Structural Health Monitoring Using Peak Of Frequency Response

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Abstract: - Methods in detecting damages in structural components and monitoring their health is on the way to develop in today's technology. Approaches; nondestructive towards the part or with the lowest risk; which locate the damage and even diagnose its size, are accentuating the importance of smart materials. One of these materials are piezoelectric that is used both as transducers and actuators in research centers, industries and laboratories. The present work is spotting on a new and totally different method compared to the current techniques in frequency analysis. ABAQUS 6.5-1 is the FEM tool to model an iron plate in this research. Piezoelectric patches are used for both shaking and sensing the resulting frequencies. Damping is neglected in this modeling. Simultaneously harmonic and modal analyses are done for 18 different diameters of a hole in the center of the plate. Both modal analysis and steady state harmonic analysis are done; without and with piezoelectric patches respectively; so that we can compare and validate the results. The result are monitored in several different points and compared as well. In this work the numbers of peak points (natural frequencies) are counted for each hole, so that formulate a way to identify its diameter. Research based on this framework is a novel job (it is based on the effect of diameter in arousing new peaks in certain frequency).

Key-Words: - Damage detection, Defect diameter, Smart materials, Piezoelectric, ABAQUS, FEM, Frequency response, Modal analysis

1 Introduction

There has been a significant increase in using solid composites in load-carrying structural components, particularly in aircraft and automobile industries. With the advances in actuator and sensor technologies that allow simultaneous excitation and sensing, many studies have been proposed to use Lamb waves for detecting defects in composite structures(Moulin et al. 1997, Sohn et al. 2004, Paget et al. 2003, Kessler et al. 2003, Wang et al. 2003) [1].

Lamb waves are mechanical waves whose wavelength is in the same order of magnitude as the thickness of the plate. The analysis and interpretation of Lamb waves can be complicated due to their dispersive and multimodal natures: Due to dispersion characteristics, the various frequency components of Lamb waves travel at different speeds and attenuate at different rates causing the shapes of wave packets to change as they propagate through a solid medium. In addition, multiple symmetric and anti-symmetric Lamb wave modes are generated as the driving frequency for wave generation increases. Recently, attention has been paid to the time reversal method developed in modern acoustics to compensate the dispersion of Lamb waves and improve the signal-to-noise ratio of propagating waves (Prada and Fink 1998, Ing and Fink 1996, Ing and Fink 1998, Fink 1999). Though the experimental results showed the spatial focusing and time compression properties of time reversal Lamb waves, the results were not directly usable for damage detection of plates (Ing and Fink 1998). A pulse-echo time reversal method, which is the time reversal method operating in a pulse-echo mode, has been employed to identify the location and size of defects in a plate (Ing and Fink 1996, Ing and Fink 1998, Fink 1999) [2]. If there exist multiple defects in a plate, the pulse-echo time reversal method tends to detect only the most distinct defect, requiring more sophisticated techniques to detect multiple defects. Furthermore, the pulse-echo time reversal method might be impractical for structural health monitoring applications, because a dense array of sensors is required to cover a large surface of the plate being investigated. In addition other works by Draeger et al. 1997, Fink and Prada 2001, proceeded on through the same frameworks. However no exact techniques are in hand for diagnosing the size of defects [3].

In order to facilitate a comparison of available techniques on the common basis, the ASCE Task Group on Structural Health Monitoring has established a benchmark problem recently. The benchmark structure is a 4-story building model and the corresponding analytical models have been developed [Johnson, et al

(2001)]. The disturbances are assumed to be unknown random uncorrelated forces (white noise processes) applied to each floor of the building. **Damage** is introduced into the structure by removing braces in the analytical model. Only acceleration measurements are available and each acceleration measurements are also polluted by uncorrelated noise. Details of the benchmark problem are given in [Johnson, et al (2001)], and various different approaches have been presented [e.g., Beck et al (2001), Yang et al (2001), Dyke et al (2000)] [4].
In this paper, damage detection systems; based on array of piezoelectric transducers sending and receiving strain waves in the parts; are discussed in this work. The frequency analysis is done in order to find number of diminished or aroused peaks by certain hole diameter in certain frequency domain. Each of the relatively maximum points sensed by strain gages are taken as a peak. In the first section, the modeling is described. In the following sections, we go through the analysis method, and finally, the result will be discussed.

2 Modeling

In the present research the model is built, meshed and analyzed in ABAQUS 6.5-1 software. The models for harmonic and modal analysis differ and are built respectively with and without piezoelectric patches on the surface.

2.1 Modal analysis model characteristics

The model includes a 200*50 mm^2 plates with the thickness of 0.3mm and a cut-extruded hole in the center. The plate is clamped on two sides. Fig.1 depicts the plate model with the hole. The plate is divided into 6 partitions and meshed using 3D stress tet element.

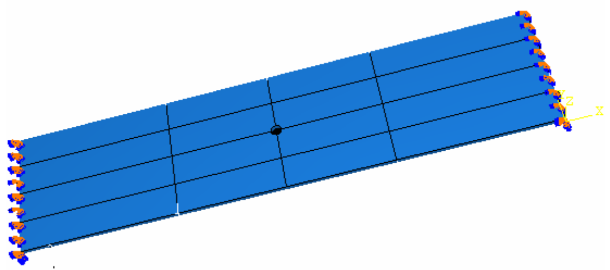


Fig.1 Base model for analysis shows displacement

A total of 18 models for modal analysis were made up, with the fixed center point and variation of the hole diameter. The diameters are 0.0625, 0.1255, 0.25, 0.5, 0.75,1, 125, 1.5, 1.75, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5 3.75, , 4mm. Fig.2 shows comparison of the holes.

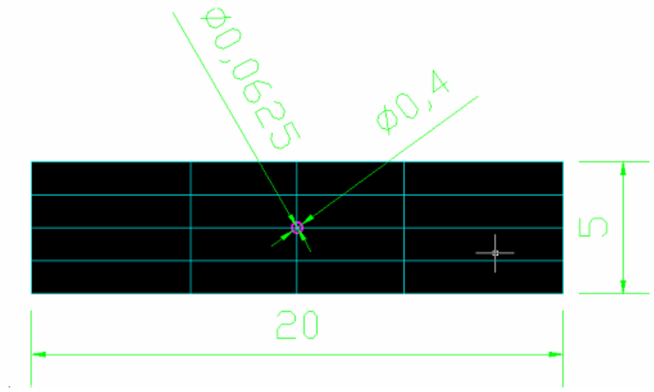


Fig.2 Dimensions and minimum and maximum of hole diameter

2.2 Harmonic analysis model characteristics

Harmonic analysis models are the same as modal ones with 4 additional piezoelectric patches on each. The piezoelectric patches with dimension of 10*10 mm^2 and thickness of 0.03 mm are attached on the surface. Fig.3 shows the harmonic analysis model. As demonstrated in the fig. the upper piezoelectric is used as shaker and the other 3 ones sense strain data. The Piezoelectric patches are meshed with one piezoelectric element. They are located 10mm and 40mm from the center and attached to the plate using Interaction/Tie command.

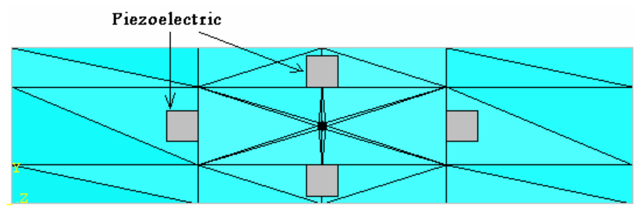


Fig.3 Patch piezo in model

3 Piezoelectric FEM

The ABAQUS linear modeling approach uses a coupled field capability, which allows for direct application of the voltage to the PZT constitutive equation for piezoelectricity. from reference [5] are:

$$\{T\} = [c]\{S\} - [e]\{E\} \quad (1)$$

$$\{D\} = [e]T\{S\} + [e]\{E\} \quad (2)$$

Where
T represents 6 components of stress,
c diagonal matrix is the system stiffness matrix,
S represents 6 components of strain,

e is the piezoelectric matrix,
E represents 3 components of the electric field,
D represents 3 components of the electric flux density, and e is a dielectric matrix relating the electric field to electric flux density.
The material properties which populate the matrices in eqs. (1) and (2) are not easily measured directly. However, the properties in the inverses of the matrices are readily available; therefore, an alternate from of the equations is introduced.

{S} = [cE] {T} + [d] {E} (3)

{D} = [d] T {T} + [p] {E} (4)

Where
cE diagonal is the compliance matrix for the elastic system,
d is the dielectric matrix which related electric field to strain, and
P is the diagonal permittivity matrix
Comparing eqs. (1) and (2) with (3) and (4) gives

[c] = [cE] – 1 (5)

[e] = [cE] – 1[d] (6)

Then

[e] T = [d] T [cE] - 1 (7)

[e] = [P] – [d] T [c E] – 1[d] (8)

In the above analysis, the material properties for all the layers, excluding the PZT layer, are isotropic.
The modulus of elasticity, the Poisson ratio , and the coefficient of thermal expansion are directly input into the matrices [cE] , [d] , and [P] and the equations (5) – (8) used to generate the matrices in equations (1) and (2) . As an aid to ABAQUS users, the PIEZMAT macro has been created that will convert the manufacturer's data into ABAQUS form.

4 Modal Analysis

The applied difference between modal and harmonic models, in terms of attaching or not attaching the piezoelectric patches comes from the ABAQUS shortcoming in modal analysis of two tied elements. The frequency modal analysis is done in the range of 0-2GHz and displacement, velocity and acceleration of the same points which later piezoelectric patches elements attached on, were extracted.
Fig.4 depicts the Frequency vs. Displacement, Frequency vs. velocity and frequency vs. acceleration diagram of the plate with a 0.25mm diameter hole.
Fig.5 shows two of its mode shapes in modal analysis.

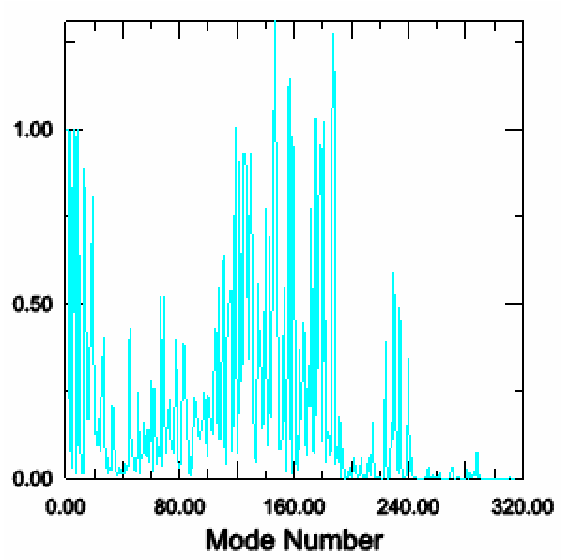
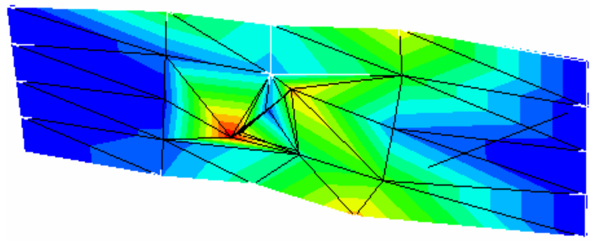
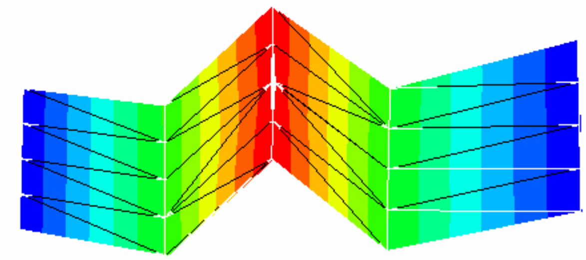


Fig.4 Chart of modal analysis displacement-frequency



a Mode shape in 85 khz

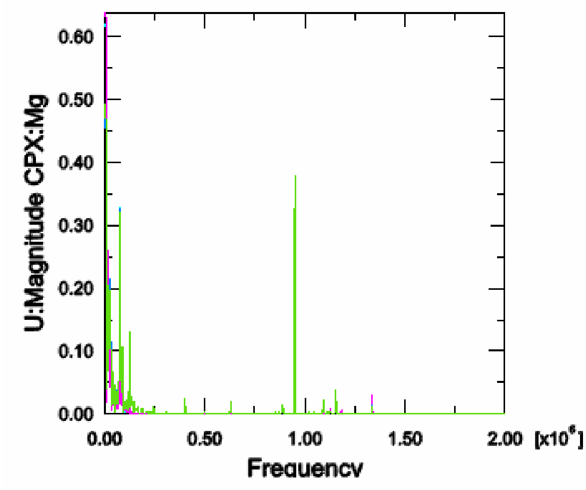


b Mode shape in 5 khz

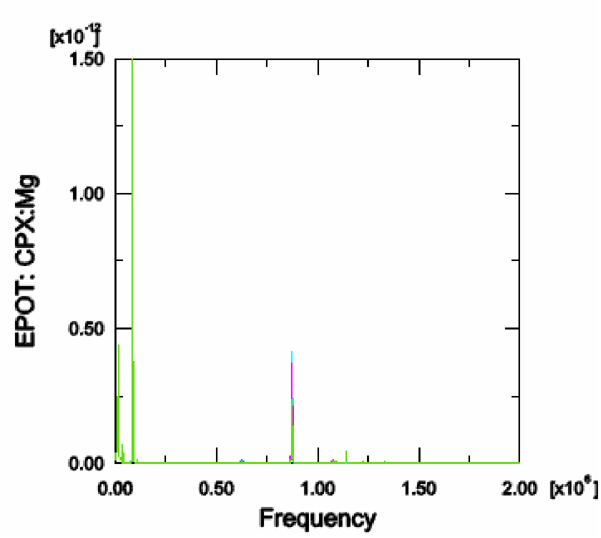
Fig.5 Two mode shape of plate in modal analysis

5 Harmonic Analysis

In harmonic analysis, the complete model with 4 piezoelectric patches has undergone a steady state dynamic analysis in range of 0-2 GHz cast into 9000 sub frequencies. Through this analysis 10V applied on the shaker piezoelectric and then the consequence horizontal and vertical piezoelectric voltages are monitored. In addition the displacement, velocity and the acceleration of the nodes under the piezoelectric patches are extracted. Fig.6 is the diagram of the motioned data for hole diameter of 0.75mm. Fig.7 also shows two of plate deformations through harmonic analysis in the frequency of 85, 145 KHz.

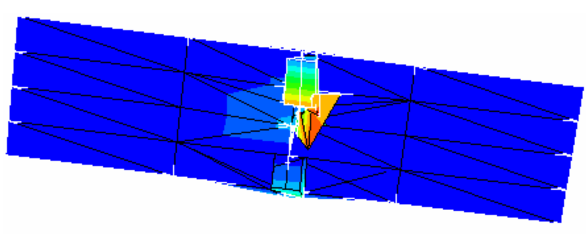


a Chart of displacement-Frequency

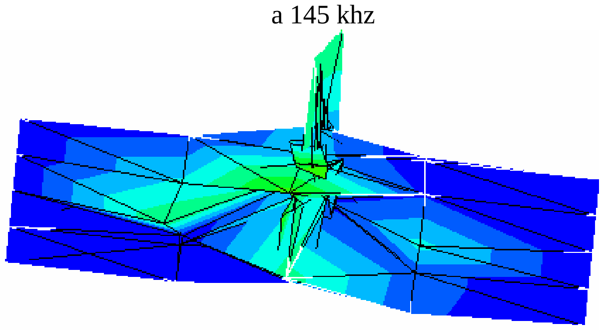


b Chart of acceleration-Frequency

Fig.6 Chart of harmonic analysis



a 145 khz

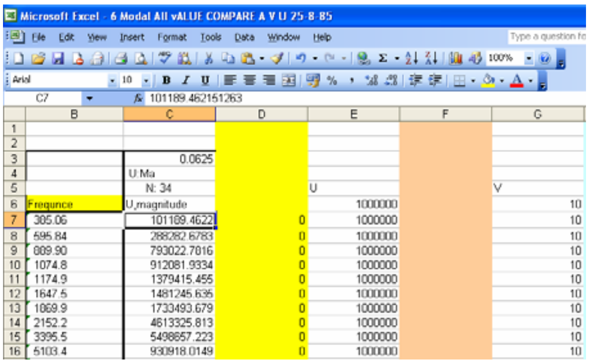


b 85 khz

Fig.7 Shape of harmonic analysis

6 Data assembling

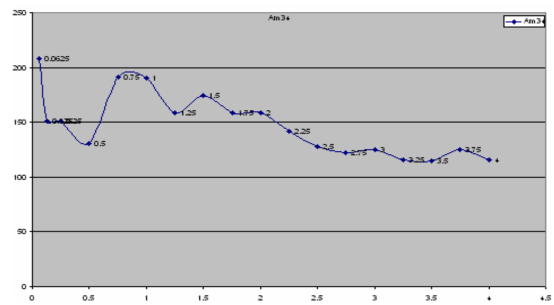
In order to assemble and analysis, the acquired data was taken to Excel data sheet as shown in Fig.8. In this file whole results of modal analysis in different condition are stored up. In order to analyze the resulting file from harmonic analysis, first the peak point were distinguished in a process that sorted the maximum out of every 5 resulting data as a peak point. Consequently, a kind of data filtering was done and low amplitude tremors were eliminated. Then we put the results as modal analysis in a single data table. This table was organized so that export the number of each and every hole peak points, in a separate data sheet, along with the capability of collecting the peak points according to magnitude of the data, for example displacements over 0.1 mm in frequency domain over 200KHz. These margins are defined by User in the software, and any redefinition immediately translates to redrawing of resulting diagrams.



	B	C	D	E	F	G
1						
2						
3		0.0625				
4		U:Ma				
5		N: 34		U		V
6	Frequnce	U,magnitude		1000000		10
7	305.06	101189.4622	0	1000000		10
8	595.84	288282.6783	0	1000000		10
9	809.90	793022.7816	0	1000000		10
10	1074.8	912081.9334	0	1000000		10
11	1174.9	1379415.455	0	1000000		10
12	1647.5	1481245.636	0	1000000		10
13	1869.9	1733493.679	0	1000000		10
14	2152.2	4613325.813	0	1000000		10
15	3395.5	5498657.223	0	1000000		10
16	5103.4	930918.0149	0	1000000		10

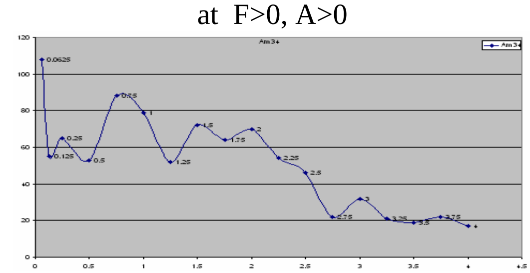
Fig.8 Exel file, arrange of variable of abaqus

Fig.9 shows the redrawing of two diagrams with changing the magnitude and frequency.



a Chart of number of peak vs.hole diameter at F>0, A>0

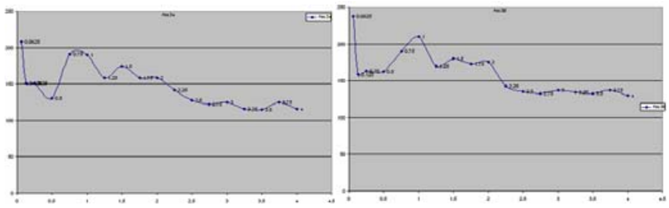
7



b Chart of number of peak vs. hole diameter at F>50Khz, A>10000000 m/s^2

Fig.9

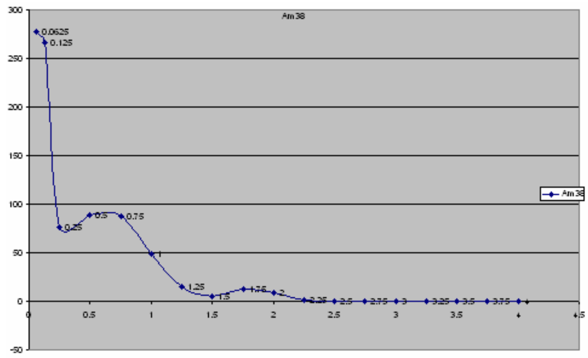
This section deals with the obtained accelerations. A common modal analysis diagram with its peaks are taken to consideration. Fig.9 shows two modal analyses corresponding to the points where vertical and horizontal piezoelectric patches locate. The diagram can be divided into two parts, holes with diameter smaller than 2.25mm which are almost scattered, and holes with diameter larger than 2.25mm which almost form a line. So as the first understanding, the approximate size of the hole is determined (Fig.10).



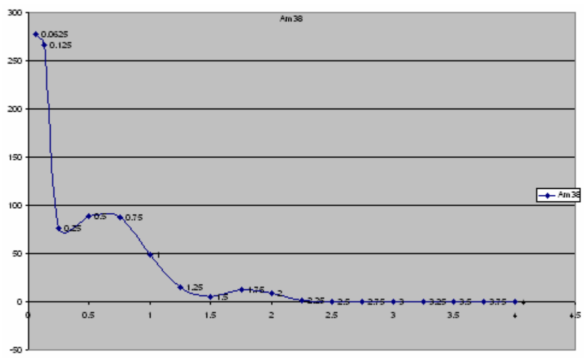
a Point A b Point B

Fig.10 Chart of number of peak vs. hole diameter at Point A, B

By frequency increase up to 200 KHz; as shown in Fig.11; all the peaks corresponding to 2.25mm hole diminish. Thus using the same approach, another way for approximate determination of the hole diameter and reassuring of that is obtained.



a Point A



b Point B

Fig.11 Chart of number of peak vs. hole diameter at F>500, A>0

In Fig.12, we simultaneously change both parameters of acceleration and frequency and consider accelerations over 1000 m/s^2 and frequencies over 5000Hz. In this situation 4 following domains are diagnosed:

- 1st : very small hole with diameters lower than 0.125 mm
- 2nd : holes with diameters from 0.125 to 1.25 mm
- 3rd : holes with diameters from 1.25 to 2.25 mm
- 4th : holes with diameters from 2.25 up to 4 mm

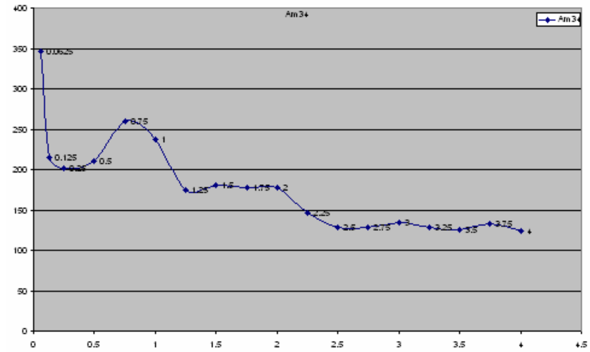


Fig.12 Chart of number of peak vs. hole diameter at F>5000, A>1000

By an increase in acceleration to 100000 m/s^2 and frequency to 150000Hz no significant change is observed in the above figure (Fig.13).

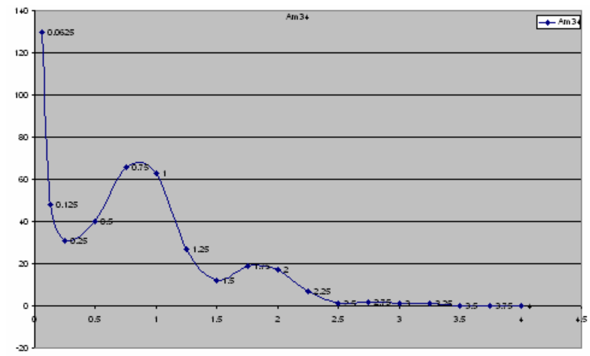


Fig.13 Chart of number of peak vs. hole diameter at F>150000, A>10000

By acceleration increase, up to 10000000 m/s^2 , the points around 0.075 goes upper and the difference become more noticeable. So the point 0.075 forms a kind of measure.

This trend goes on and on, however from the acceleration of over 15000000 m/s^2 the region corresponding to the hole with the diameter of 1.25 moves towards upper portion of the diagram and the difference between sizes disappears.

In accelerations over 20000000 m/s^2, the whole diagram comes irregular and scattered (Fig.14).

The distances among acceleration over 10^6 m/s^2 and frequency over 10^5 Hz, is the most distinguishable.

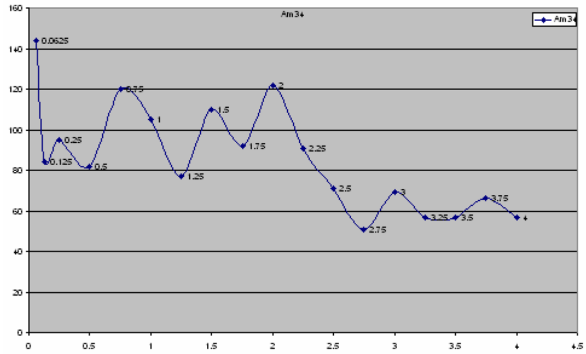
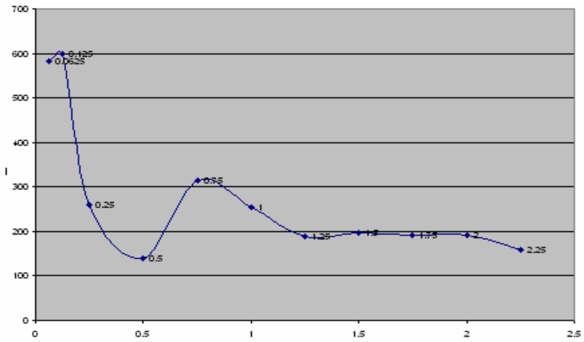
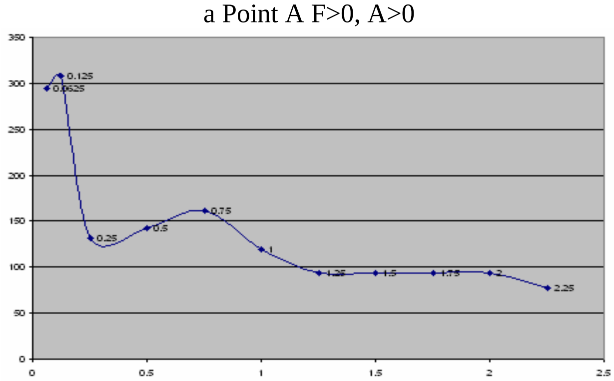


Fig.14 Chart of number of peak vs. hole diameter at F>5000, A>20000000

It's visible in Fig.15 that the shape of two modal and harmonic analysis diagrams are very like each other and have an approximate compliance.
The disparity seen in the results is because of presence of piezoelectric patches.



a Point A F>0, A>0



b Point B F>0, A>0

Fig.15 Chart of number of peak vs. hole diameter at F>0. A>0 in harmonic analysis

7 conclusion

The determination of number of peaks in several points, caused by acceleration and frequency over a certain amount, leads to determination of the hole diameter. For instance: acceleration of 0 and frequency of 50000 Hz which have the total number of 526 peaks. So in first step, by getting to know the number of peaks, the approximate diameter of the hole is determined. Then by testing several frequencies for the obtained numbers and compare them with the component analysis, exact diameter of the hole can be determined.
Finally Table 1 contains the results of some holes, presented as a sample to test and determining the hole diameter.
In addition with attachment of small number of piezoelectric patches, the harmonic and modal analysis will be in an approximate compliance, anyhow that'll be more reliable to make use of the harmonic analysis results with the extended parts taken to account.

0.125	0.25	0.75	2.5	A	F
598	259	315	141	0	0
526	186	239	62	0	50000
342	157	204	62	10000	50000
266	76	88	0	10000	200000
19	15	10	0	1000000	200000

Table 1 Diameter, Accelerate, Frequency, Number of peak for instance: at F>0, A>0, number of peak at hole diameter 0.125mm is 598

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