	742
68	12	6	746
69	19	20	750
70	39	43	752
71	44	58	756
72	34	30	784
73	25	70	796
74	40	47	803
75	36	34	813
76	30	83	835
77	23	67	875
78	29	80	883
79	13	7	907
80	15	14	922
81	30	82	930
82	38	42	935
83	41	51	947
84	15	15	958
85	26	75	959
86	35	33	961
87	32	88	966
88	14	12	987
89	23	68	991
90	14	10	998

Appendix B: Frequency response data

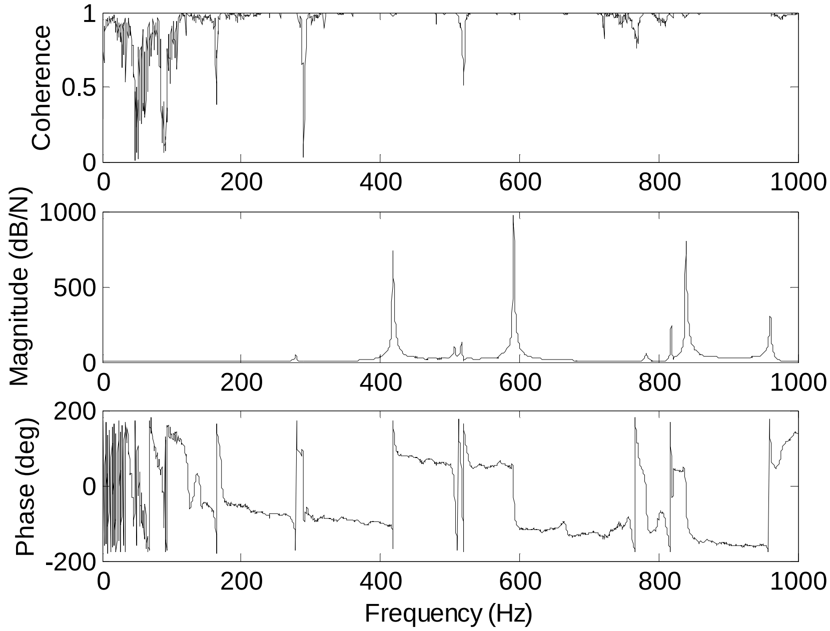

Figure B.1 Frequency response data of crack-free wafer number 29

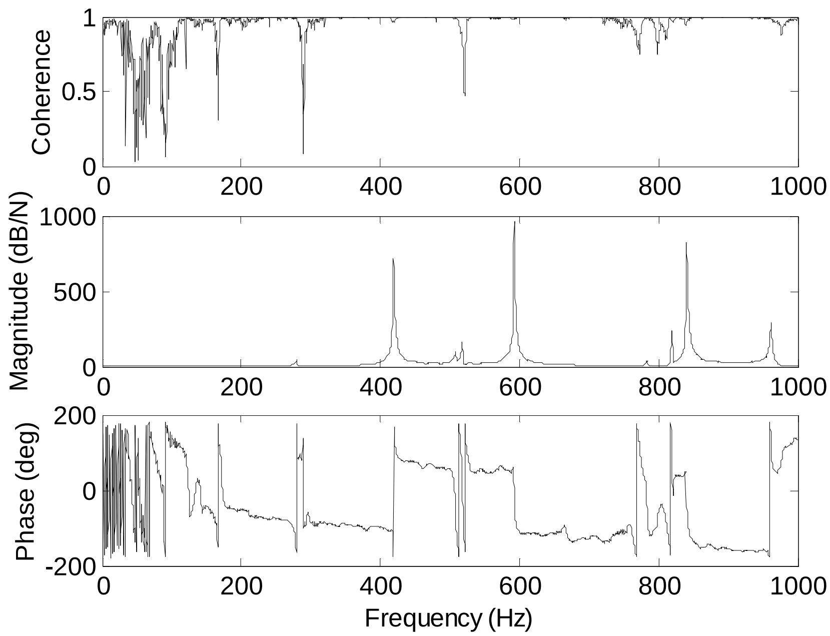

Figure B.2 Frequency response data of crack-free wafer number 34

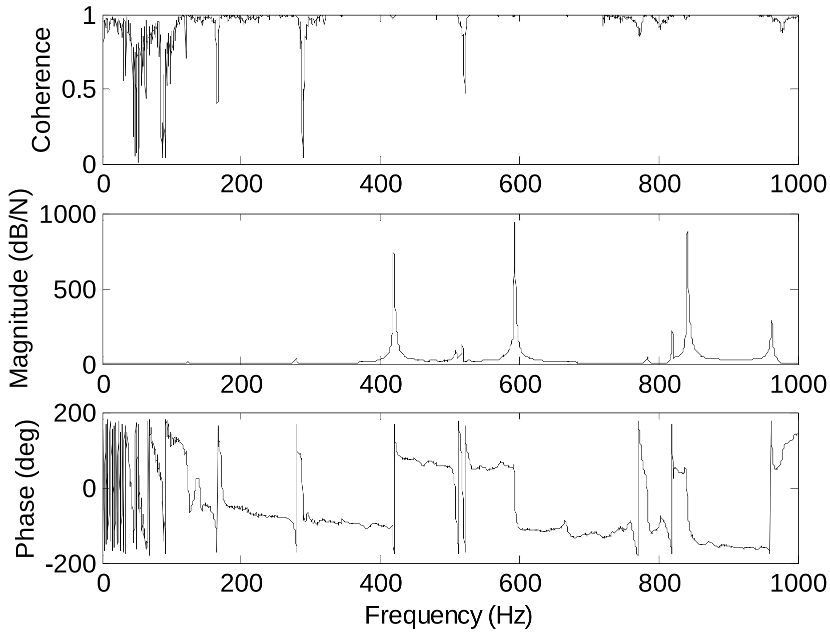

Figure B.3 Frequency response data of crack-free wafer number 38

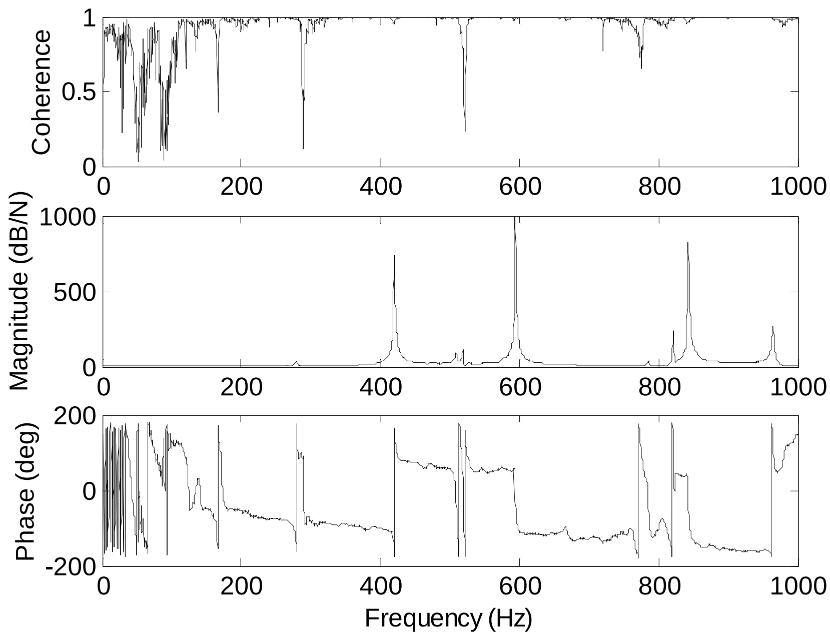

Figure B.4 Frequency response data of crack-free wafer number 47

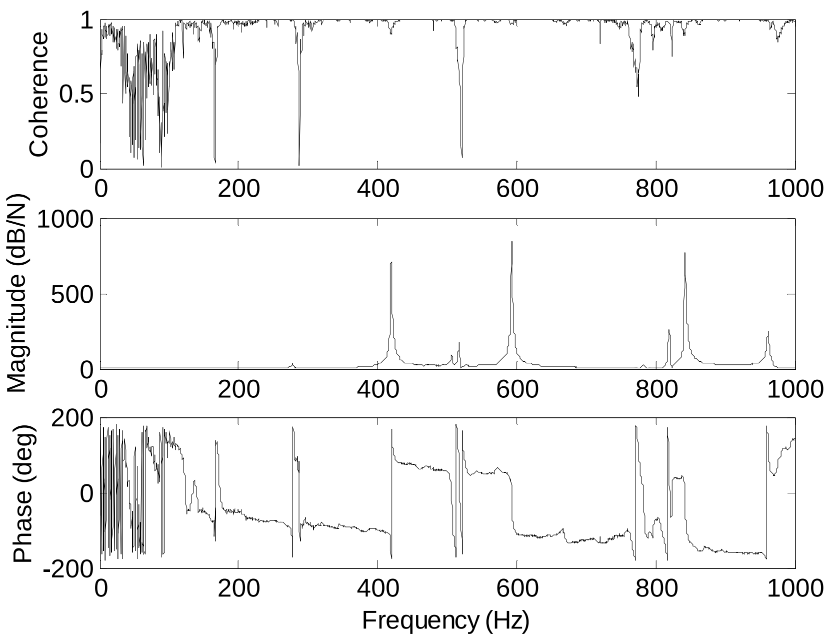

Figure B.5 Frequency response data of cracked wafer number 39

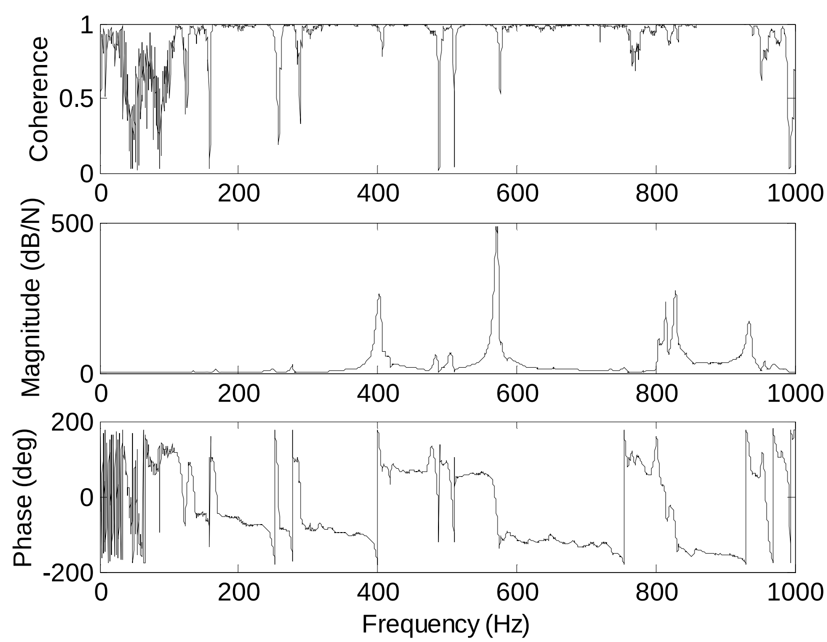

Figure B.6 Frequency response data of cracked wafer number 31 (Test 1)

Appendix B (Continued)

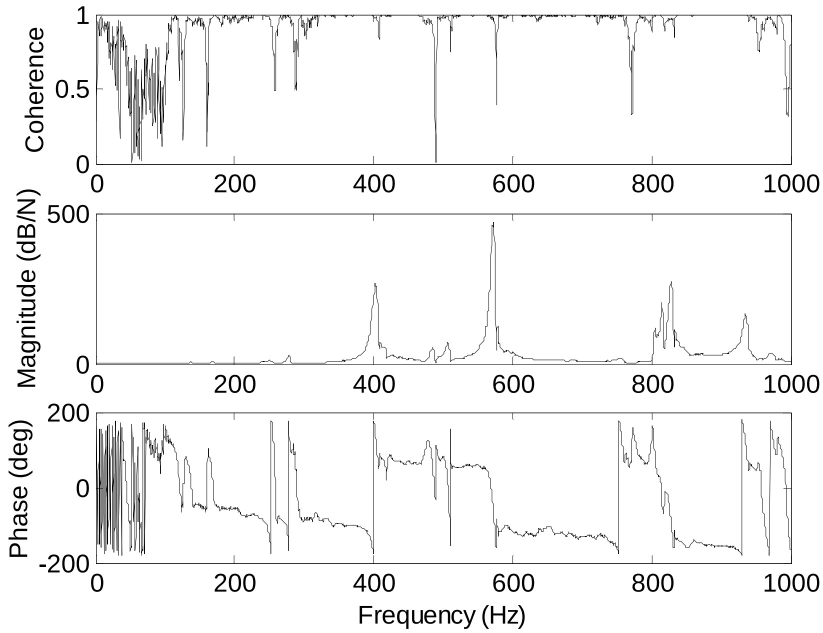

Figure B.7 Frequency response data of cracked wafer number 31 (Test 2)

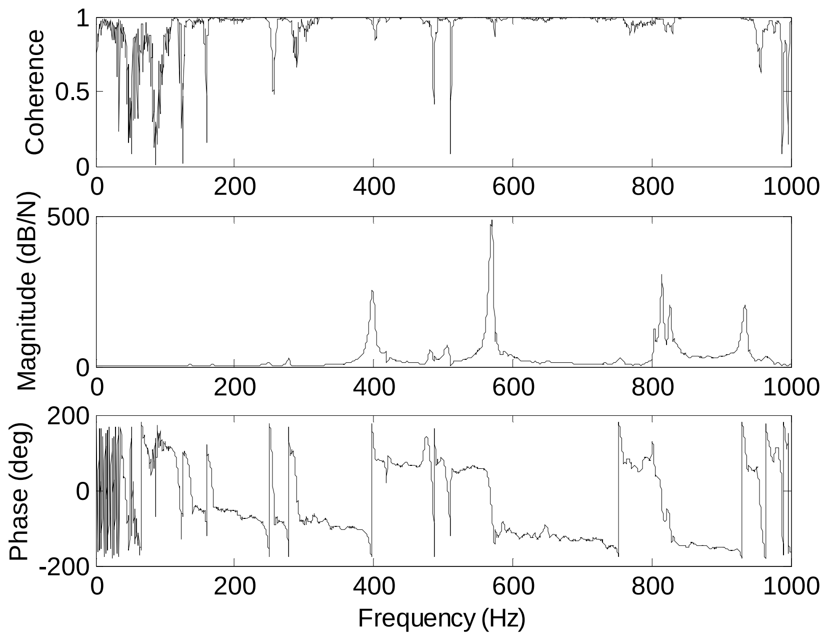

Figure B.8 Frequency response data of cracked wafer number 31 (Test 3)

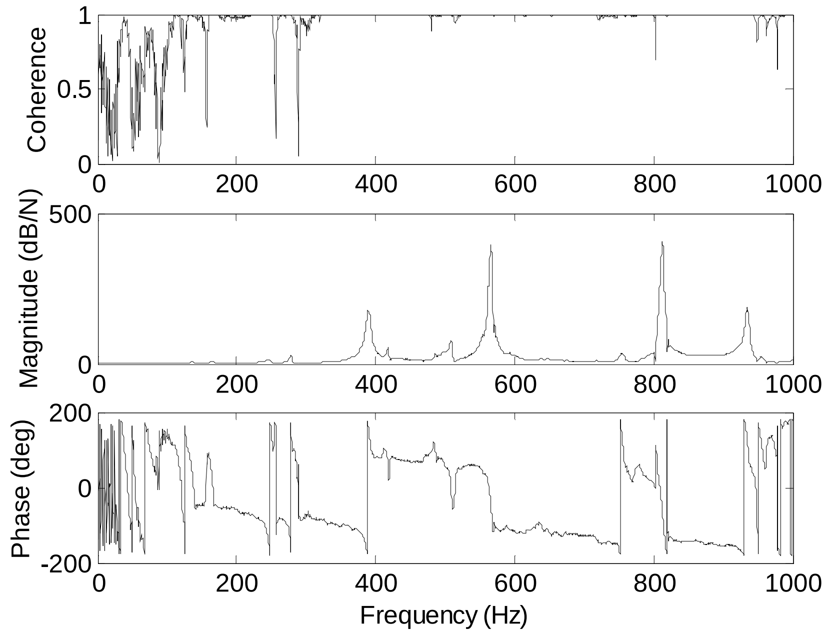

Figure B.9 Frequency response data of cracked wafer number 35

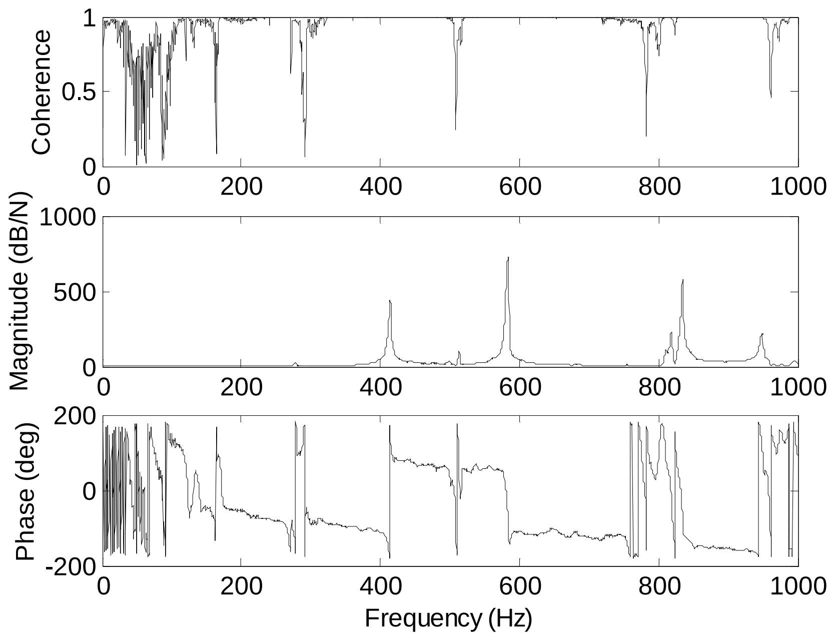

Figure B.10 Frequency response data of cracked wafer number 48

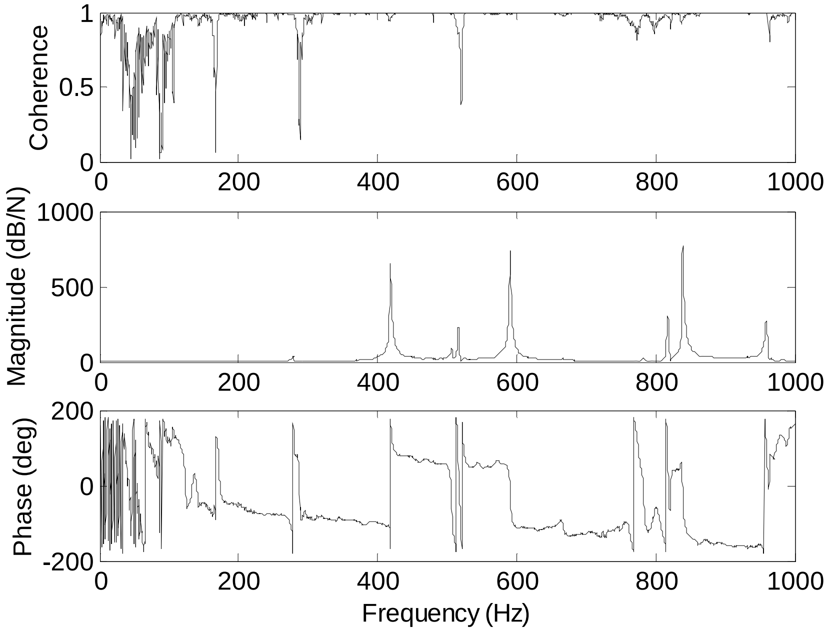

Figure B.11 Frequency response data of cracked wafer number 32

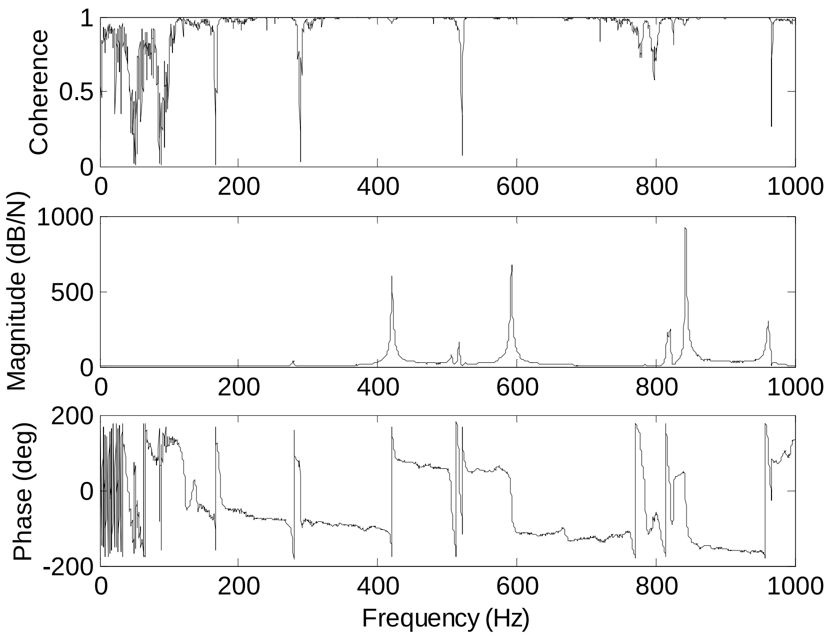

Figure B.12 Frequency response data of cracked wafer number 40

Appendix B (Continued)

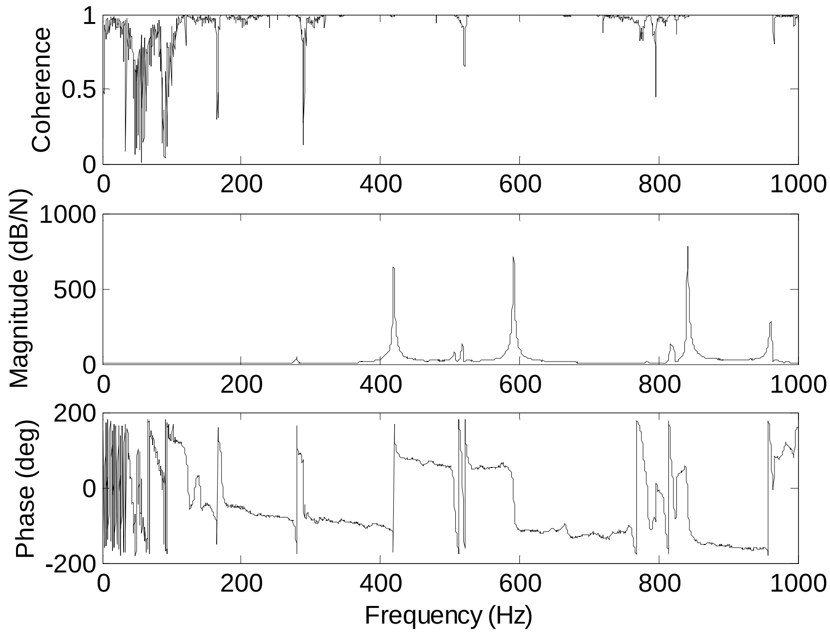

Figure B.13 Frequency response data of cracked wafer number 36

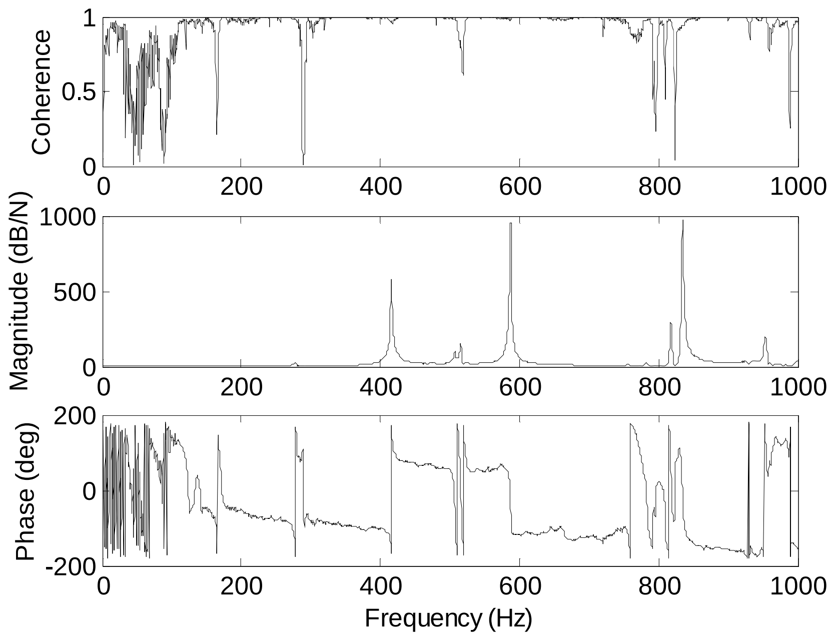

Figure B.14 Frequency response data of cracked wafer number 27 (Test 1)

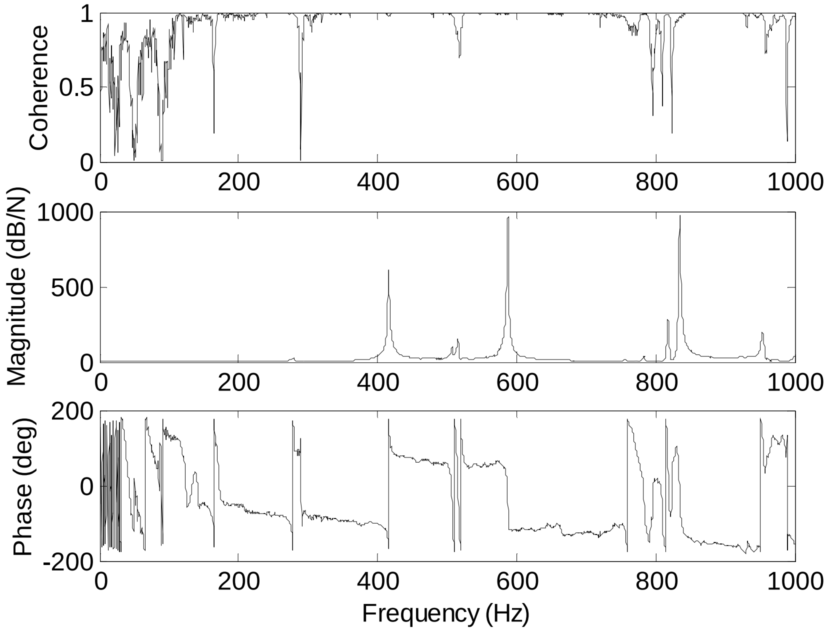

Figure B.15 Frequency response data of cracked wafer number 27 (Test 2)

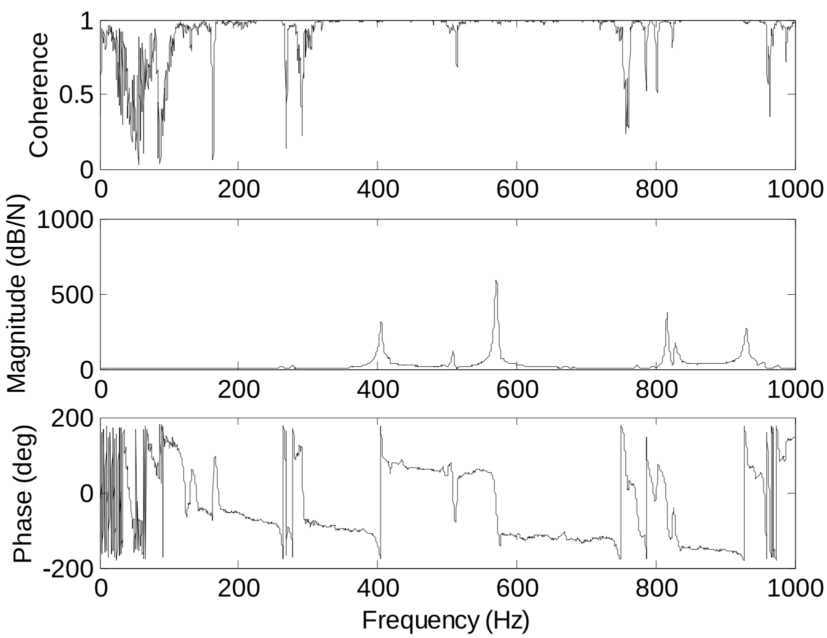

Figure B.16 Frequency response data of cracked wafer number 27 (Test 3)

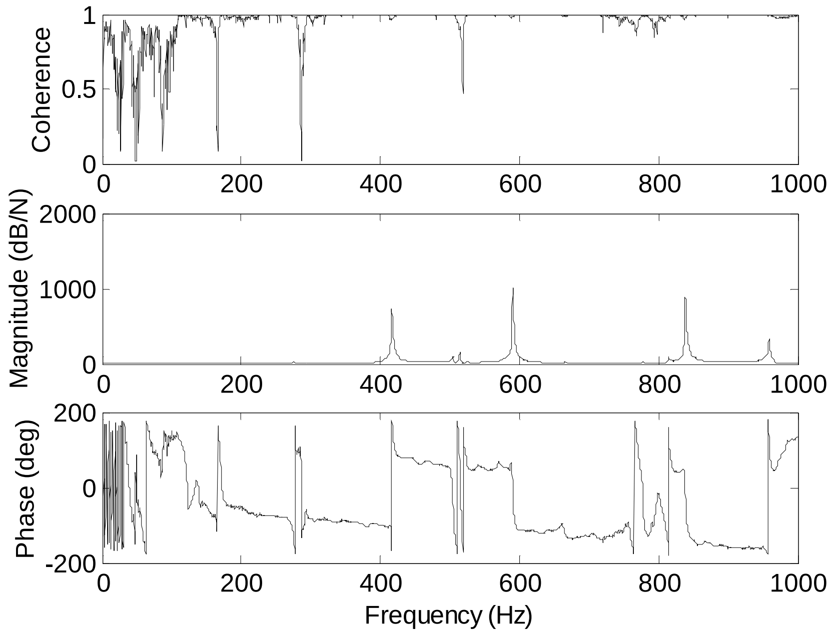

Figure B.17 Frequency response data of cracked wafer number 8

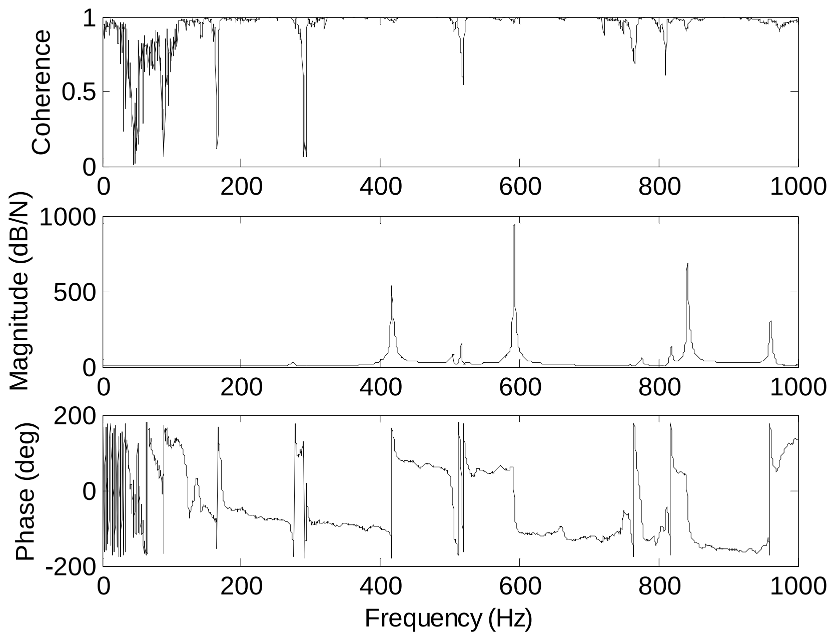

Figure B.18 Frequency response data of cracked wafer number 6

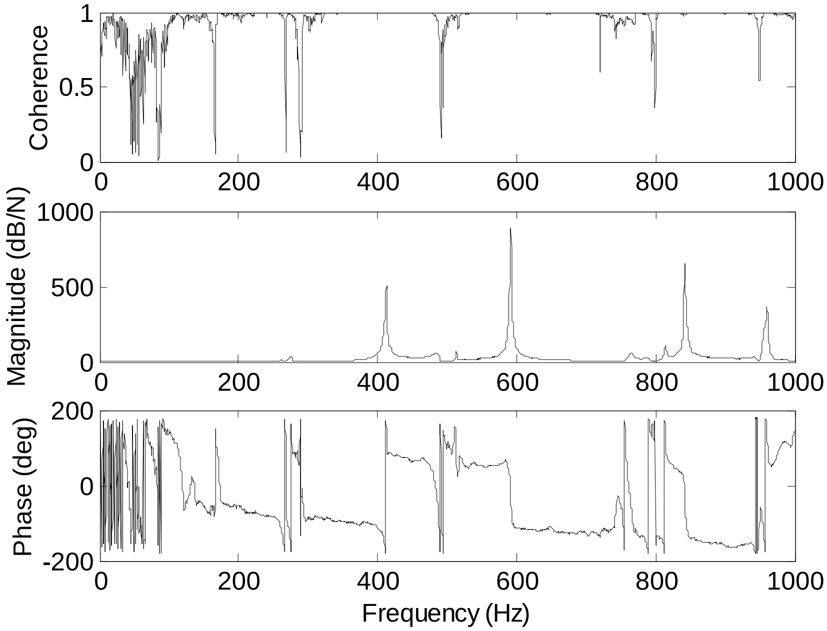

Figure B.19 Frequency response data of cracked wafer number 33

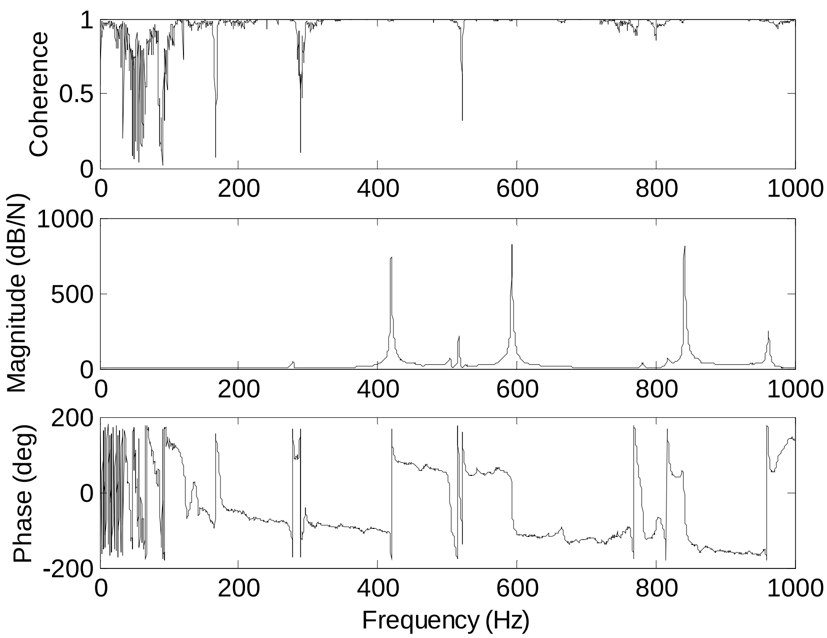

Figure B.20 Frequency response data of cracked wafer number 41

Appendix C: Data from the large crack wafer set

Table C.1 First mode natural frequency for large crack wafer set

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	418.1	418.1	418.1	418.1
34	418.4	418.8	419.1	418.8
38	419.1	419.1	419.4	419.2
47	419.7	420.0	419.7	419.8
39	419.4	419.4	419.7	419.5
31	402.5	402.8	398.4	401.3
35	390.3	390.3	389.4	390.0
48	415.0	414.4	413.8	414.4
32	418.1	418.4	418.4	418.3
40	420.9	420.9	420.9	420.9
36	419.1	419.1	419.1	419.1
27	415.9	415.9	405.3	412.4
8	416.6	416.9	416.9	416.8
6	416.6	416.3	416.6	416.5
33	413.1	412.8	413.4	413.1
41	419.1	419.4	419.4	419.3

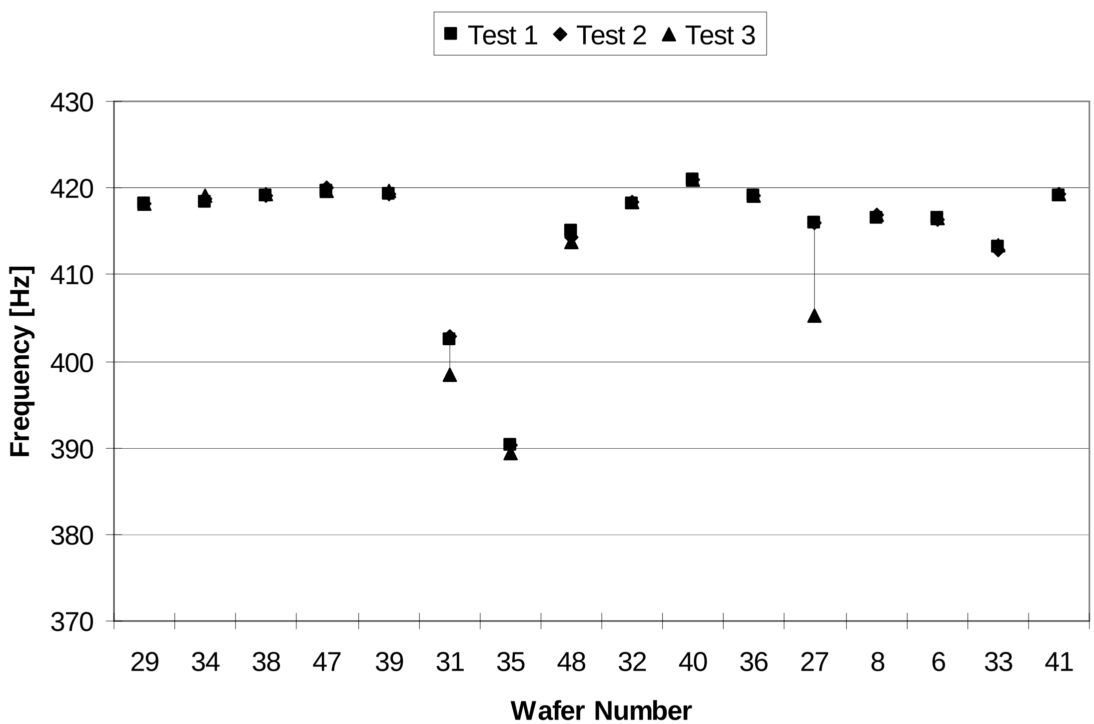

Figure C.1 First mode natural frequency for large crack wafer set

Appendix C (Continued)

Table C.2 First mode normalized frequency for large crack wafer set

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	0.0785	0.0785	0.0785	0.0785
34	0.0784	0.0785	0.0785	0.0785
38	0.0784	0.0784	0.0785	0.0784
47	0.0783	0.0783	0.0783	0.0783
39	0.0784	0.0784	0.0784	0.0784
31	0.0754	0.0754	0.0746	0.0752
35	0.0733	0.0733	0.0731	0.0732
48	0.0776	0.0775	0.0773	0.0775
32	0.0784	0.0784	0.0784	0.0784
40	0.0783	0.0783	0.0783	0.0783
36	0.0782	0.0782	0.0782	0.0782
27	0.0780	0.0780	0.0760	0.0773
8	0.0784	0.0784	0.0784	0.0784
6	0.0781	0.0780	0.0781	0.0781
33	0.0773	0.0772	0.0774	0.0773
41	0.0785	0.0785	0.0785	0.0785

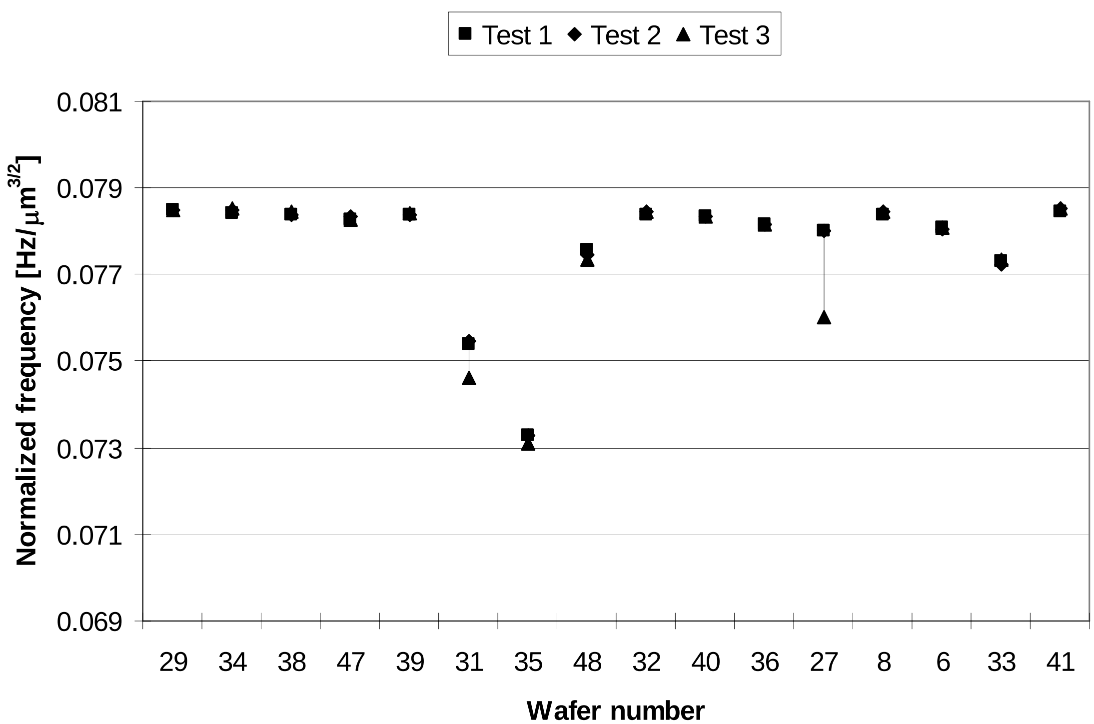

Figure C.2 First mode normalized frequency for large crack wafer set

Appendix C (Continued)

Table C.3 Second mode natural frequency for large crack wafer set

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	591.6	591.6	591.6	591.6
34	592.2	592.2	592.2	592.2
38	592.8	593.1	593.1	593.0
47	594.1	594.1	594.1	594.1
39	592.8	592.8	592.8	592.8
31	571.9	571.9	569.7	571.1
35	565.9	565.9	566.3	566.0
48	584.4	583.4	582.8	583.5
32	590.6	590.9	590.6	590.7
40	592.5	592.8	592.8	592.7
36	591.9	591.9	591.9	591.9
27	587.8	587.8	570.9	582.2
8	590.3	590.6	590.6	590.5
6	592.2	592.2	592.2	592.2
33	591.9	591.6	591.9	591.8
41	592.8	592.8	592.8	592.8

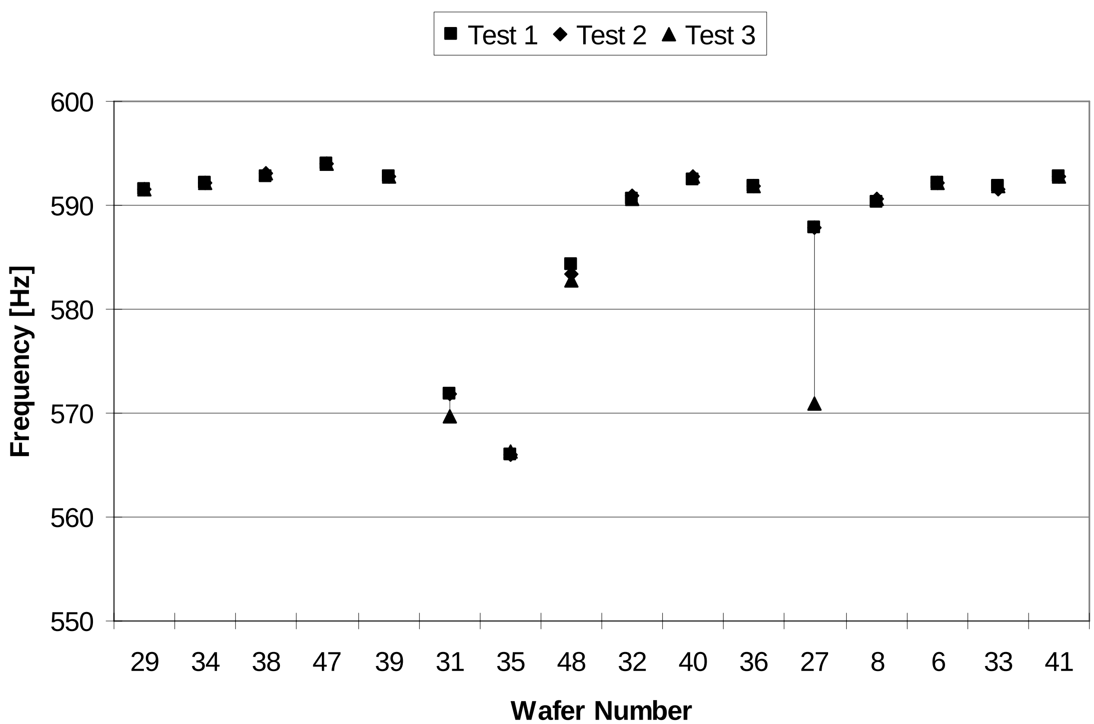

Figure C.3 Second mode natural frequency for large crack wafer set

Appendix C (Continued)

Table C.4 Second mode normalized frequency for large crack wafer set

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	0.1110	0.1110	0.1110	0.1110
34	0.1110	0.1110	0.1110	0.1110
38	0.1109	0.1110	0.1110	0.1109
47	0.1108	0.1108	0.1108	0.1108
39	0.1108	0.1108	0.1108	0.1108
31	0.1071	0.1071	0.1067	0.1070
35	0.1062	0.1062	0.1063	0.1063
48	0.1092	0.1091	0.1089	0.1091
32	0.1107	0.1108	0.1107	0.1107
40	0.1103	0.1103	0.1103	0.1103
36	0.1104	0.1104	0.1104	0.1104
27	0.1102	0.1102	0.1071	0.1092
8	0.1111	0.1111	0.1111	0.1111
6	0.1110	0.1110	0.1110	0.1110
33	0.1107	0.1107	0.1107	0.1107
41	0.1110	0.1110	0.1110	0.1110

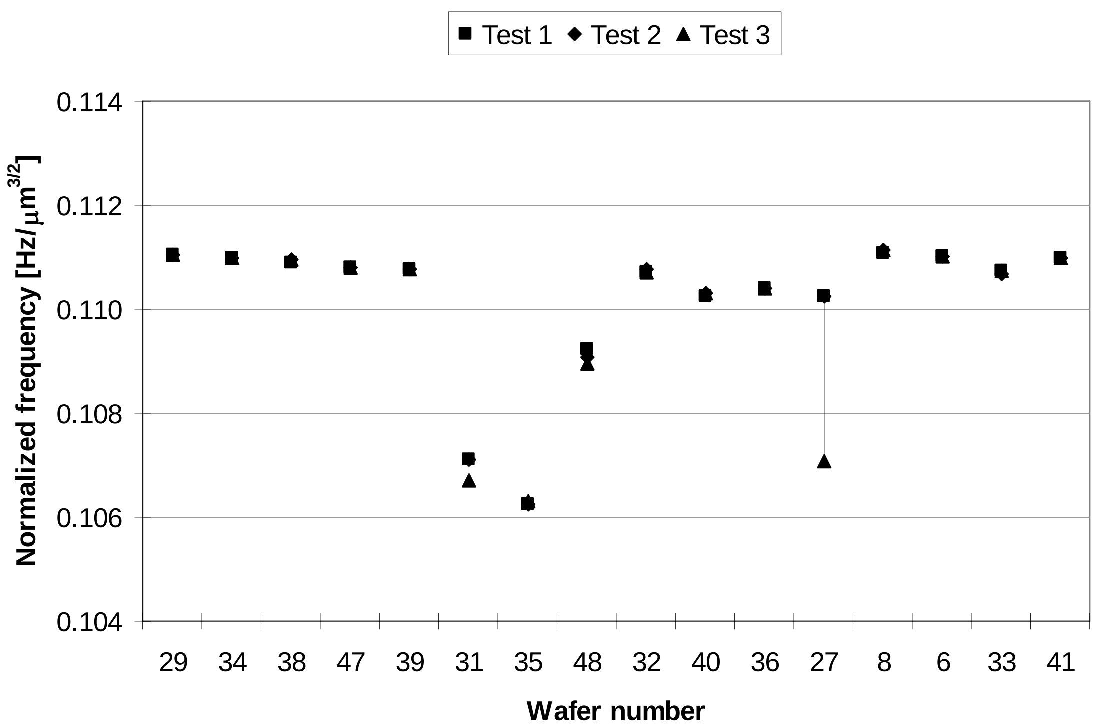

Figure C.4 Second mode normalized frequency for large crack wafer set

Appendix C (Continued)

Table C.5 Third mode natural frequency for large crack wafer set

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	839.1	839.1	839.4	839.2
34	840.3	840.3	840.3	840.3
38	840.9	841.3	841.3	841.1
47	842.8	842.8	842.5	842.7
39	842.2	842.2	842.2	842.2
31	828.8	828.8	815.3	824.3
35	813.1	812.8	812.5	812.8
48	835.0	834.7	834.1	834.6
32	838.8	838.8	838.8	838.8
40	843.1	843.4	843.4	843.3
36	841.9	841.9	841.9	841.9
27	834.7	835.0	816.6	828.8
8	838.4	838.8	838.8	838.6
6	841.6	841.3	841.6	841.5
33	841.9	841.9	841.9	841.9
41	841.3	841.6	841.6	841.5

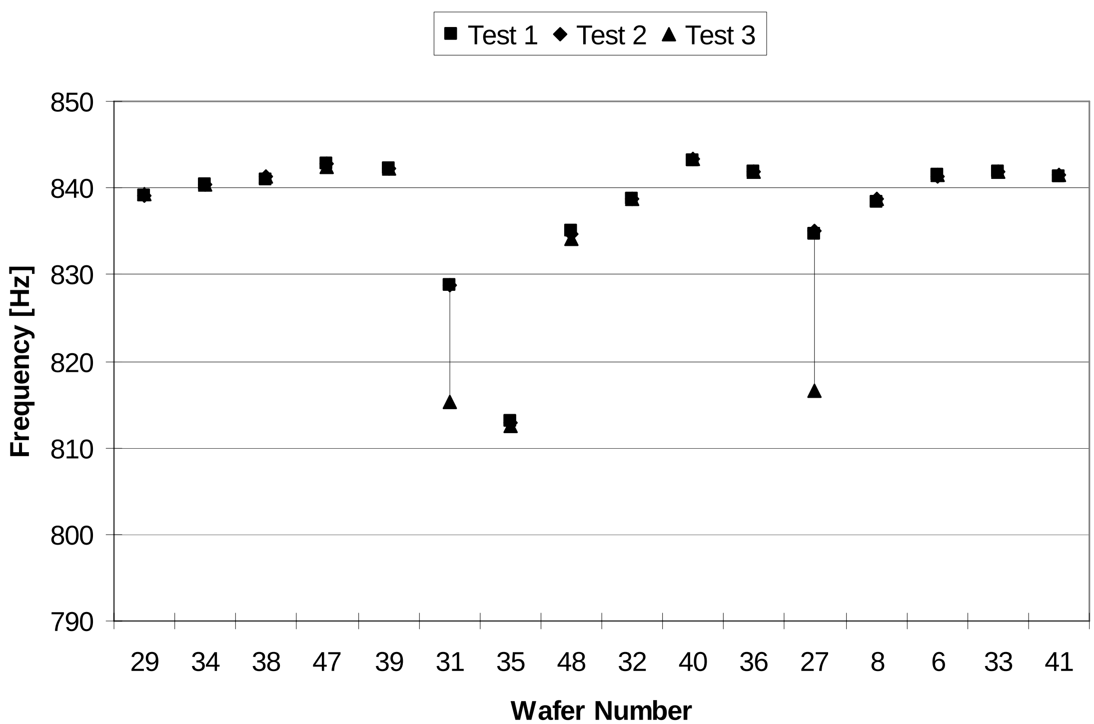

Figure C.5 Third mode natural frequency for large crack wafer set

Appendix C (Continued)

Table C.6 Third mode normalized frequency for large crack wafer set

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	0.1575	0.1575	0.1576	0.1575
34	0.1575	0.1575	0.1575	0.1575
38	0.1573	0.1574	0.1574	0.1574
47	0.1572	0.1572	0.1572	0.1572
39	0.1574	0.1574	0.1574	0.1574
31	0.1552	0.1552	0.1527	0.1544
35	0.1526	0.1526	0.1525	0.1526
48	0.1561	0.1560	0.1559	0.1560
32	0.1572	0.1572	0.1572	0.1572
40	0.1569	0.1570	0.1570	0.1569
36	0.1570	0.1570	0.1570	0.1570
27	0.1565	0.1566	0.1531	0.1554
8	0.1578	0.1578	0.1578	0.1578
6	0.1578	0.1577	0.1578	0.1577
33	0.1575	0.1575	0.1575	0.1575
41	0.1575	0.1576	0.1576	0.1576

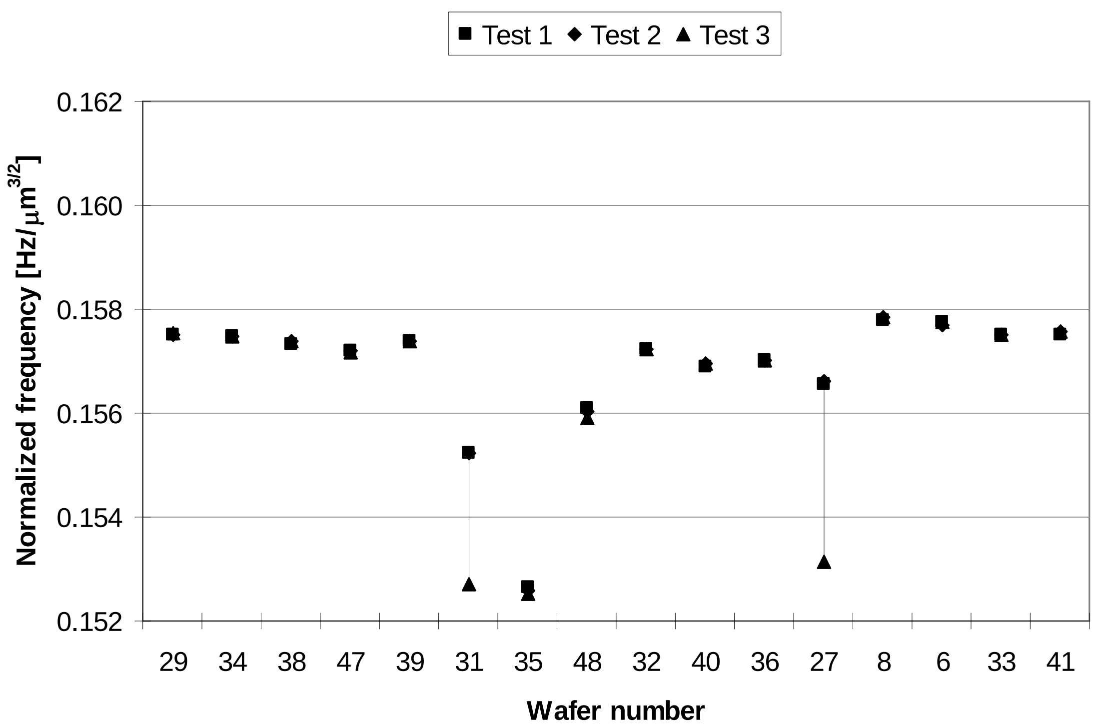

Figure C.6 Third mode normalized frequency for large crack wafer set

Appendix C (Continued)

Table C.7 Fourth mode natural frequency for large crack wafer set

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	960.6	960.6	960.6	960.6
34	961.9	961.9	961.9	961.9
38	962.8	962.8	962.8	962.8
47	964.4	964.7	964.7	964.6
39	961.6	961.6	961.9	961.7
31	935.0	935.0	935.0	935.0
35	935.0	934.4	934.7	934.7
48	950.6	949.1	948.1	949.3
32	958.4	958.8	959.1	958.8
40	961.9	961.9	961.9	961.9
36	960.9	960.9	960.9	960.9
27	954.1	954.1	930.6	946.3
8	958.8	959.1	959.1	959.0
6	961.3	961.6	961.3	961.4
33	960.3	960.3	960.3	960.3
41	962.2	962.2	962.2	962.2

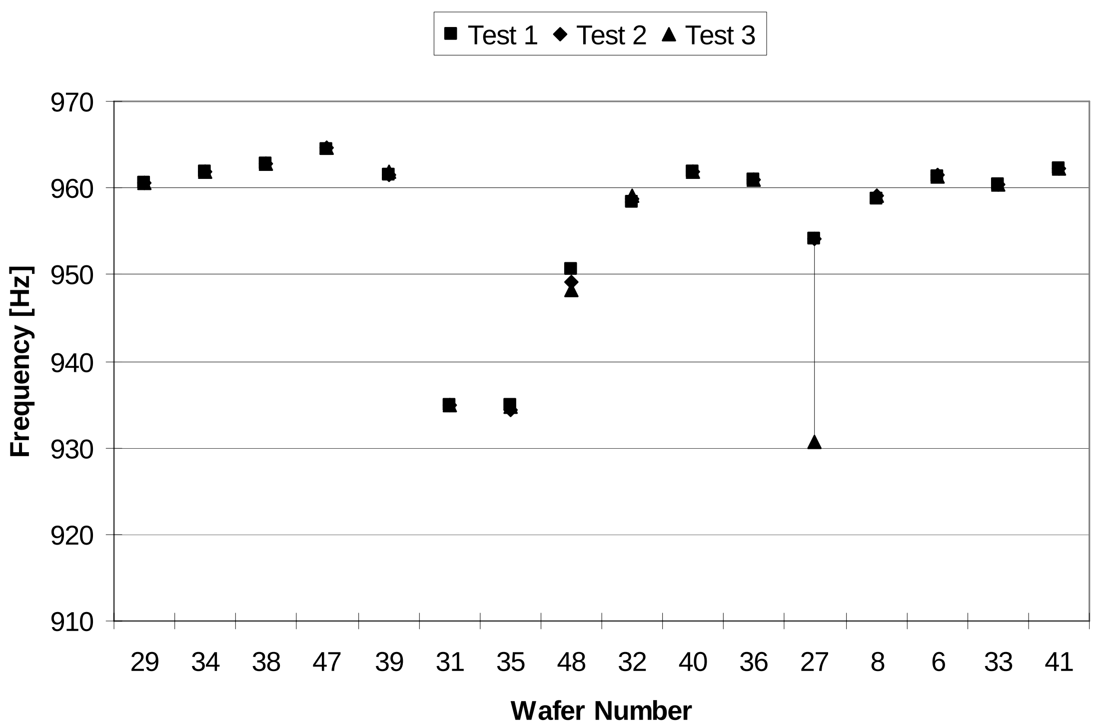

Figure C.7 Fourth mode natural frequency for large crack wafer set

Appendix C (Continued)

Table C.8 Fourth mode normalized frequency for large crack wafer set

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	0.1803	0.1803	0.1803	0.1803
34	0.1803	0.1803	0.1803	0.1803
38	0.1801	0.1801	0.1801	0.1801
47	0.1799	0.1799	0.1799	0.1799
39	0.1797	0.1797	0.1797	0.1797
31	0.1751	0.1751	0.1751	0.1751
35	0.1755	0.1754	0.1755	0.1755
48	0.1777	0.1774	0.1772	0.1775
32	0.1797	0.1797	0.1798	0.1797
40	0.1790	0.1790	0.1790	0.1790
36	0.1792	0.1792	0.1792	0.1792
27	0.1789	0.1789	0.1745	0.1775
8	0.1804	0.1805	0.1805	0.1805
6	0.1802	0.1803	0.1802	0.1802
33	0.1797	0.1797	0.1797	0.1797
41	0.1802	0.1802	0.1802	0.1802

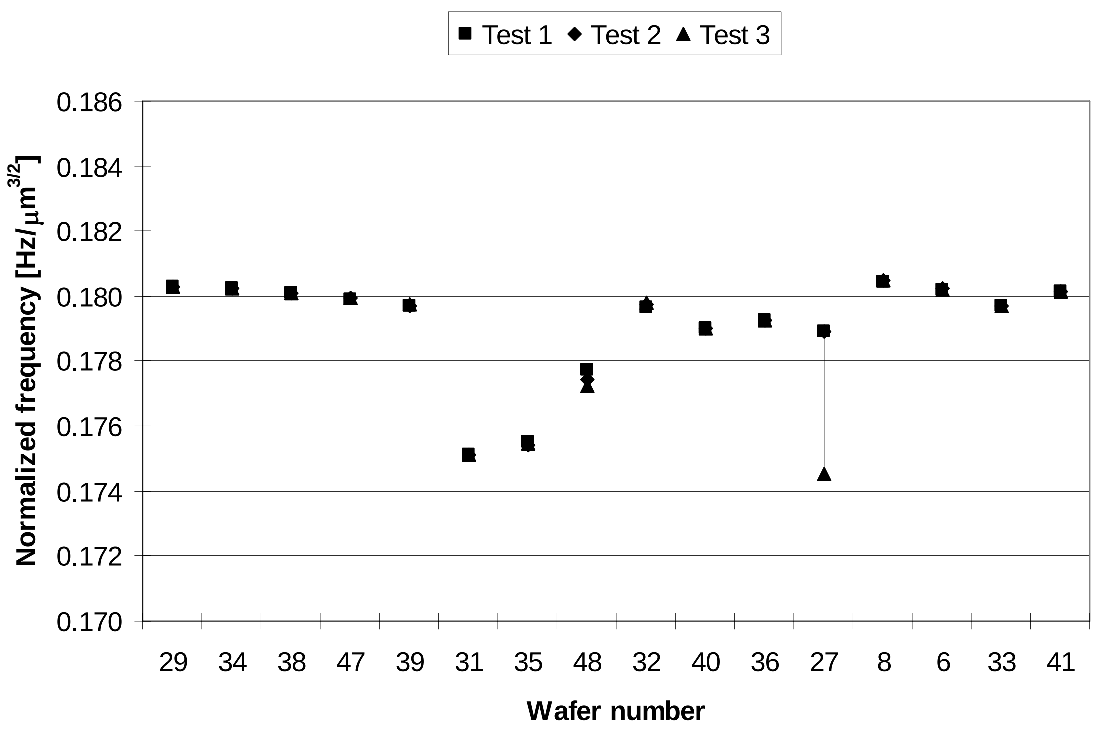

Figure C.8 Fourth mode normalized frequency for large crack wafer set

Table C.9 First mode peak magnitude for large crack wafer set

Specimen number	Test 1 [dB/N]	Test 2 [dB/N]	Test 3 [dB/N]	Mean [dB/N]
29	720.3	734.2	743.9	732.8
34	729.4	642.6	721.8	697.9
38	741.0	735.1	744.2	740.1
47	663.7	718.7	741.2	707.9
39	703.4	666.8	655.6	675.3
31	265.0	266.9	252.4	261.4
35	175.9	180.8	180.8	179.2
48	476.7	445.8	426.5	449.7
32	536.6	629.7	649.4	605.2
40	600.4	594.7	595.9	597.0
36	646.4	627.8	614.7	629.6
27	575.9	617.0	314.5	502.5
8	725.8	620.7	687.4	678.0
6	499.1	491.0	532.0	507.4
33	504.8	484.6	501.5	496.9
41	725.3	725.8	742.3	731.1

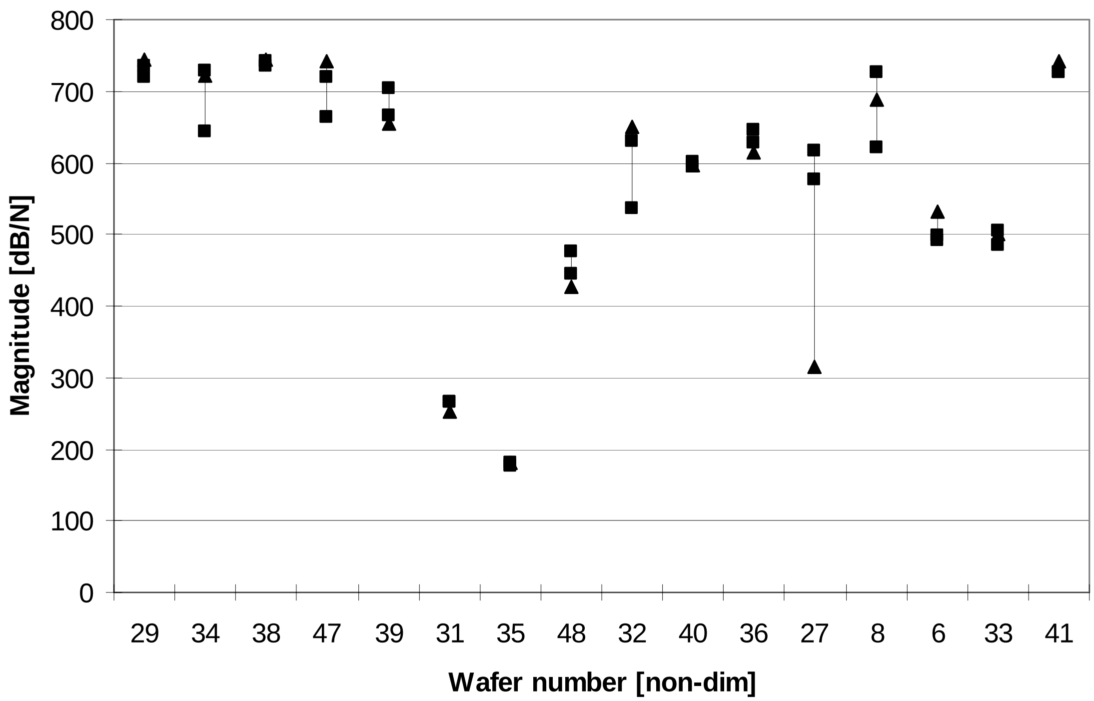

Figure C.9 First mode peak magnitude for large crack wafer set

Appendix C (Continued)

Table C.10 Second mode peak magnitude for large crack wafer set

Specimen number	Test 1 [dB/N]	Test 2 [dB/N]	Test 3 [dB/N]	Mean [dB/N]
29	907.7	992.4	978.4	959.5
34	976.4	894.9	960.0	943.8
38	1025.3	944.5	935.7	968.5
47	899.9	922.8	990.8	937.8
39	848.5	722.9	754.3	775.2
31	487.0	468.5	487.1	480.8
35	398.1	397.3	402.7	399.4
48	801.1	730.8	666.7	732.9
32	805.4	736.4	735.7	759.2
40	674.5	709.6	684.8	689.7
36	711.5	718.0	691.6	707.0
27	949.1	967.9	591.4	836.1
8	1005.9	860.8	919.0	928.6
6	923.2	979.0	946.8	949.7
33	887.6	835.7	870.5	864.6
41	903.0	824.1	826.0	851.0

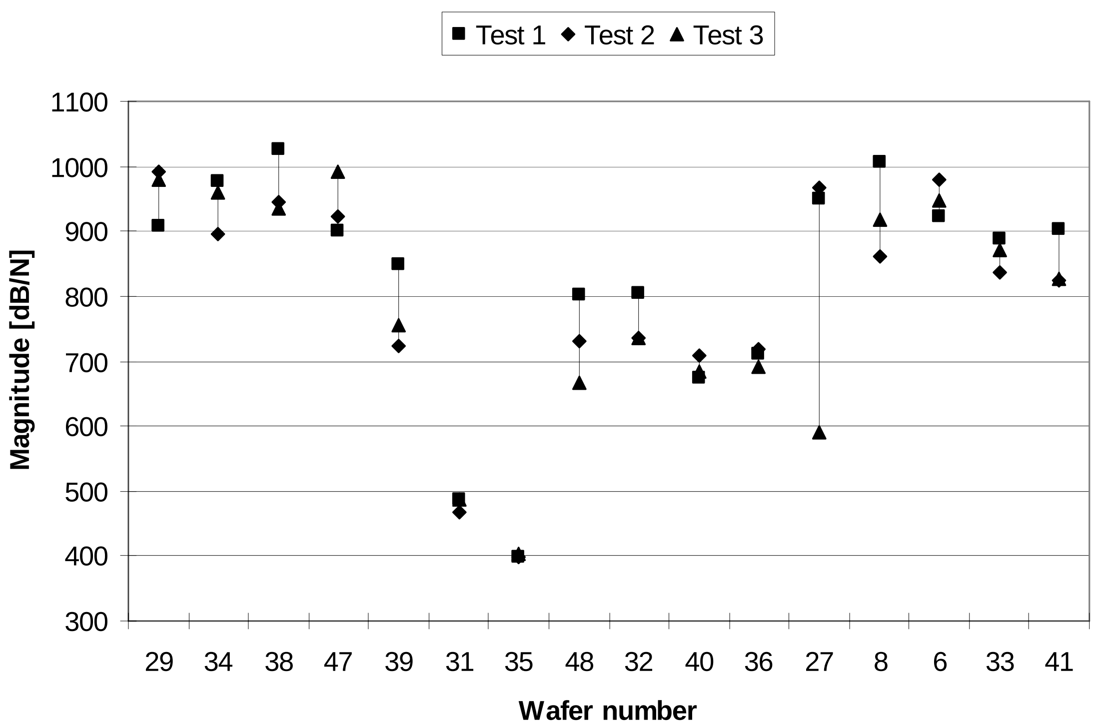

Figure C.10 Second mode peak magnitude for large crack wafer set

Table C.11 Third mode peak magnitude for large crack wafer set

Specimen number	Test 1 [dB/N]	Test 2 [dB/N]	Test 3 [dB/N]	Mean [dB/N]
29	818.8	859.1	799.1	825.6
34	845.6	796.8	821.6	821.3
38	968.4	879.3	865.2	904.3
47	766.3	771.5	827.7	788.5
39	769.4	715.2	687.6	724.1
31	828.8	271.4	304.9	468.4
35	403.3	405.1	394.0	400.8
48	685.3	581.5	517.1	594.6
32	789.0	757.5	774.9	773.8
40	924.9	845.2	816.5	862.2
36	783.7	774.6	755.6	771.3
27	972.8	969.4	379.6	773.9
8	873.5	688.6	734.6	765.6
6	684.1	700.0	685.0	689.7
33	658.1	637.4	638.9	644.8
41	813.0	780.2	816.5	803.2

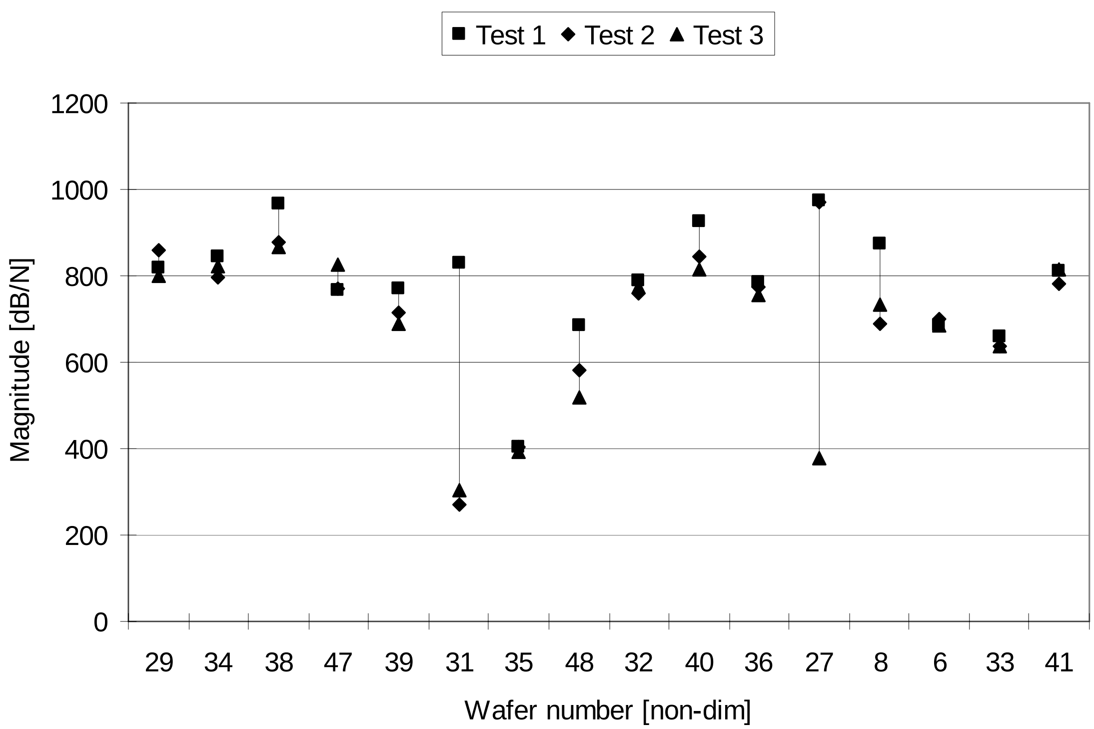

Figure C.11 Third mode magnitude for large crack wafer set

Table C.12 Fourth mode peak magnitude for large crack wafer set

Specimen number	Test 1 [dB/N]	Test 2 [dB/N]	Test 3 [dB/N]	Mean [dB/N]
29	289.8	319.2	299.7	302.9
34	292.2	318.4	297.6	302.8
38	368.9	291.3	308.8	323.0
47	288.0	289.8	275.5	284.5
39	245.7	232.1	219.4	232.4
31	174.9	165.3	202.8	181.0
35	181.9	187.2	193.3	187.5
48	224.1	219.6	236.1	226.6
32	339.9	294.6	276.5	303.7
40	298.2	261.9	279.8	280.0
36	278.7	260.0	282.9	273.9
27	195.2	202.1	268.7	222.0
8	320.2	291.5	252.8	288.1
6	308.7	305.3	308.0	307.3
33	369.1	341.8	345.6	352.2
41	257.9	248.4	248.0	251.4

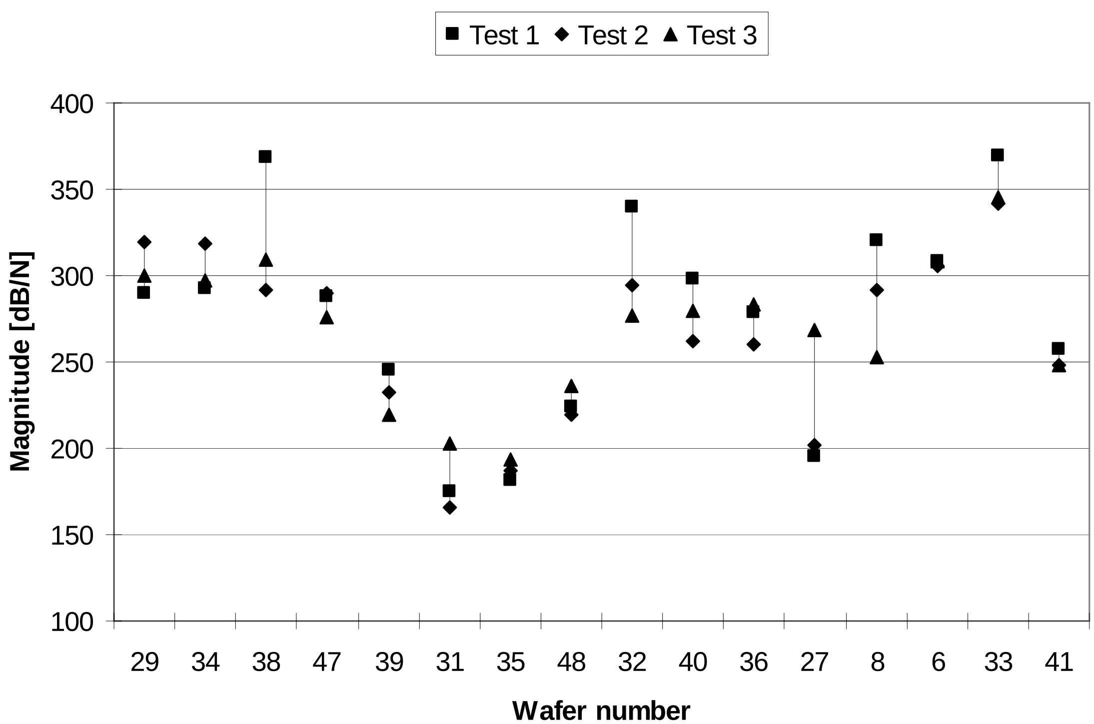

Figure C.12 Fourth mode peak magnitude for large crack wafer set

Appendix C (Continued)

Table C.13 First mode damping ratio for large crack wafer set

Specimen number	Test 1 [non-dim]	Test 2 [non-dim]	Test 3 [non-dim]	Mean [non-dim]
29	0.0025	0.0024	0.0024	0.0024
34	0.0026	0.0029	0.0025	0.0027
38	0.0026	0.0024	0.0025	0.0025
47	0.0026	0.0024	0.0023	0.0024
39	0.0024	0.0027	0.0025	0.0025
31	0.0086	0.0086	0.0087	0.0086
35	0.0091	0.0094	0.0091	0.0092
48	0.0034	0.0040	0.0040	0.0038
32	0.0033	0.0028	0.0026	0.0029
40	0.0025	0.0027	0.0025	0.0026
36	0.0026	0.0027	0.0027	0.0027
27	0.0026	0.0025	0.0054	0.0035
8	0.0024	0.0027	0.0026	0.0026
6	0.0023	0.0024	0.0024	0.0024
33	0.0031	0.0033	0.0033	0.0032
41	0.0024	0.0025	0.0023	0.0024

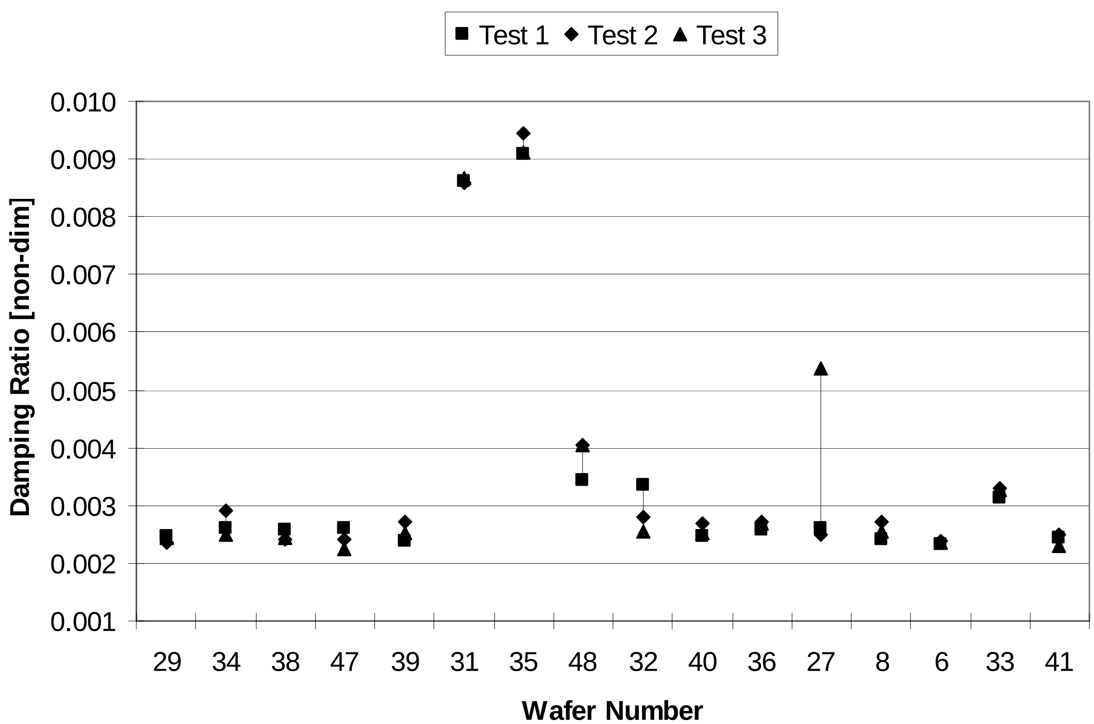

Figure C.13 First mode damping ratio for large crack wafer set

Table C.14 Second mode damping ratio for large crack wafer set

Specimen number	Test 1 [non-dim]	Test 2 [non-dim]	Test 3 [non-dim]	Mean [non-dim]
29	0.0015	0.0014	0.0016	0.0015
34	0.0015	0.0016	0.0015	0.0016
38	0.0015	0.0015	0.0016	0.0015
47	0.0015	0.0016	0.0014	0.0015
39	0.0016	0.0018	0.0016	0.0017
31	0.0049	0.0054	0.0052	0.0052
35	0.0044	0.0047	0.0046	0.0046
48	0.0032	0.0033	0.0036	0.0034
32	0.0015	0.0018	0.0020	0.0018
40	0.0020	0.0019	0.0019	0.0019
36	0.0019	0.0021	0.0021	0.0020
27	0.0020	0.0019	0.0036	0.0025
8	0.0015	0.0017	0.0016	0.0016
6	0.0016	0.0015	0.0016	0.0016
33	0.0017	0.0018	0.0018	0.0017
41	0.0015	0.0016	0.0015	0.0015

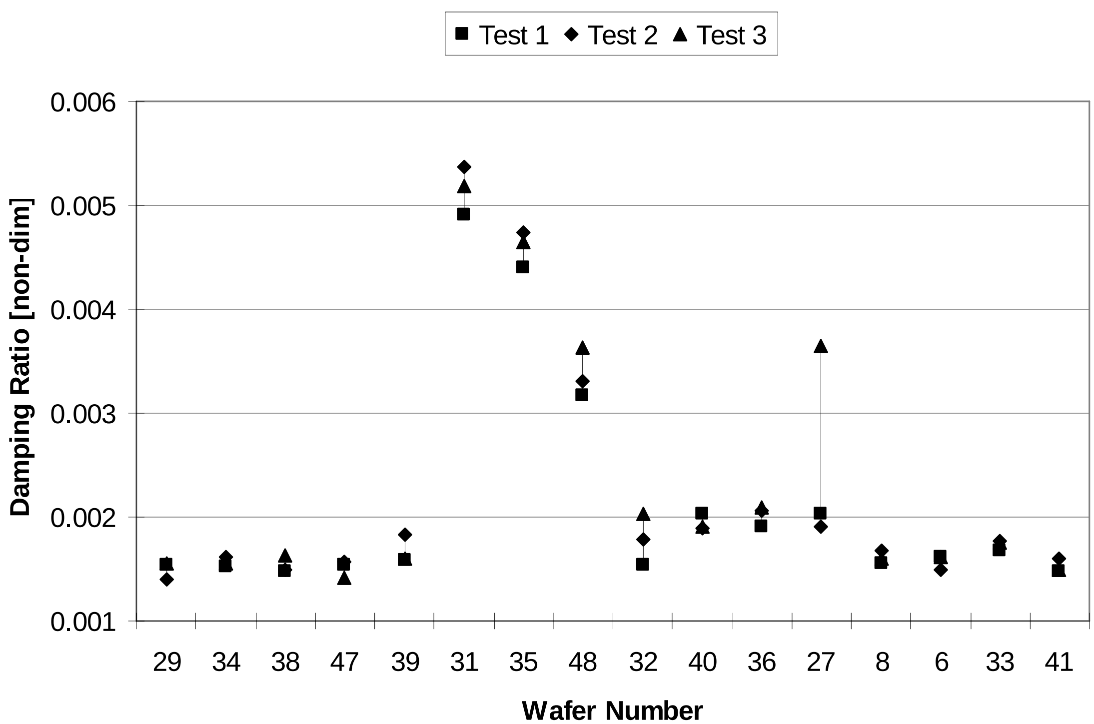

Figure C.14 Second mode damping ratio for large crack wafer set

Table C.15 Third mode damping ratio for large crack wafer set

Specimen number	Test 1 [non-dim]	Test 2 [non-dim]	Test 3 [non-dim]	Mean [non-dim]
29	0.0013	0.0013	0.0013	0.0013
34	0.0013	0.0014	0.0013	0.0013
38	0.0013	0.0013	0.0013	0.0013
47	0.0014	0.0013	0.0012	0.0013
39	0.0013	0.0014	0.0013	0.0013
31	0.0030	0.0037	0.0021	0.0029
35	0.0034	0.0034	0.0034	0.0034
48	0.0018	0.0019	0.0022	0.0020
32	0.0014	0.0014	0.0014	0.0014
40	0.0013	0.0012	0.0013	0.0013
36	0.0013	0.0013	0.0014	0.0013
27	0.0014	0.0014	0.0016	0.0014
8	0.0013	0.0015	0.0013	0.0014
6	0.0014	0.0015	0.0013	0.0014
33	0.0012	0.0013	0.0012	0.0013
41	0.0013	0.0013	0.0012	0.0013

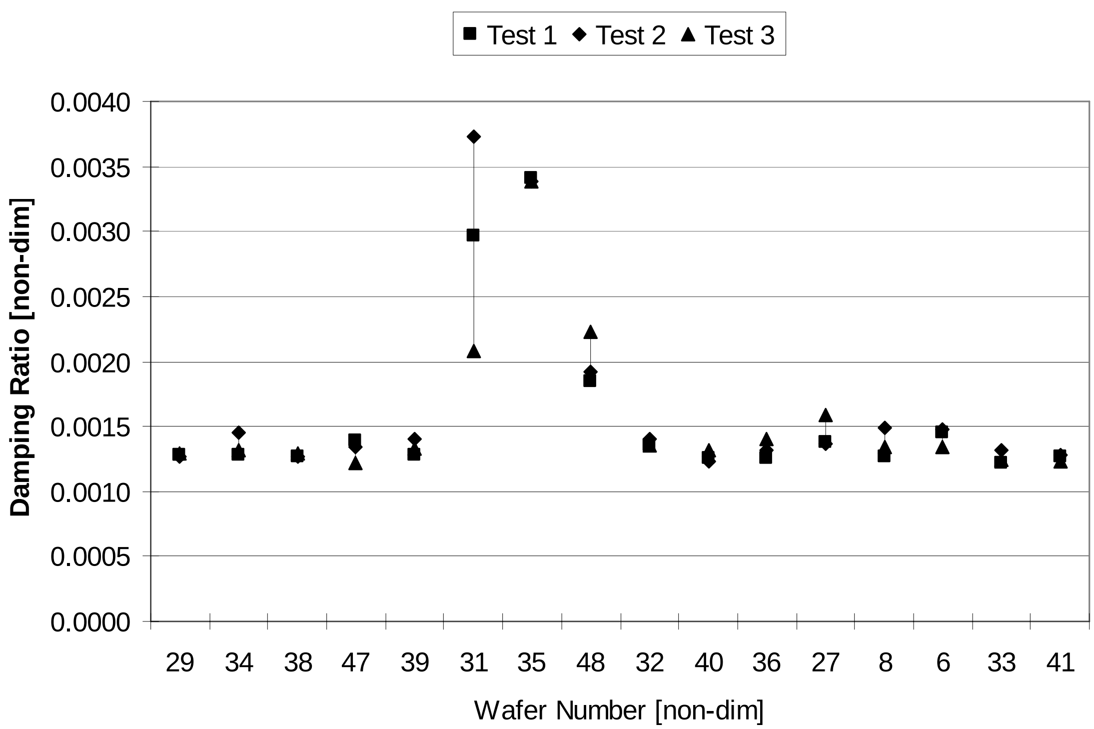

Figure C.15 Third mode damping ratio for large crack wafer set

Appendix C (Continued)

Table C.16 Fourth mode damping ratio for large crack wafer set

Specimen number	Test 1 [non-dim]	Test 2 [non-dim]	Test 3 [non-dim]	Mean [non-dim]
29	0.0014	0.0014	0.0013	0.0014
34	0.0014	0.0013	0.0014	0.0014
38	0.0014	0.0013	0.0015	0.0014
47	0.0013	0.0013	0.0014	0.0013
39	0.0015	0.0016	0.0015	0.0015
31	0.0037	0.0038	0.0034	0.0036
35	0.0032	0.0033	0.0033	0.0033
48	0.0029	0.0029	0.0028	0.0029
32	0.0016	0.0017	0.0017	0.0016
40	0.0020	0.0020	0.0020	0.0020
36	0.0019	0.0019	0.0019	0.0019
27	0.0019	0.0020	0.0030	0.0023
8	0.0013	0.0013	0.0013	0.0013
6	0.0017	0.0018	0.0018	0.0018
33	0.0016	0.0018	0.0018	0.0017
41	0.0014	0.0013	0.0014	0.0014

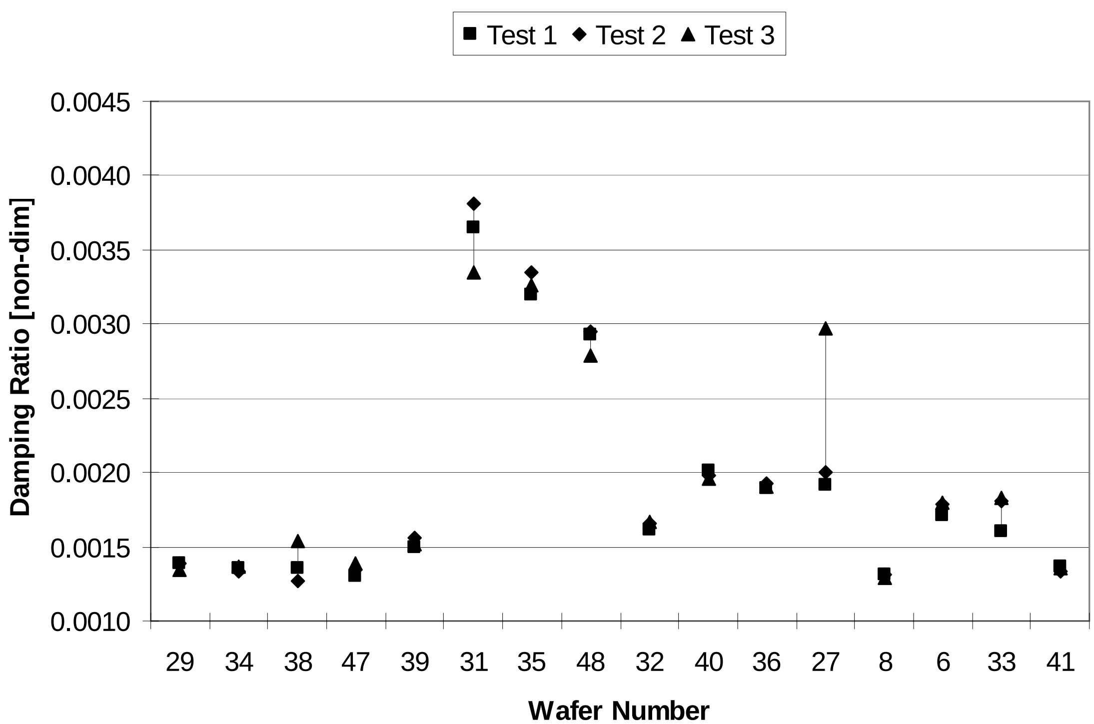

Figure C.16 Fourth mode damping ratio for large crack wafer set

Appendix D: Data from the miscellaneous wafer set

Table D.1 First mode natural frequency for miscellaneous wafer set

Wafer number	Test 1 [Hz]	Test 2 [Hz]	Average [Hz]
20	418.8	418.8	418.8
42	402.2	401.3	401.7
49	402.2	402.2	402.2
2	405.0	405.0	405.0
11	417.2	417.5	417.3
23	381.9	373.1	377.5
25	420.0	420.0	420.0
45	417.5	417.8	417.7
46	416.3	417.2	416.7
7	401.6	401.9	401.7
47	402.2	401.9	402.0
8	391.9	390.3	391.1

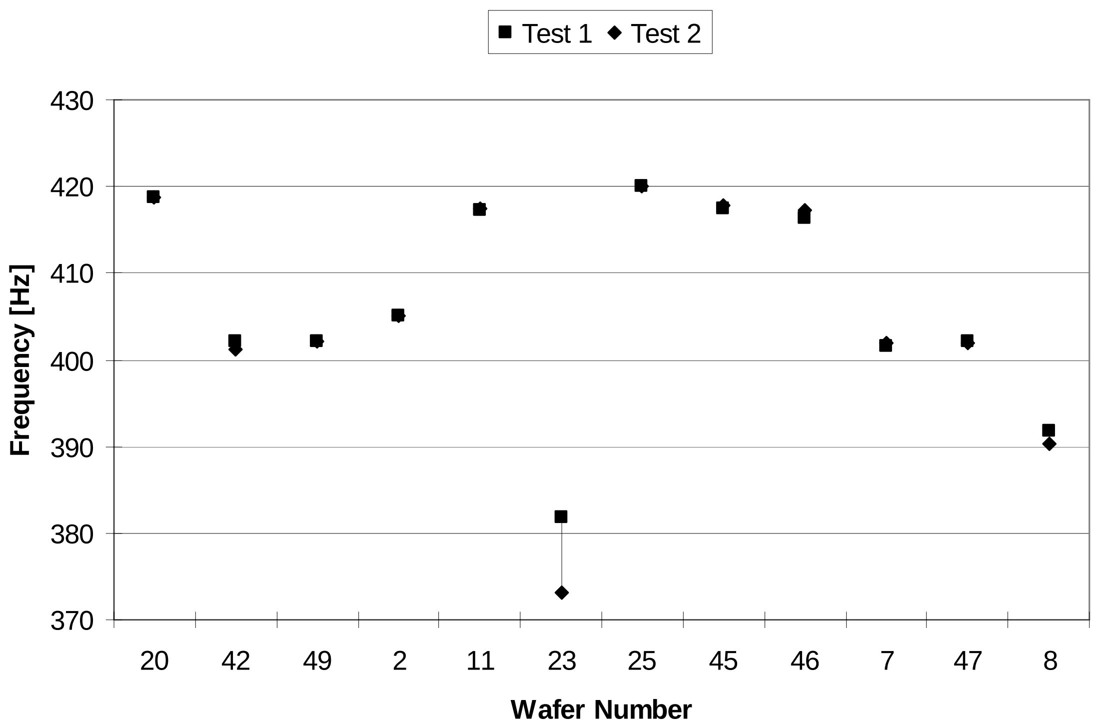

Figure D.1 First mode natural frequency for miscellaneous wafer set

Appendix D (Continued)

Table D.2 First mode normalized frequency for miscellaneous wafer set

Wafer number	Test 1 [Hz/μm^(3/2)]	Test 2 [Hz/μm^(3/2)]	Average [Hz/μm^(3/2)]
20	0.0784	0.0784	0.0784
42	0.0802	0.0800	0.0801
49	0.0799	0.0799	0.0799
2	0.0799	0.0799	0.0799
11	0.0783	0.0783	0.0783
23	0.0714	0.0698	0.0706
25	0.0787	0.0787	0.0787
45	0.0780	0.0781	0.0780
46	0.0779	0.0781	0.0780
7	0.0797	0.0797	0.0797
47	0.0801	0.0800	0.0800
8	0.0776	0.0773	0.0775

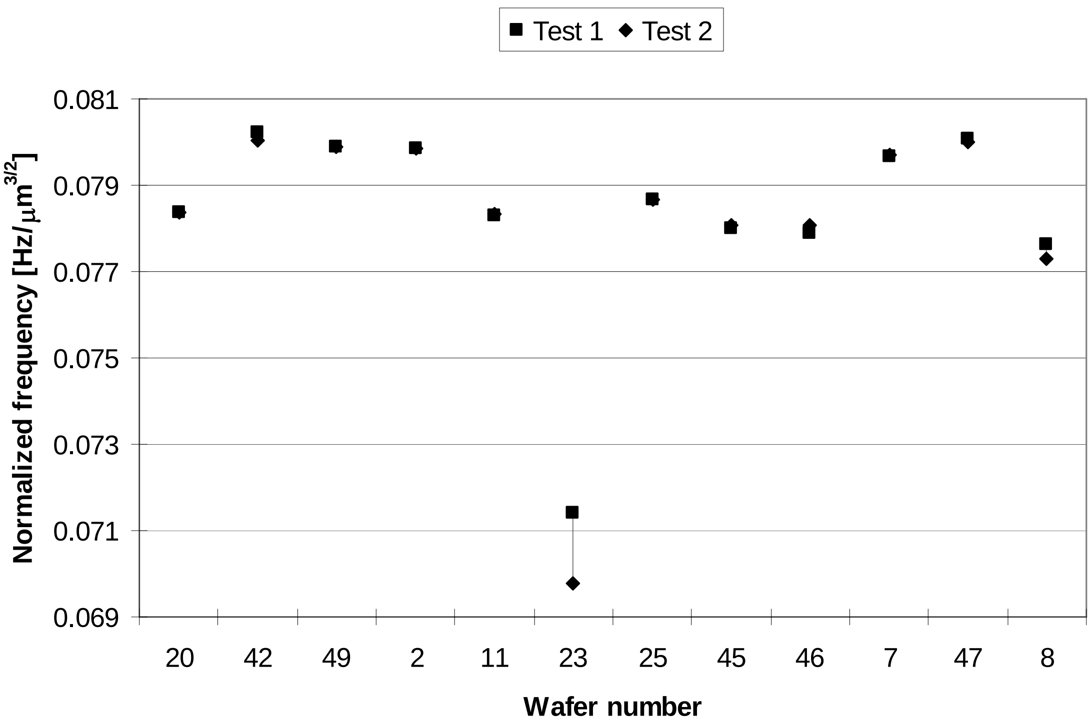

Figure D.2 First mode normalized frequency for miscellaneous wafer set

Appendix D (Continued)

Table D.3 Second mode natural frequency for miscellaneous wafer set

Wafer number	Test 1 [Hz]	Test 2 [Hz]	Average [Hz]
20	592.8	592.8	592.8
42	569.1	569.1	569.1
49	570.3	570.3	570.3
2	573.1	573.4	573.3
11	591.9	592.2	592.0
23	559.7	557.5	558.6
25	591.3	592.2	591.7
45	593.1	593.1	593.1
46	592.2	592.5	592.3
7	569.1	569.1	569.1
47	566.9	565.0	565.9
8	555.6	554.7	555.2

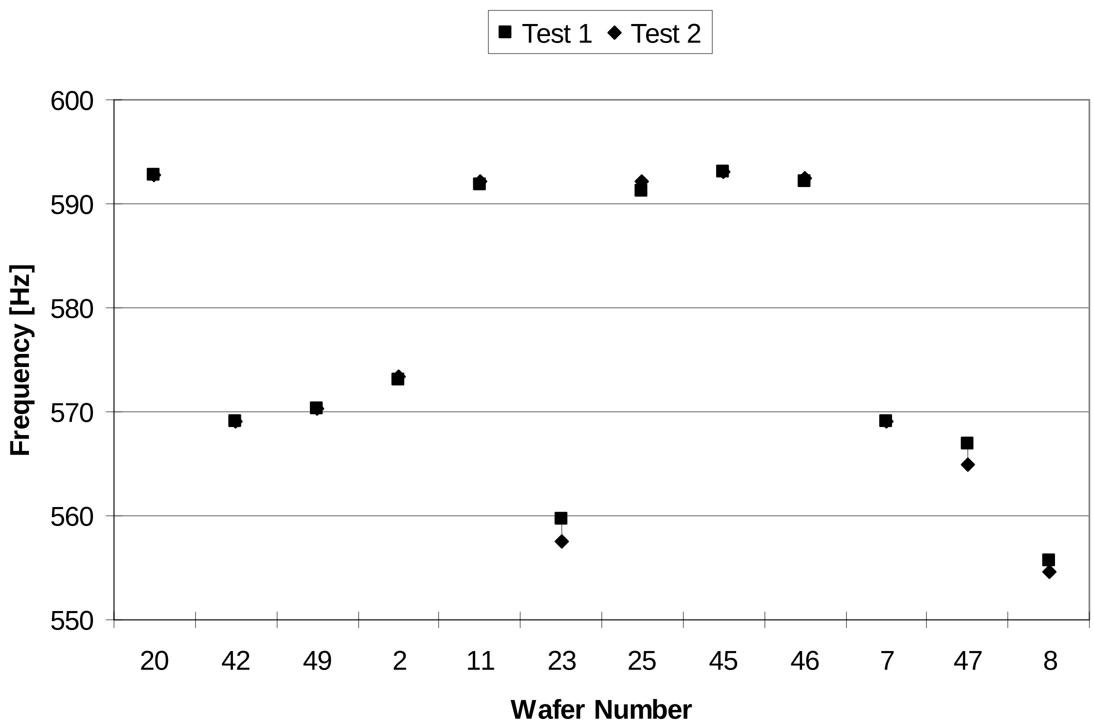

Figure D.3 Second mode natural frequency for miscellaneous wafer set

Table D.4 Second mode normalized frequency for miscellaneous wafer set

Wafer number	Test 1 [Hz/µm^(3/2)]	Test 2 [Hz/µm^(3/2)]	Average [Hz/µm^(3/2)]
20	0.1110	0.1110	0.1110
42	0.1135	0.1135	0.1135
49	0.1133	0.1133	0.1133
2	0.1130	0.1131	0.1130
11	0.1111	0.1111	0.1111
23	0.1047	0.1043	0.1045
25	0.1107	0.1109	0.1108
45	0.1108	0.1108	0.1108
46	0.1108	0.1109	0.1109
7	0.1129	0.1129	0.1129
47	0.1129	0.1125	0.1127
8	0.1100	0.1099	0.1100

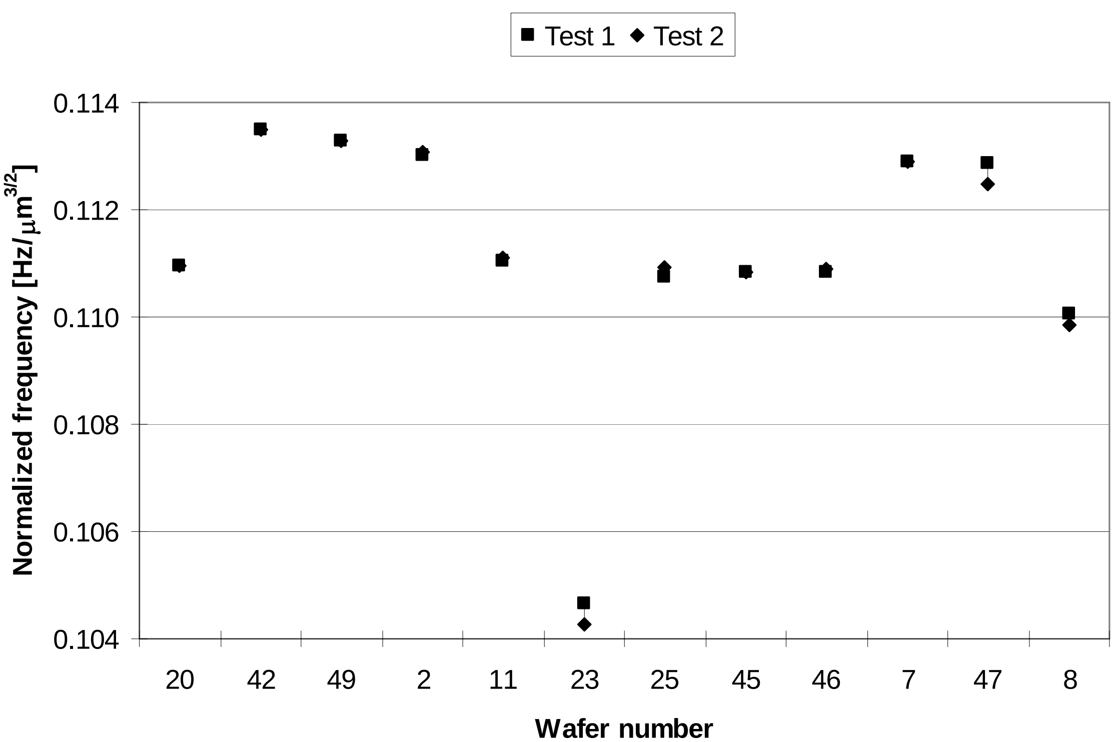

Figure D.4 Second mode normalized frequency for miscellaneous wafer set

Appendix D (Continued)

Table D.5 Third mode natural frequency for miscellaneous wafer set

Wafer number	Test 1 [Hz]	Test 2 [Hz]	Average [Hz]
20	841.3	840.9	841.1
42	805.9	806.3	806.1
49	807.8	807.8	807.8
2	811.9	811.9	811.9
11	839.7	839.7	839.7
23	820.9	820.6	820.8
25	842.5	842.2	842.3
45	843.1	843.1	843.1
46	841.9	842.2	842.0
7	805.9	805.9	805.9
47	805.6	805.3	805.5
8	801.3	800.0	800.6

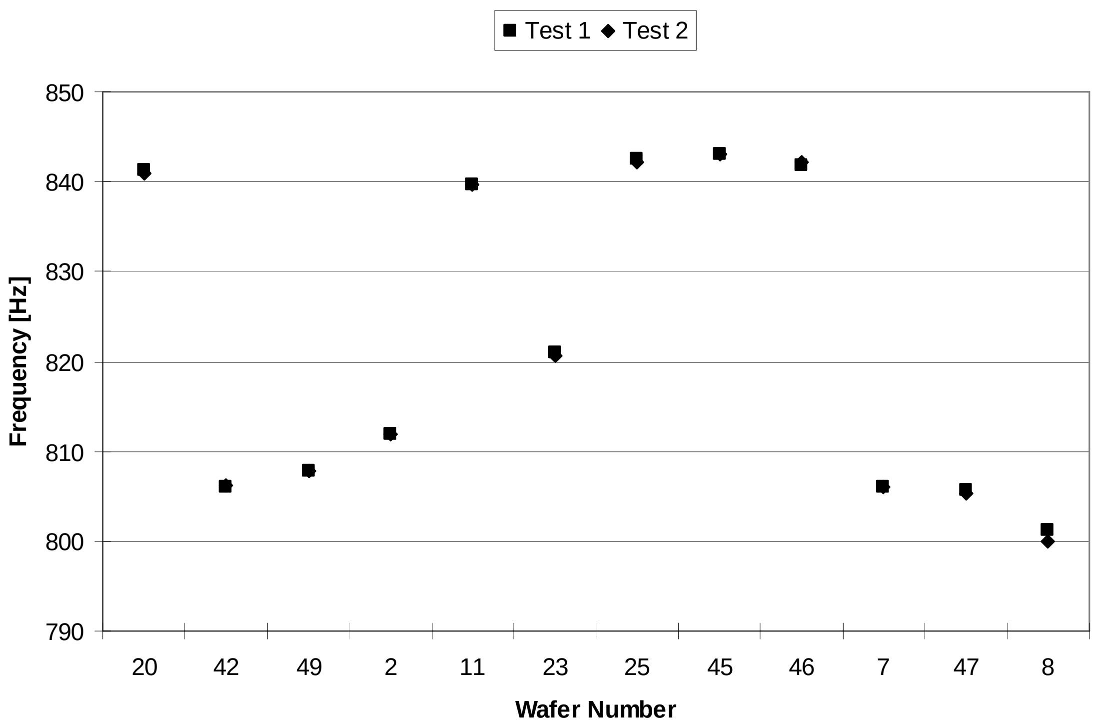

Figure D.5 Third mode natural frequency for miscellaneous wafer set

Appendix D (Continued)

Table D.6 Third mode normalized frequency for miscellaneous wafer set

Wafer number	Test 1 [Hz/μm^(3/2)]	Test 2 [Hz/μm^(3/2)]	Average [Hz/μm^(3/2)]
20	0.1575	0.1574	0.1574
42	0.1607	0.1608	0.1608
49	0.1604	0.1604	0.1604
2	0.1601	0.1601	0.1601
11	0.1576	0.1576	0.1576
23	0.1535	0.1535	0.1535
25	0.1578	0.1578	0.1578
45	0.1575	0.1575	0.1575
46	0.1576	0.1576	0.1576
7	0.1599	0.1599	0.1599
47	0.1604	0.1603	0.1604
8	0.1587	0.1584	0.1586

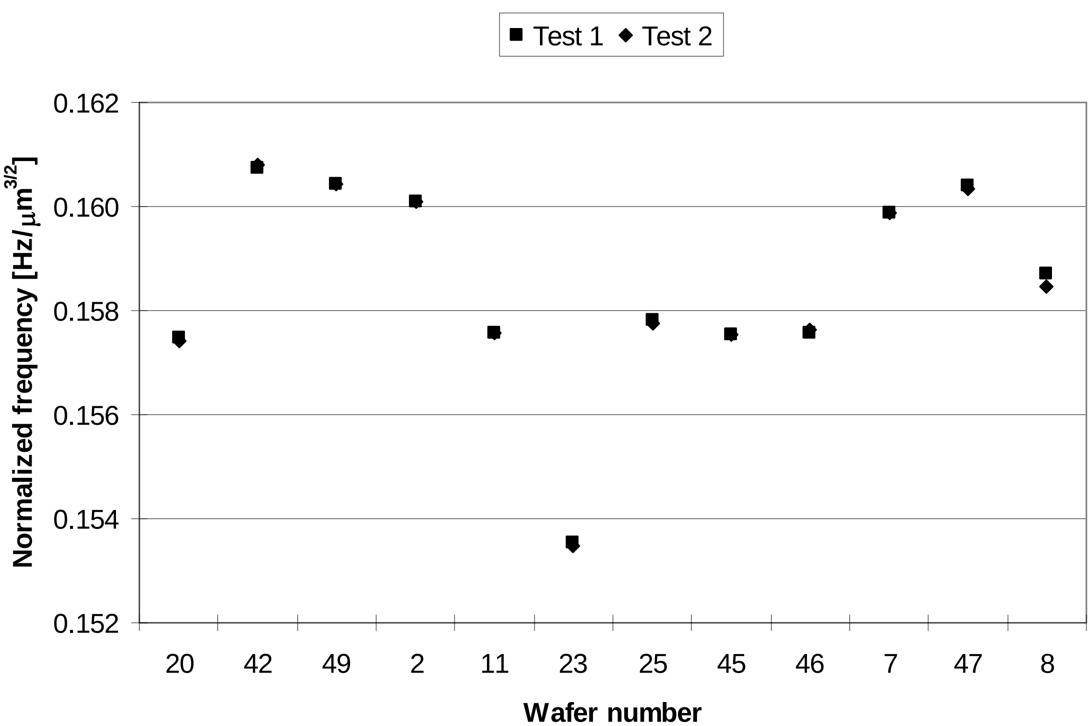

Figure D.6 Third mode normalized frequency for miscellaneous wafer set

Table D.7 Fourth mode natural frequency for miscellaneous wafer set

Wafer number	Test 1 [Hz]	Test 2 [Hz]	Average [Hz]
20	962.8	962.8	962.8
42	925.0	924.1	924.5
49	926.3	925.9	926.1
2	931.6	931.6	931.6
11	960.9	961.3	961.1
23	920.0	918.1	919.1
25	959.7	959.7	959.7
45	959.7	959.7	959.7
46	958.8	959.4	959.1
7	923.4	923.1	923.3
47	919.7	916.6	918.1
8	923.1	922.2	922.7

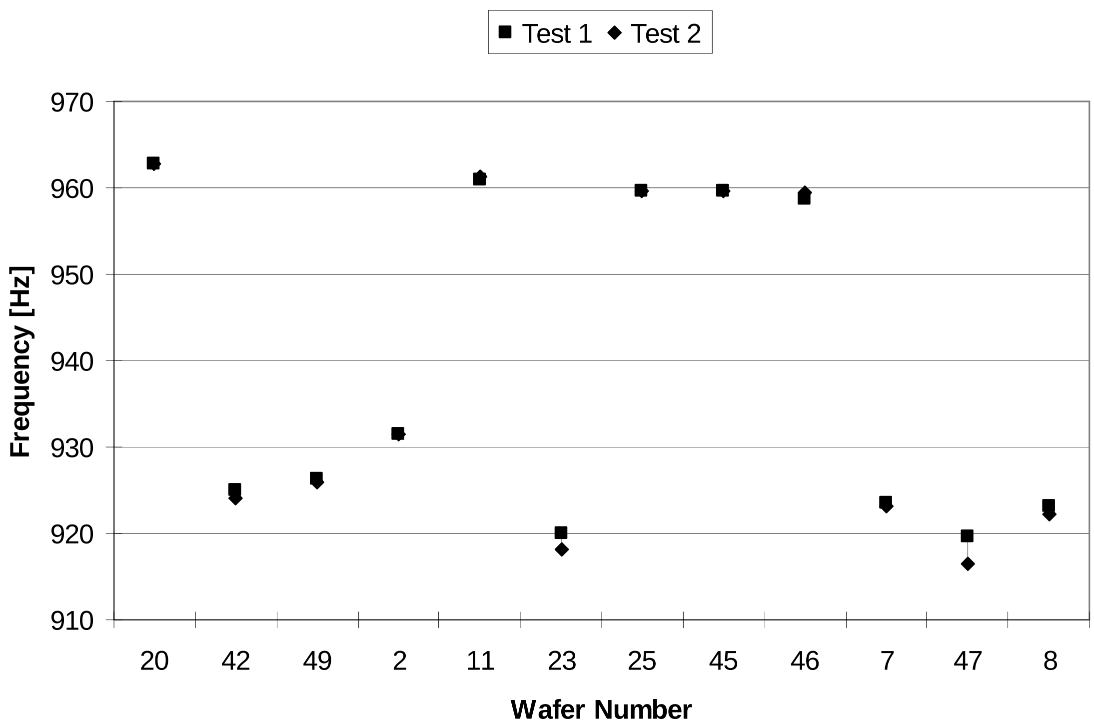

Figure D.7 Fourth mode natural frequency for miscellaneous wafer set

Table D.8 Fourth mode normalized frequency for miscellaneous wafer set

Wafer number	Test 1 [Hz/μm^(3/2)]	Test 2 [Hz/μm^(3/2)]	Average [Hz/μm^(3/2)]
20	0.1802	0.1802	0.1802
42	0.1845	0.1843	0.1844
49	0.1840	0.1839	0.1839
2	0.1837	0.1837	0.1837
11	0.1803	0.1804	0.1803
23	0.1721	0.1717	0.1719
25	0.1798	0.1798	0.1798
45	0.1793	0.1793	0.1793
46	0.1794	0.1796	0.1795
7	0.1832	0.1831	0.1831
47	0.1831	0.1825	0.1828
8	0.1828	0.1826	0.1827

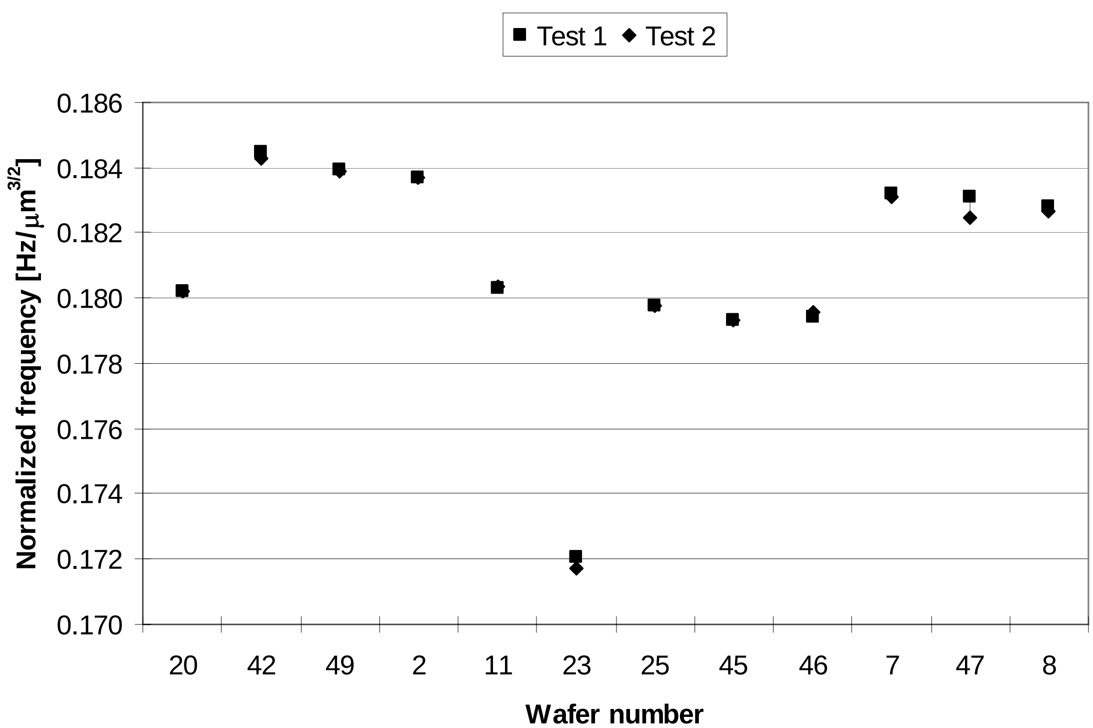

Figure D.8 Fourth mode normalized frequency for miscellaneous wafer set

Table D.9 First mode peak magnitude for miscellaneous wafer set

Wafer number	Test 1 [dB/N]	Test 2 [dB/N]	Average [dB/N]
20	606.7	636.5	621.6
42	676.2	489.9	583.0
49	464.0	425.1	444.6
2	693.8	691.0	692.4
11	671.3	601.0	636.2
23	180.8	189.0	184.9
25	388.2	585.4	486.8
45	779.8	704.3	742.1
46	600.4	620.0	610.2
7	605.3	652.4	628.9
47	480.2	394.2	437.2
8	316.4	279.3	297.8

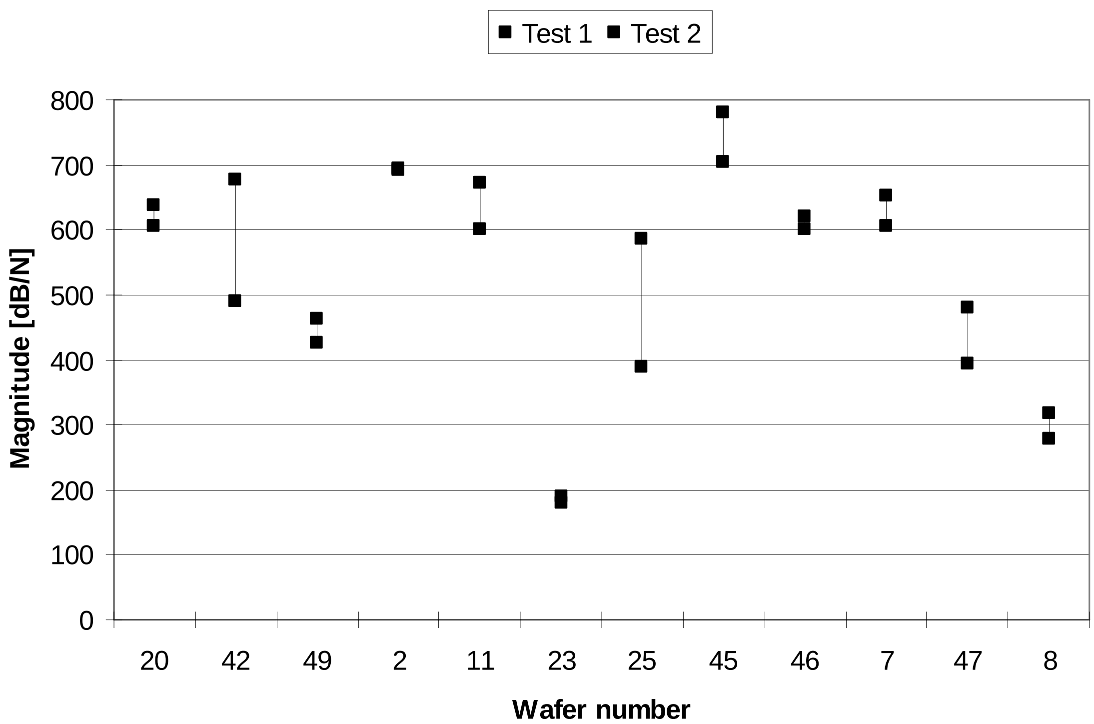

Figure D.9 First mode peak magnitude for miscellaneous wafer set

Appendix D (Continued)

Table D.10 Second mode peak magnitude for miscellaneous wafer set

Wafer number	Test 1 [dB/N]	Test 2 [dB/N]	Average [dB/N]
20	930.1	964.9	947.5
42	949.3	927.2	938.2
49	976.3	944.2	960.3
2	959.9	1009.6	984.7
11	940.0	863.3	901.7
23	522.8	638.1	580.5
25	386.5	370.7	378.6
45	836.3	785.2	810.7
46	692.1	624.5	658.3
7	1027.7	995.9	1011.8
47	701.4	543.3	622.3
8	555.6	590.2	572.9

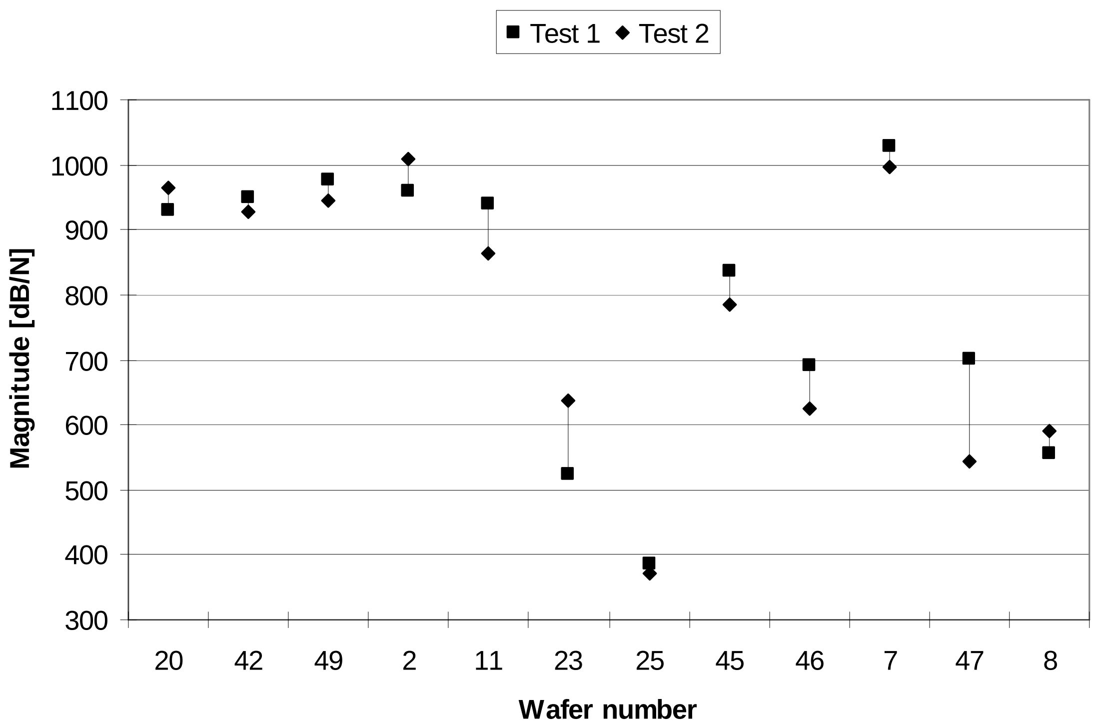

Figure D.10 Second mode peak magnitude for miscellaneous wafer set

Table D.11 Third mode peak magnitude for miscellaneous wafer set

Wafer number	Test 1 [dB/N]	Test 2 [dB/N]	Average [dB/N]
20	784.9	901.4	843.1
42	528.9	700.6	614.7
49	391.3	386.8	389.1
2	512.2	509.6	510.9
11	827.1	756.8	792.0
23	180.6	171.6	176.1
25	506.2	651.2	578.7
45	783.1	756.3	769.7
46	796.9	872.0	834.4
7	566.3	644.4	605.4
47	675.0	619.1	647.1
8	490.0	421.2	455.6

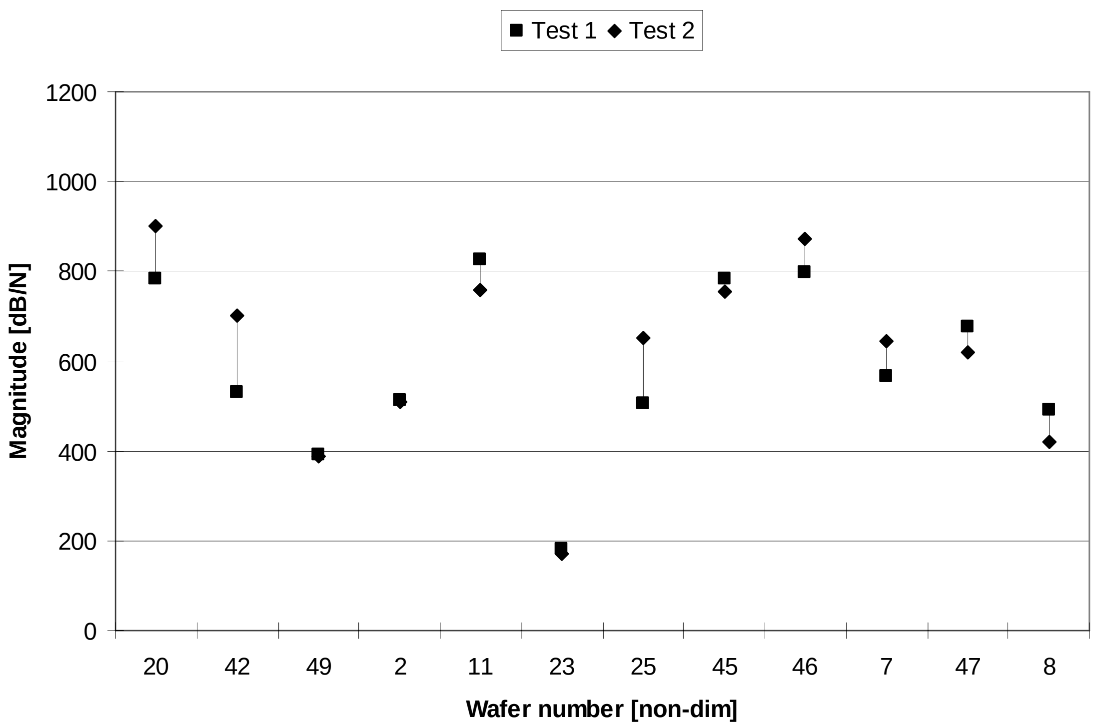

Figure D.11 Third mode peak magnitude for miscellaneous wafer set

Table D.12 Fourth mode peak magnitude for miscellaneous wafer set

Wafer number	Test 1 [dB/N]	Test 2 [dB/N]	Average [dB/N]
20	314.8	346.6	330.7
42	219.3	294.0	256.6
49	200.3	253.7	227.0
2	151.9	164.9	158.4
11	280.1	278.8	279.4
23	368.2	390.1	379.2
25	218.5	224.8	221.7
45	209.6	228.4	219.0
46	253.5	242.7	248.1
7	130.6	155.5	143.0
47	198.0	135.9	167.0
8	159.0	167.8	163.4

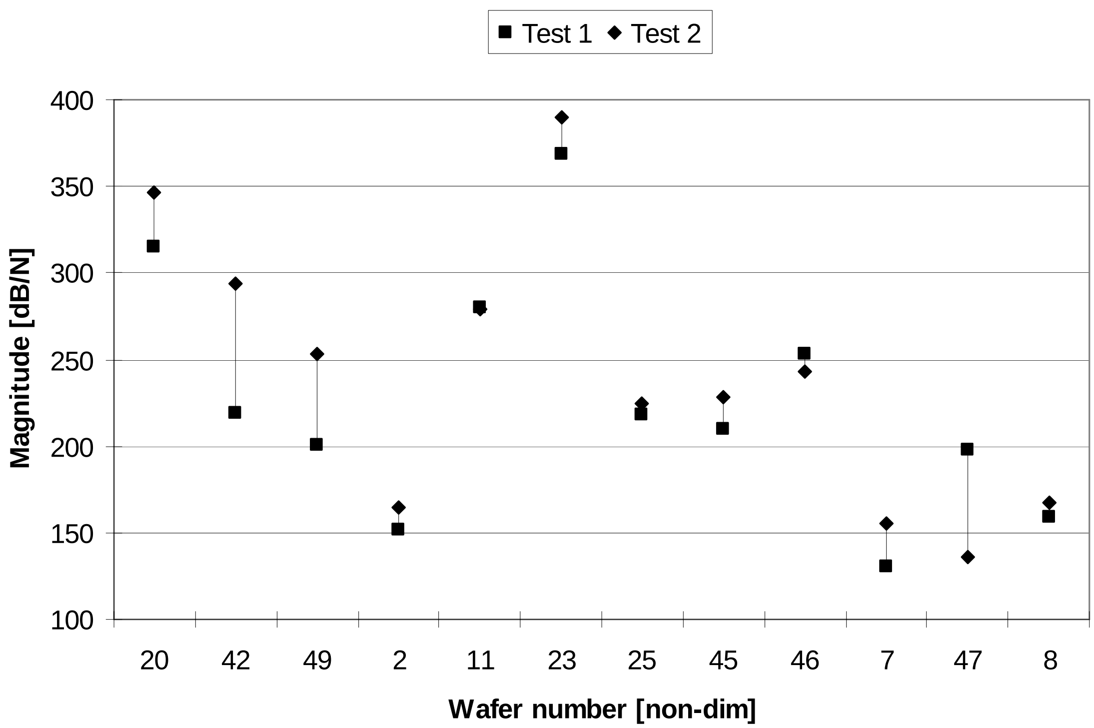

Figure D.12 Fourth mode peak magnitude for miscellaneous wafer set

Appendix D (Continued)

Table D.13 First mode damping ratio for miscellaneous wafer set

Wafer number	Test 1 [non-dim]	Test 2 [non-dim]	Average [non-dim]
20	0.0029	0.0028	0.0028
42	0.0028	0.0041	0.0034
49	0.0041	0.0044	0.0043
2	0.0024	0.0025	0.0024
11	0.0026	0.0023	0.0025
23	0.0073	0.0083	0.0078
25	0.0037	0.0027	0.0032
45	0.0024	0.0025	0.0025
46	0.0017	0.0024	0.0021
7	0.0025	0.0023	0.0024
47	0.0029	0.0032	0.0031
8	0.0050	0.0059	0.0054

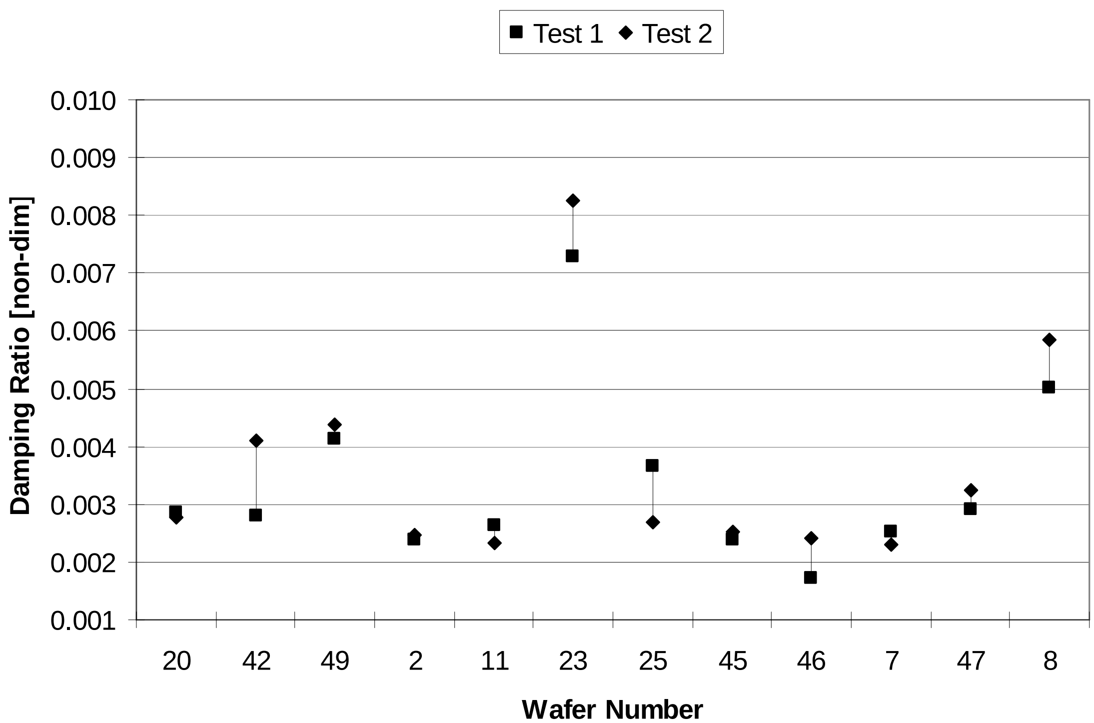

Figure D.13 First mode damping ratio for miscellaneous wafer set

Table D.14 Second mode damping ratio for miscellaneous wafer set

Wafer number	Test 1 [non-dim]	Test 2 [non-dim]	Average [non-dim]
20	0.0015	0.0015	0.0015
42	0.0016	0.0016	0.0016
49	0.0016	0.0015	0.0015
2	0.0015	0.0014	0.0014
11	0.0015	0.0015	0.0015
23	0.0039	0.0025	0.0032
25	0.0034	0.0041	0.0037
45	0.0017	0.0015	0.0016
46	0.0017	0.0017	0.0017
7	0.0016	0.0015	0.0015
47	0.0023	0.0030	0.0027
8	0.0034	0.0038	0.0036

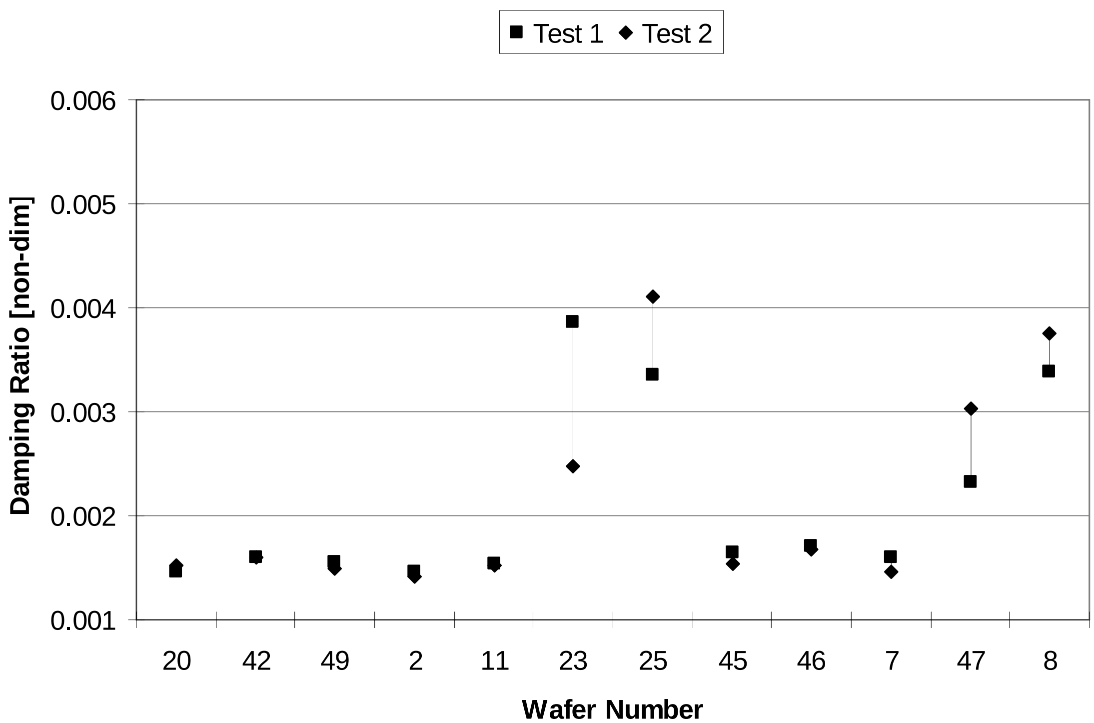

Figure D.14 Second mode damping ratio for miscellaneous wafer set

Appendix D (Continued)

Table D.15 Third mode damping ratio for miscellaneous wafer set

Wafer number	Test 1 [non-dim]	Test 2 [non-dim]	Average [non-dim]
20	0.0013	0.0014	0.0013
42	0.0014	0.0016	0.0015
49	0.0016	0.0017	0.0017
2	0.0014	0.0013	0.0013
11	0.0013	0.0012	0.0013
23	0.0024	0.0020	0.0022
25	0.0018	0.0015	0.0016
45	0.0013	0.0013	0.0013
46	0.0014	0.0013	0.0013
7	0.0014	0.0014	0.0014
47	0.0015	0.0015	0.0015
8	0.0017	0.0019	0.0018

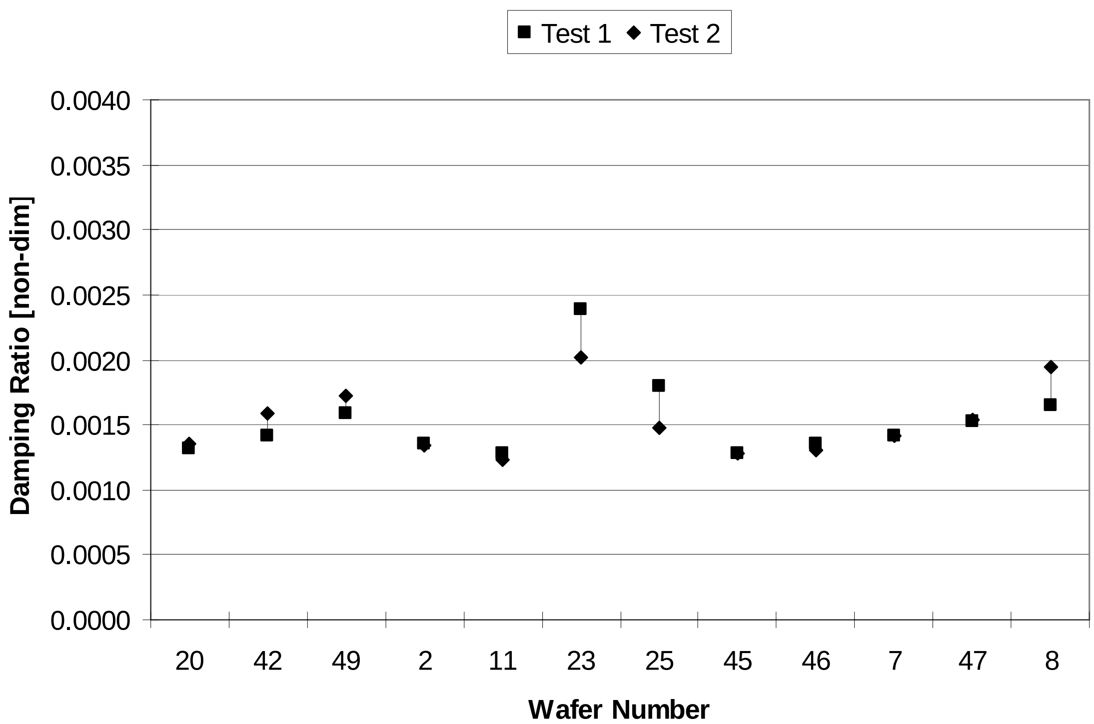

Figure D.15 Third mode damping ratio for miscellaneous wafer set

Appendix D (Continued)

Table D.16 Fourth mode damping ratio for miscellaneous wafer set

Wafer number	Test 1 [non-dim]	Test 2 [non-dim]	Average [non-dim]
20	0.0012	0.0013	0.0013
42	0.0018	0.0017	0.0018
49	0.0019	0.0017	0.0018
2	0.0019	0.0018	0.0019
11	0.0013	0.0013	0.0013
23	0.0024	0.0018	0.0021
25	0.0021	0.0021	0.0021
45	0.0017	0.0016	0.0017
46	0.0015	0.0015	0.0015
7	0.0031	0.0035	0.0033
47	0.0026	0.0040	0.0033
8	0.0018	0.0018	0.0018

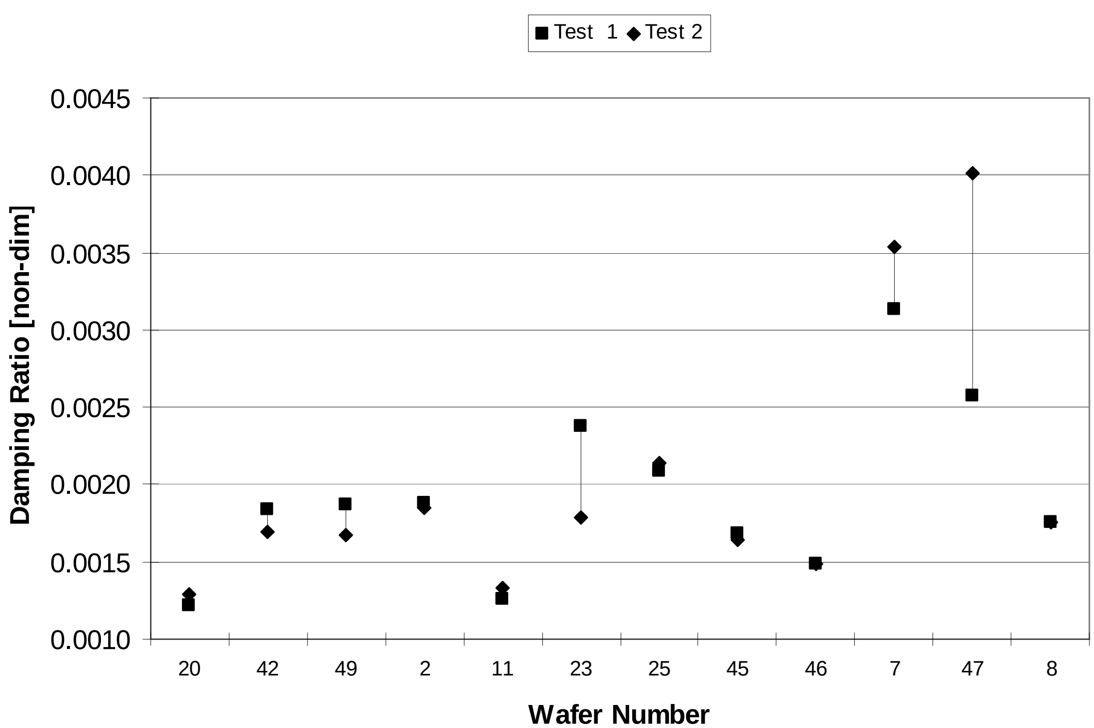

Figure D.16 Fourth mode damping ratio for miscellaneous wafer set

Appendix E: Data from the small crack wafer set

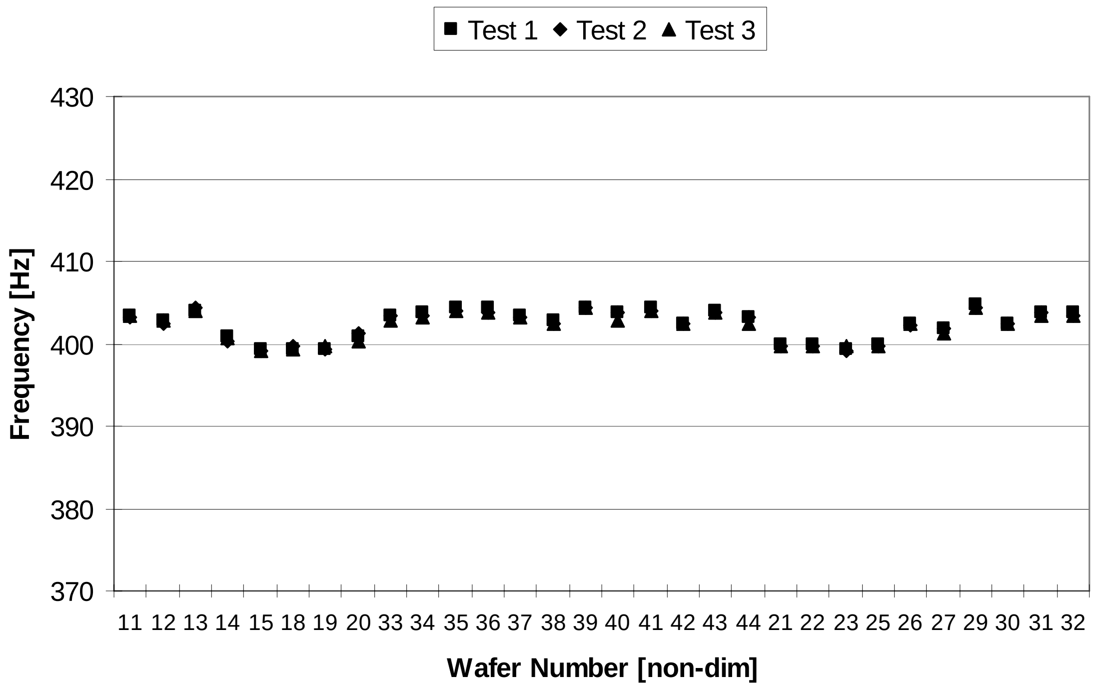

Figure E.1 First mode natural frequency for small crack wafer set

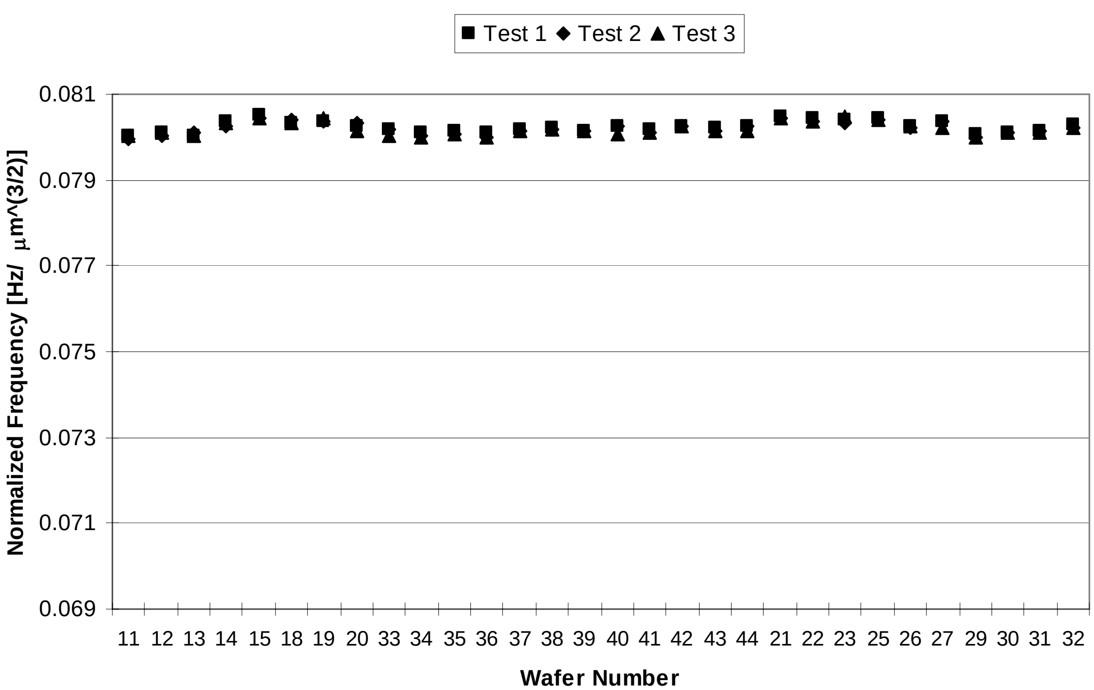

Figure E.2 First mode normalized frequency for small crack wafer set

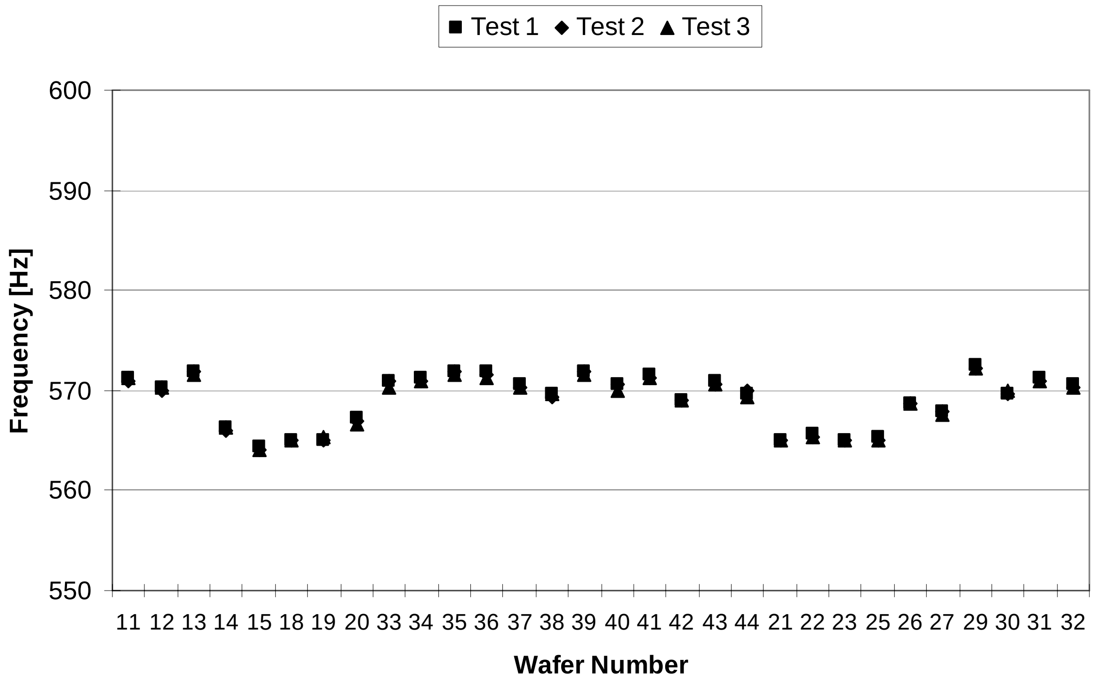

Figure E.3 Second mode natural frequency for small wafer set

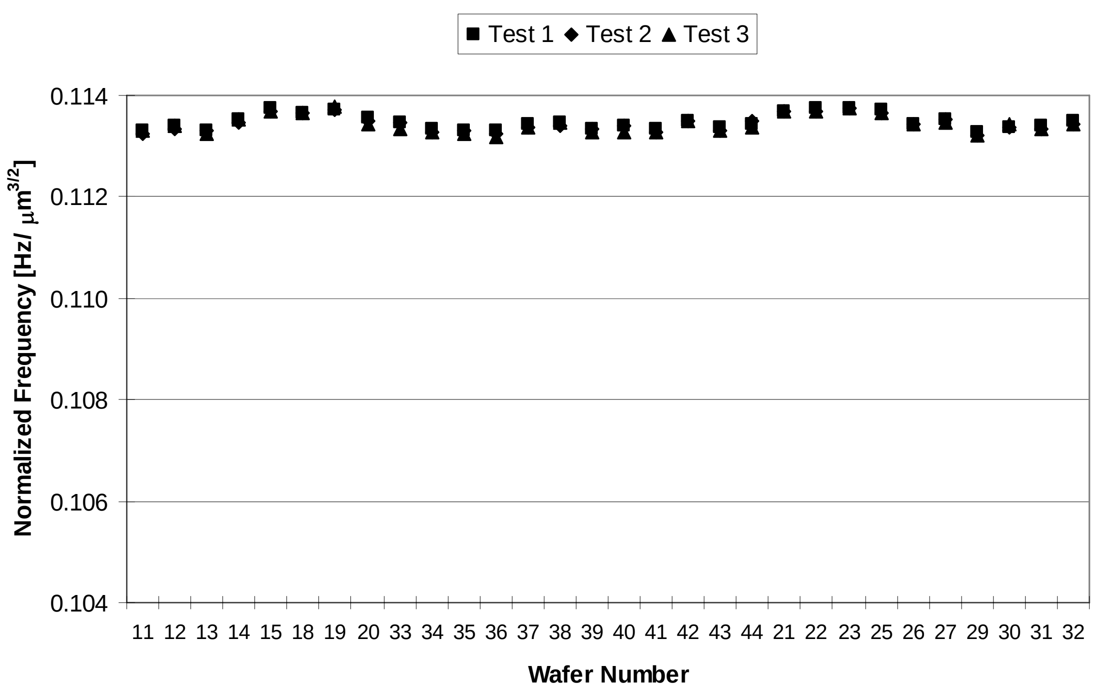

Figure E.4 Second mode normalized frequency for small crack wafer set

Appendix E (Continued)

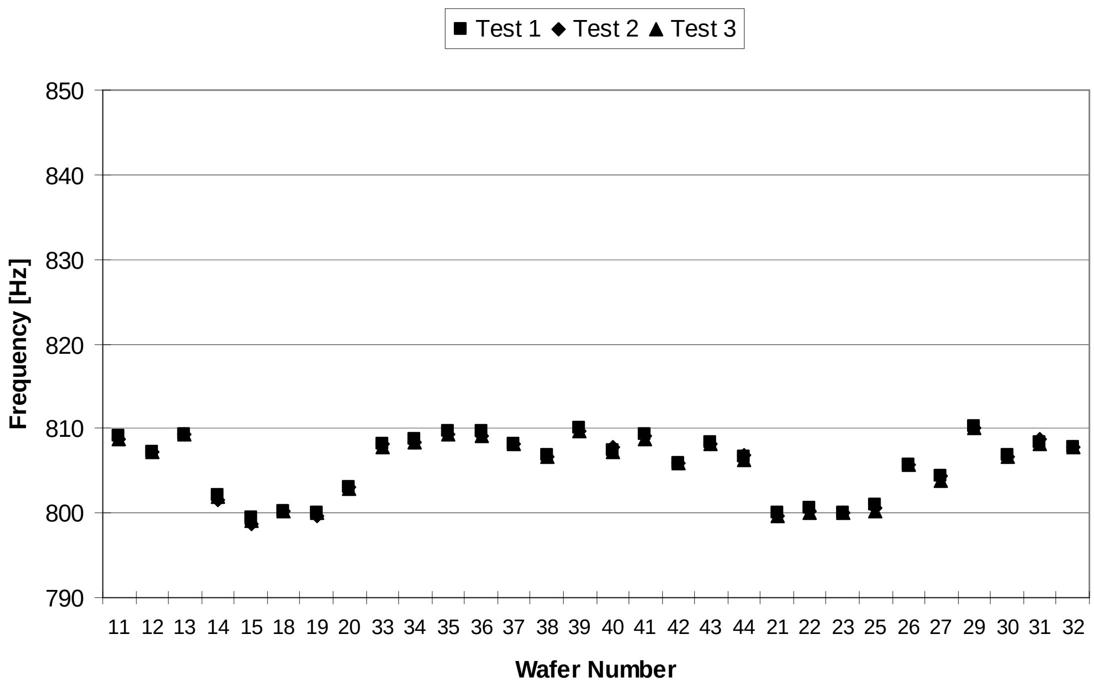

Figure E.5 Third mode natural frequency for small crack wafer set

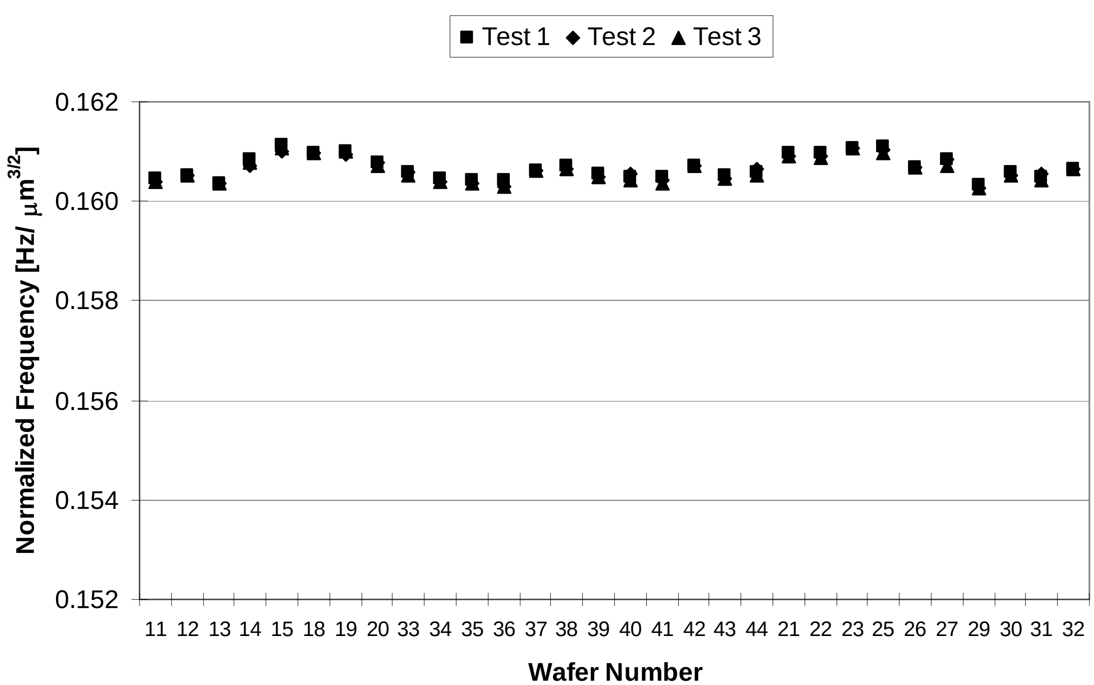

Figure E.6 Third mode normalized frequency for small crack wafer set

Appendix E (Continued)

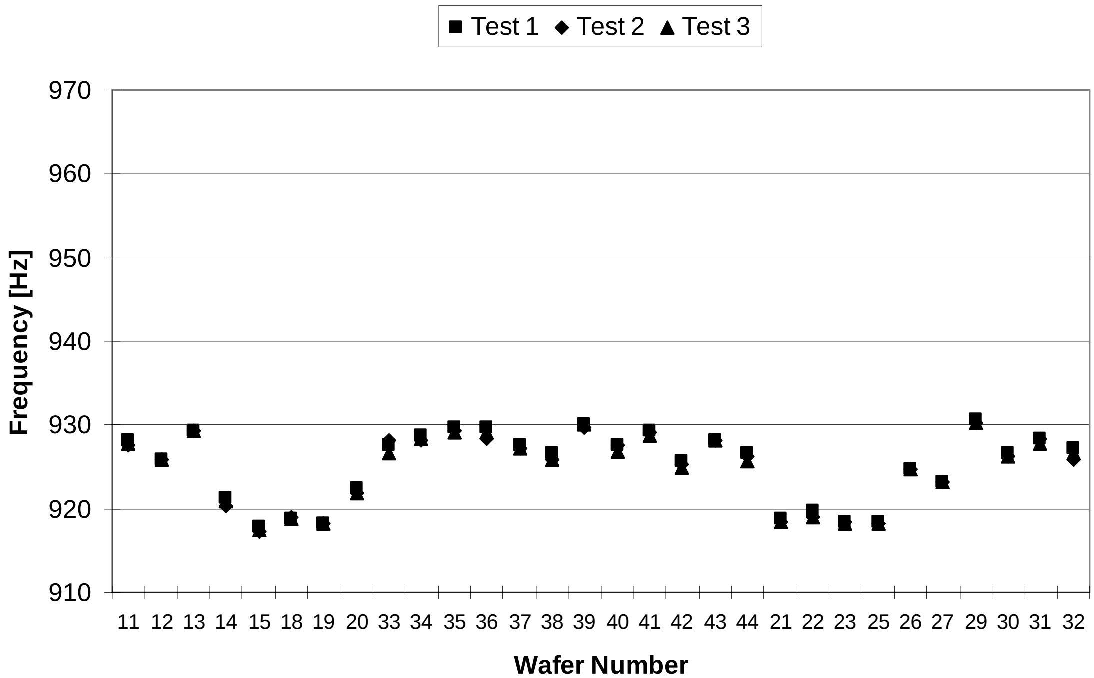

Figure E.7 Fourth mode natural frequency for small crack wafer set

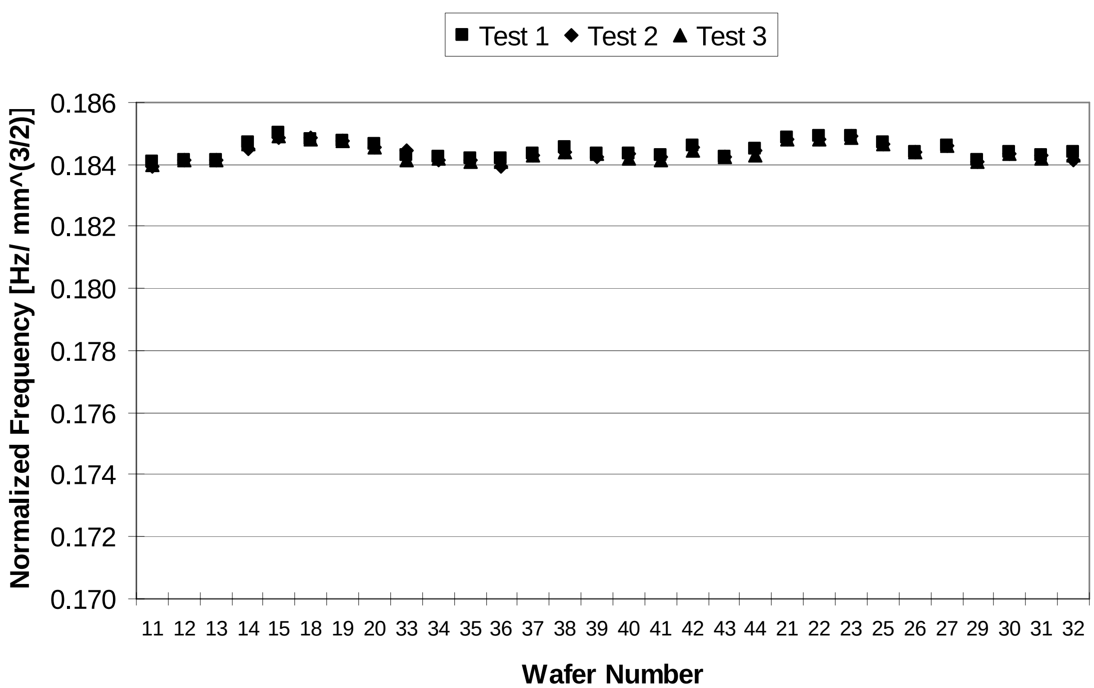

Figure E.8 Fourth mode normalized frequency for small crack wafer set

Appendix E (Continued)

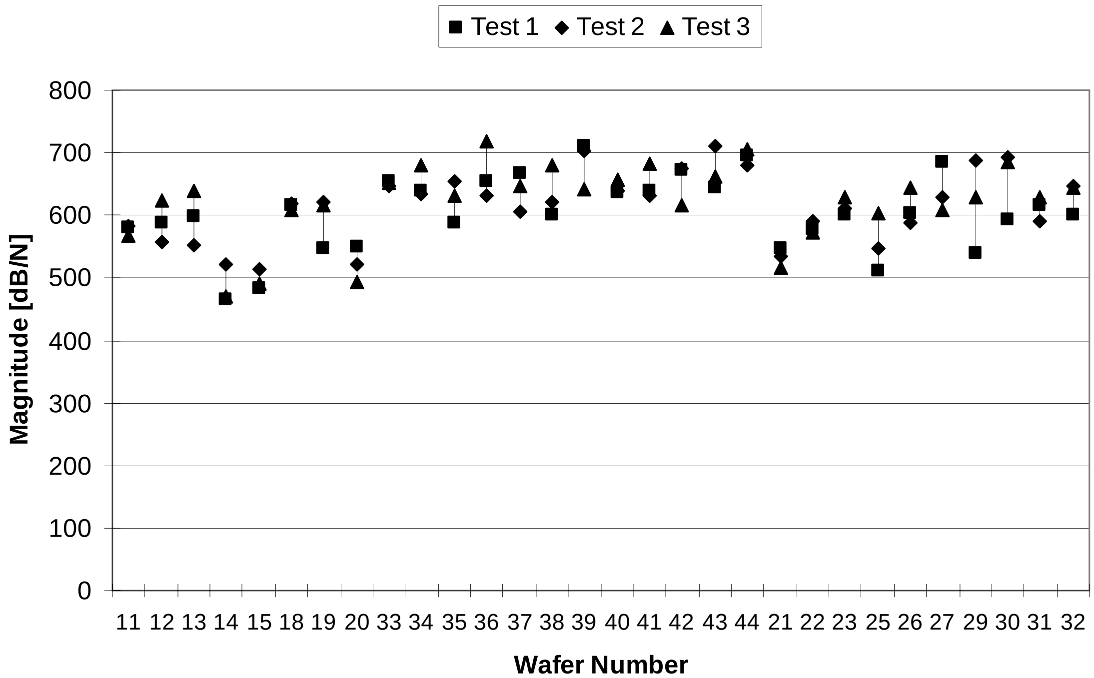

Figure E.9 First mode peak magnitude for small crack wafer set

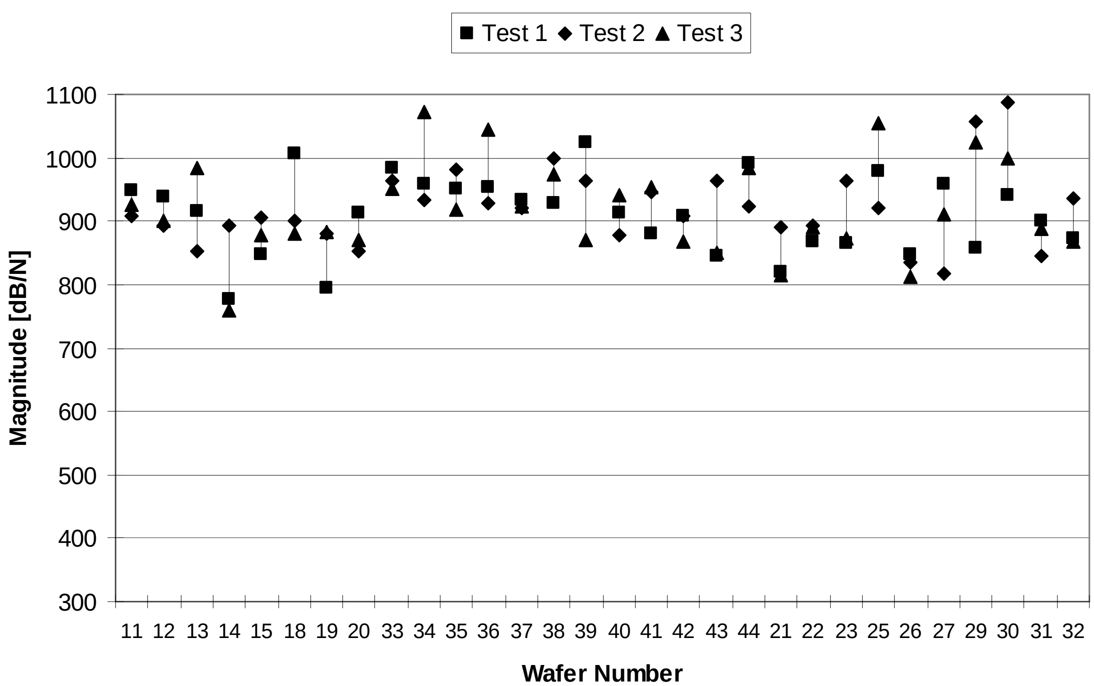

Figure E.10 Second mode peak magnitude for small crack wafer set

Appendix E (Continued)

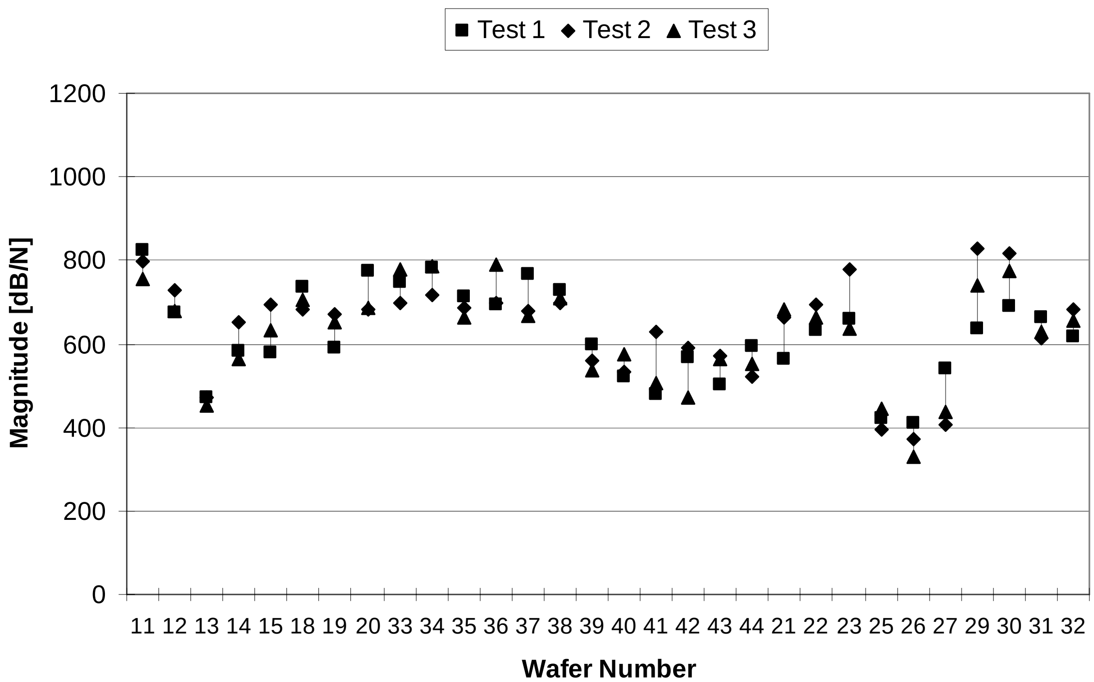

Figure E.11 Third mode peak magnitude for small crack wafer set

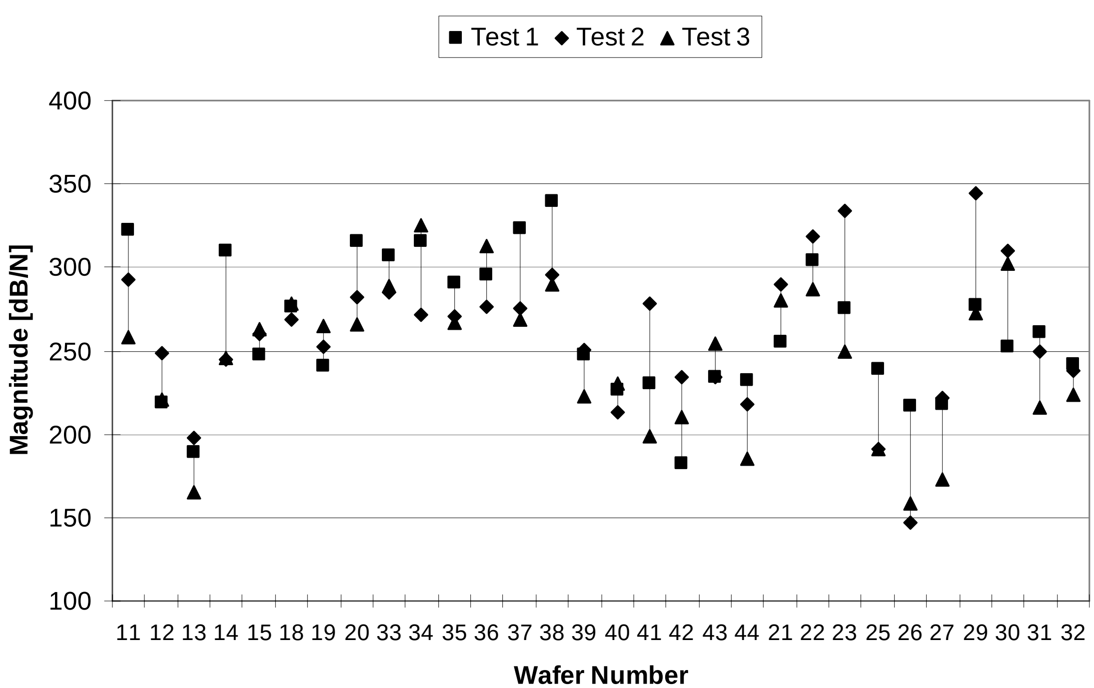

Figure E.12 Fourth mode peak magnitude for small crack wafer set

Appendix E (Continued)

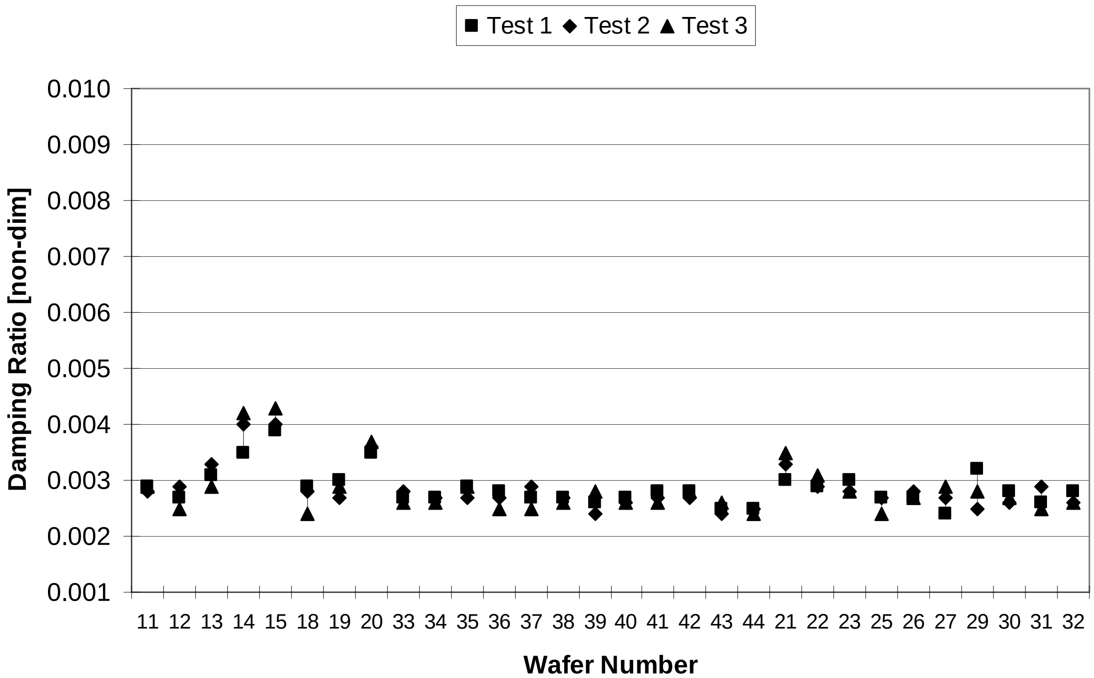

Figure E.13 First mode damping ratio for small crack wafer set

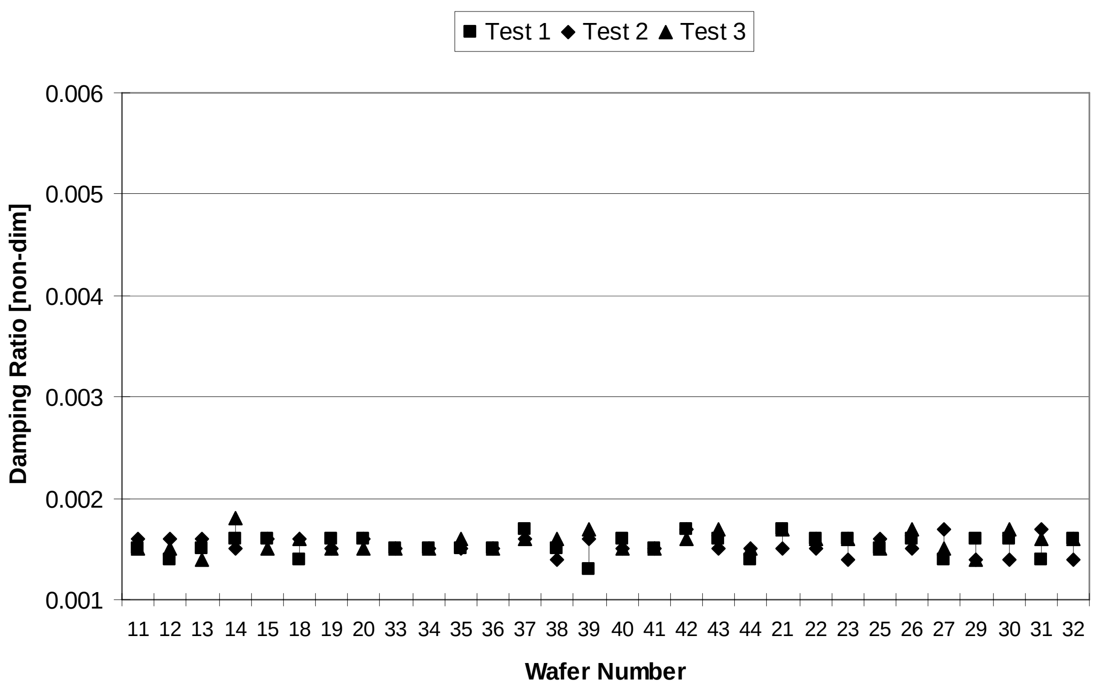

Figure E.14 Second mode damping ratio for small crack wafer set

Appendix E (Continued)

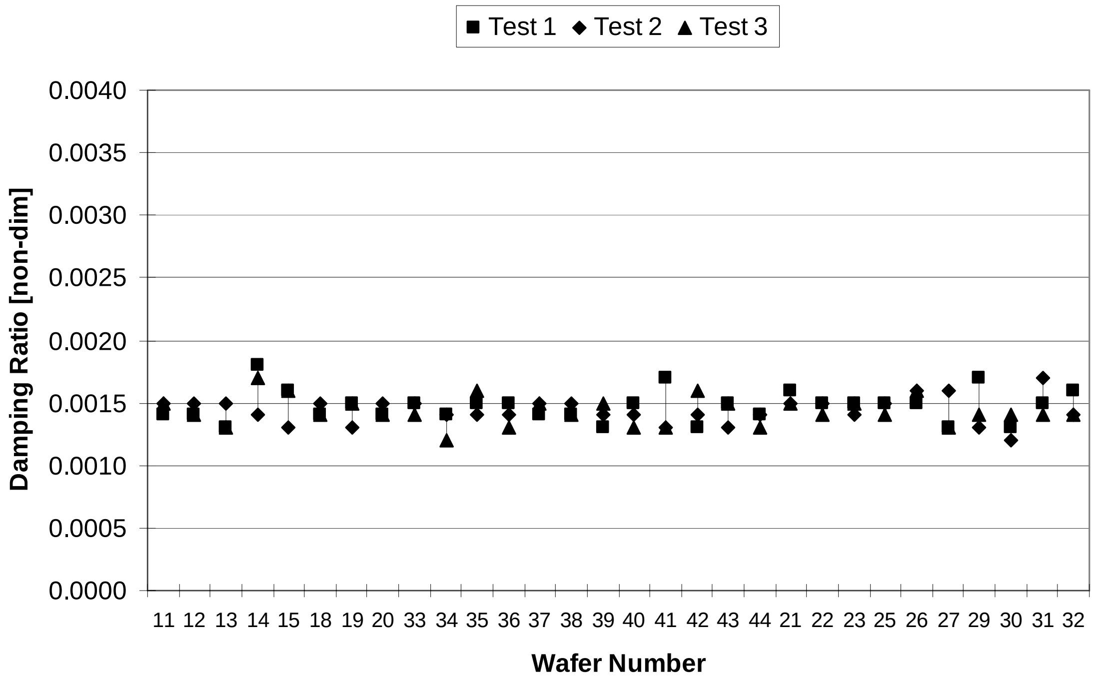

Figure E.15 Third mode damping ratio for small crack wafer set

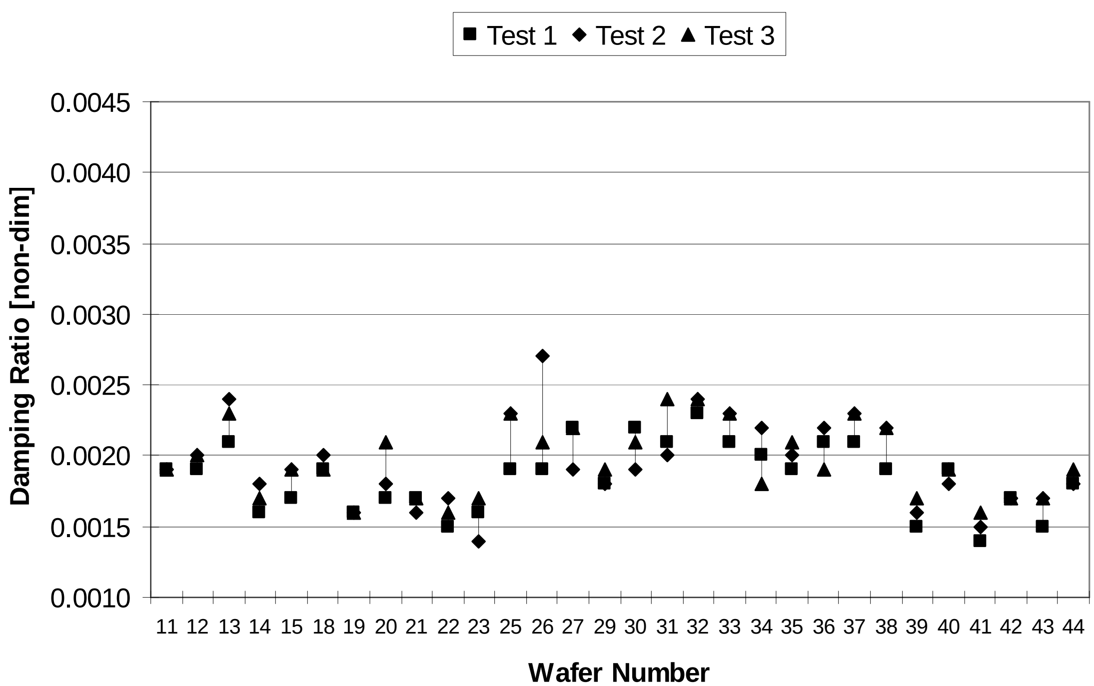

Figure E.16 Fourth mode damping ratio for small crack wafer set

Appendix F: Set up frequency response data

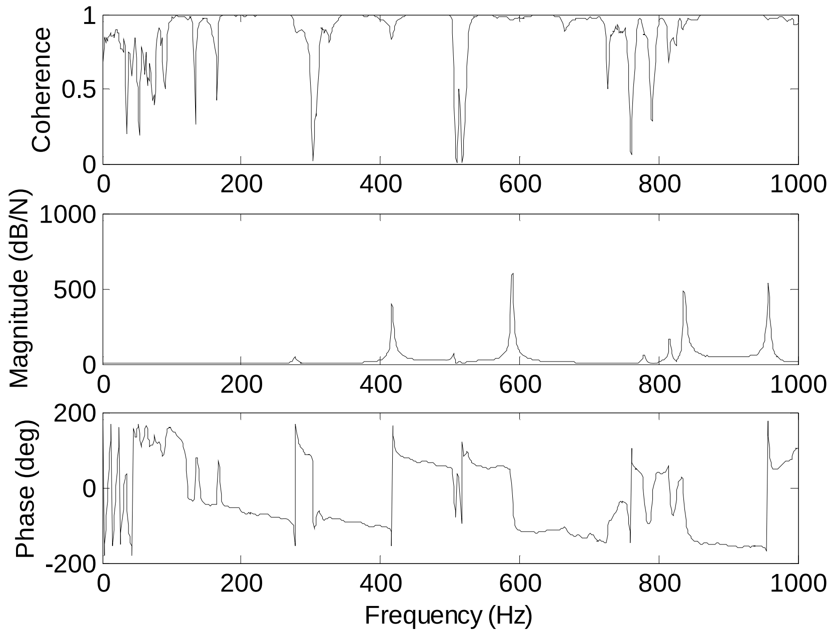

Figure F.1 Hammer (x=33 mm, y=45 mm)

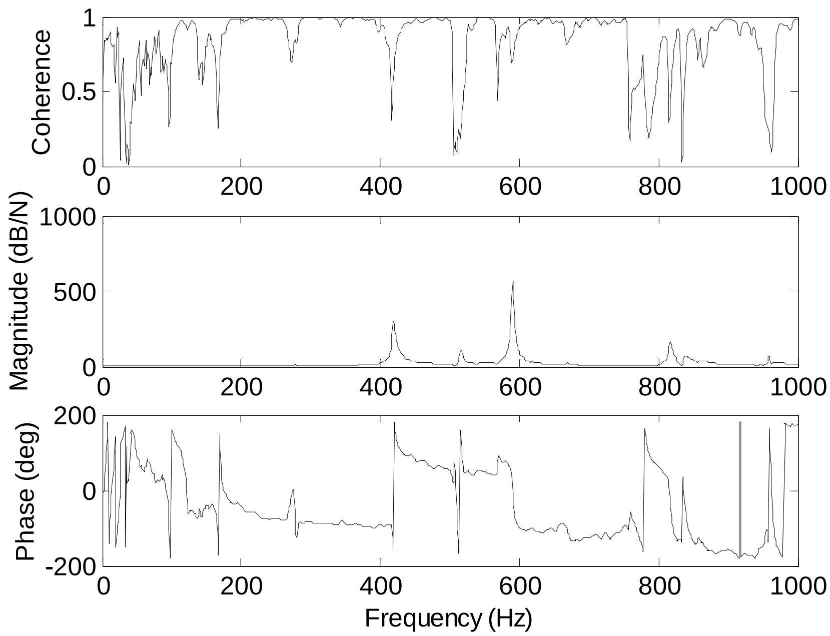

Figure F.2 Hammer (x=43 mm, y=45 mm)

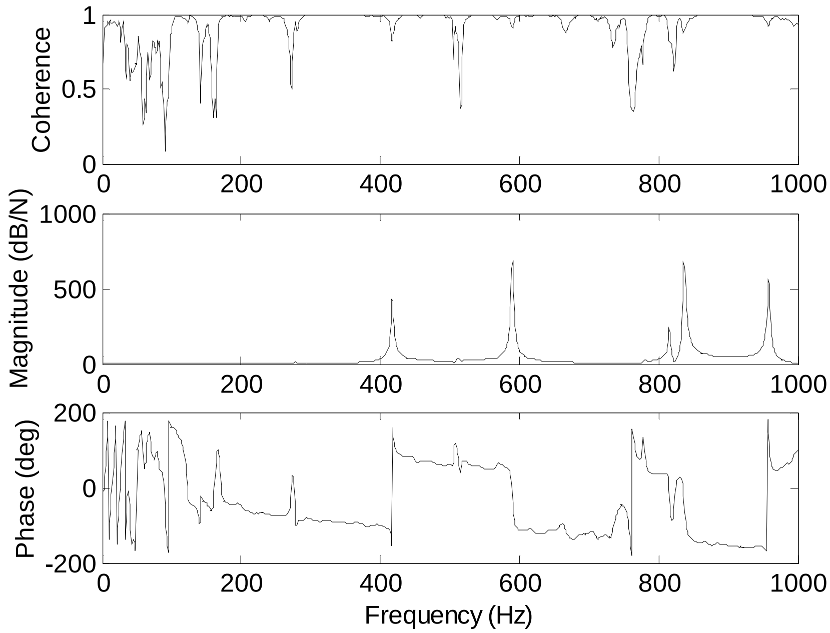

Figure F.3 Hammer (x=38 mm, y=40 mm)

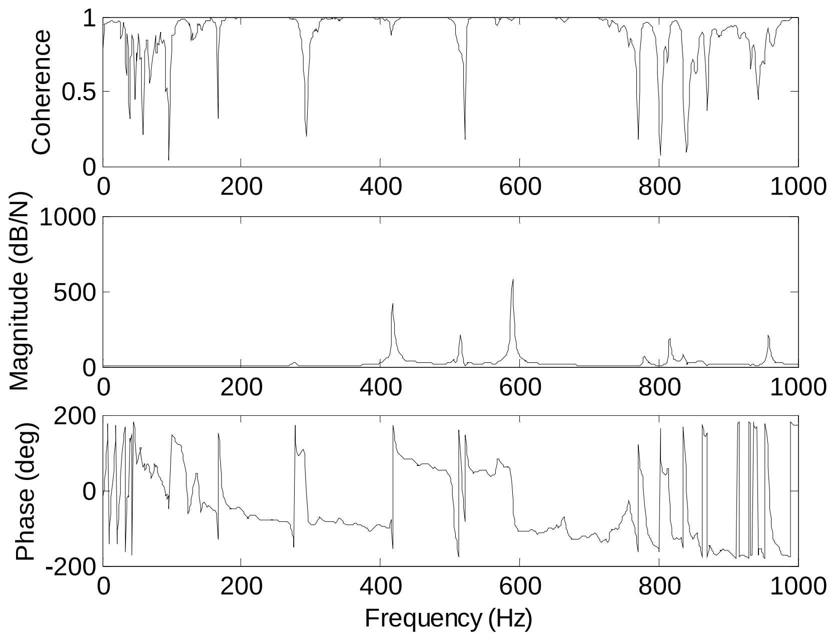

Figure F.4 Hammer (x=38 mm, y=50 mm)