

LA-UR-06-8867

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*Title:* FATIGUE CRACK MONITORING WITH NONLINEAR  
ACOUSTICS

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*Submitted to:* International Modal Analysis Conference XXV



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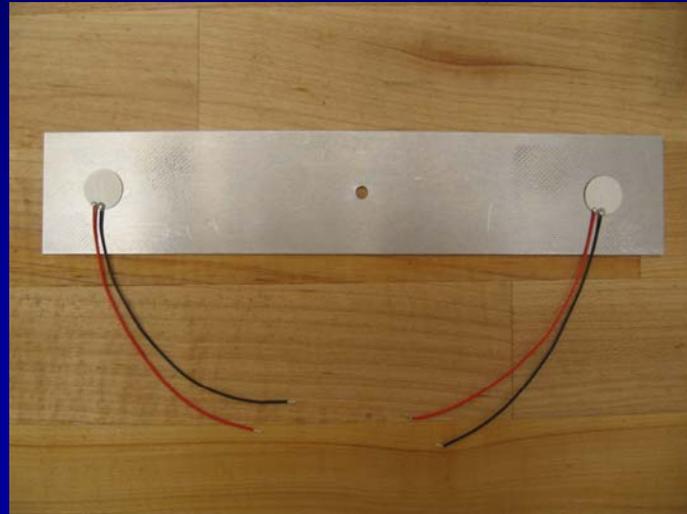
# Fatigue Crack Monitoring with Nonlinear Acoustics

Sarah Bailey  
Luis Estevez  
Devon Murphy

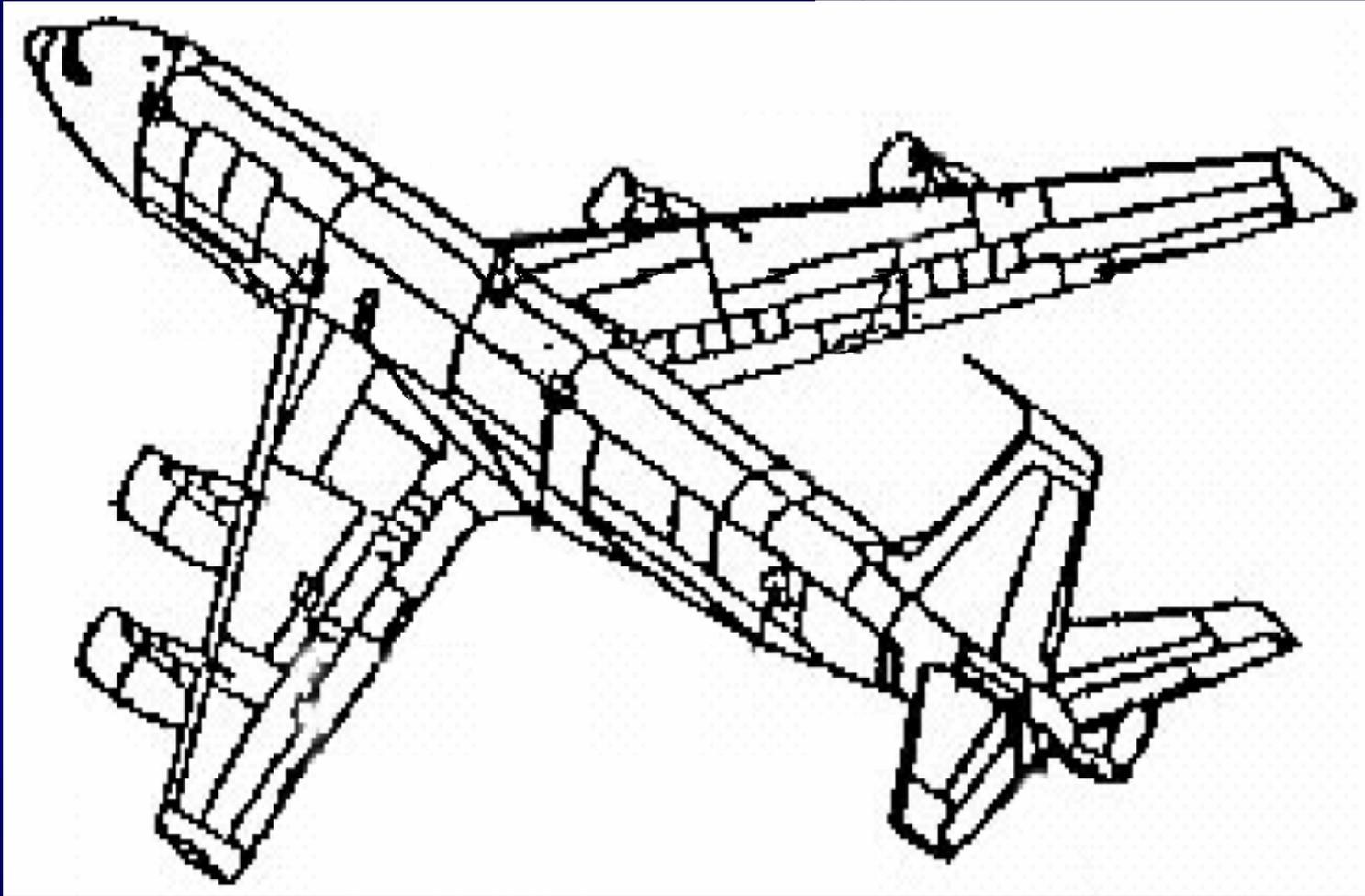
Mentor: Anthony Puckett

Dynamics Summer School  
Los Alamos, NM

10 August, 2006



# NDE assesses fatigue damage caused by cyclic loading, and SHM will establish NDE scheduling



[Roy et al.]

# The Civilian and military airline industries require accurate monitoring of aircraft structural integrity



[[http://pictopia.com/perl/gal?provider\\_id=237&process=gallery&photo\\_name=k59293](http://pictopia.com/perl/gal?provider_id=237&process=gallery&photo_name=k59293)]

**Non-Destructive Evaluation (NDE) and the prospective of Structural Health Monitoring (SHM) aim to achieve:**

**The safe travel of pilots and passengers**

**Military mission assurance**

**Reduction in costs associated with plane inspection downtime**



[<http://www.sitontop.com/KDIImages/SonicBoom.jpg>]

# Eddy current sensing and Visual Inspection are the most widely used techniques of NDE

Eddy currents induce magnetic fields in skin defects

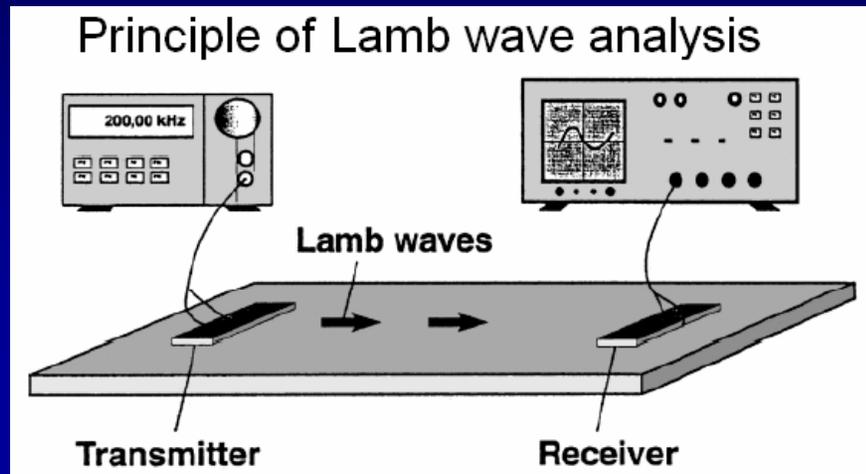
Magneto-optics form images of fields caused by defects



Tools needed: Trained eyes, flashlight, and 10x magnifying glass

Full inspection of airplane can take more than a month

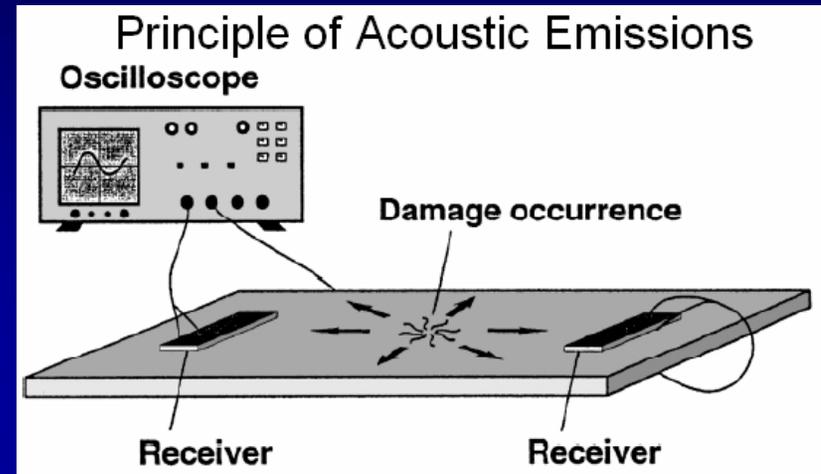
# The research conducted in the field of SHM for aircraft skin is extensive and evolving



[Sebastien et al.]

↓

Identification through wave attenuation



[Sebastien et al.]

↓

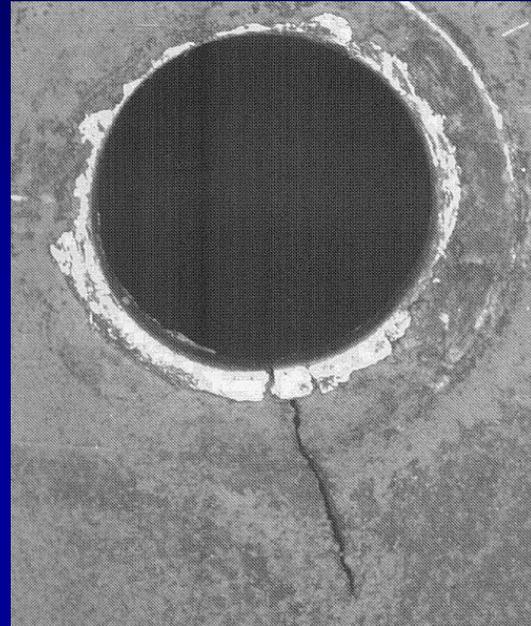
Passive sensors “listen” for indications of damage

↙ ↘

Both techniques formulated on linear system responses

# Our objective is to excite and sense the nonlinear response of the fatigue cracks using PZTs

Eliminates need for a baseline analysis for comparison of time signals



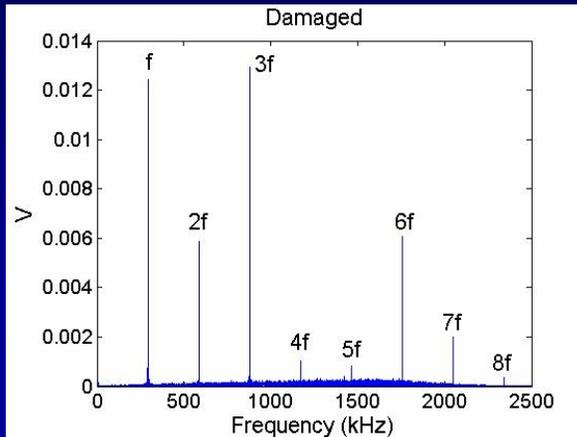
[[http://www.t-34.com/aircraft/G-13/G-13\\_Fatigue\\_Crack\\_Hole\\_8.JPG](http://www.t-34.com/aircraft/G-13/G-13_Fatigue_Crack_Hole_8.JPG)]



[<http://aar400.tc.faa.gov/Programs/AgingAircraft/Structural/Background/background.htm>]

Damage is identified by presence of harmonics or sum and difference frequencies

# This presentation focuses on the procedures, results, and conclusions drawn from our research



## Introduction to nonlinear system responses

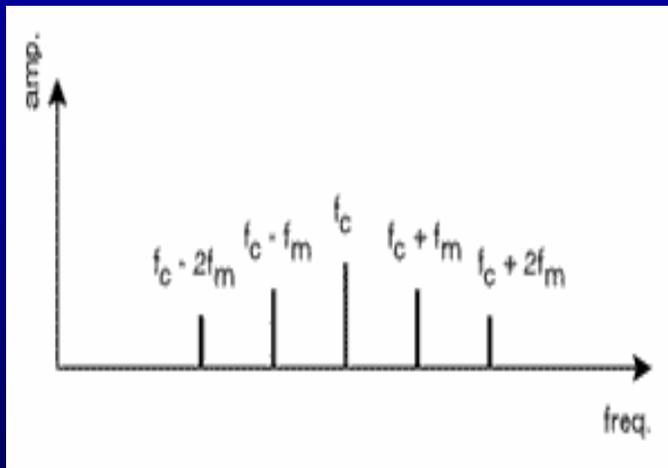
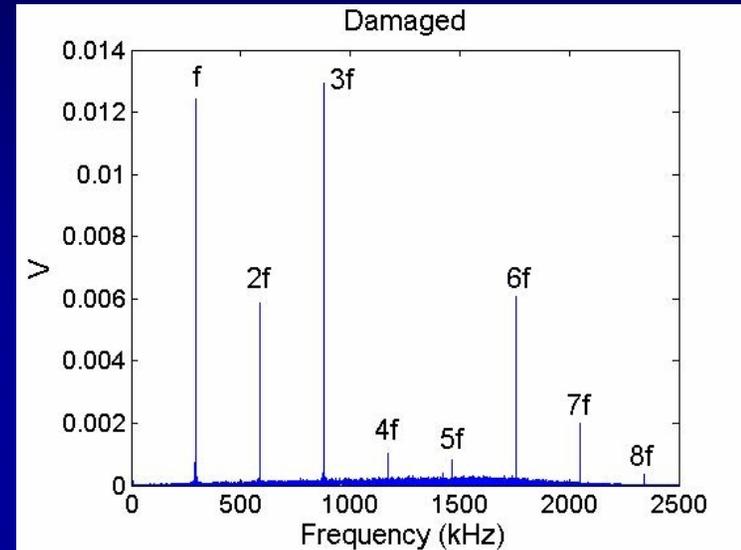
## Experiments and results on small plates



## Experiments and results on 737 Lap-Joint

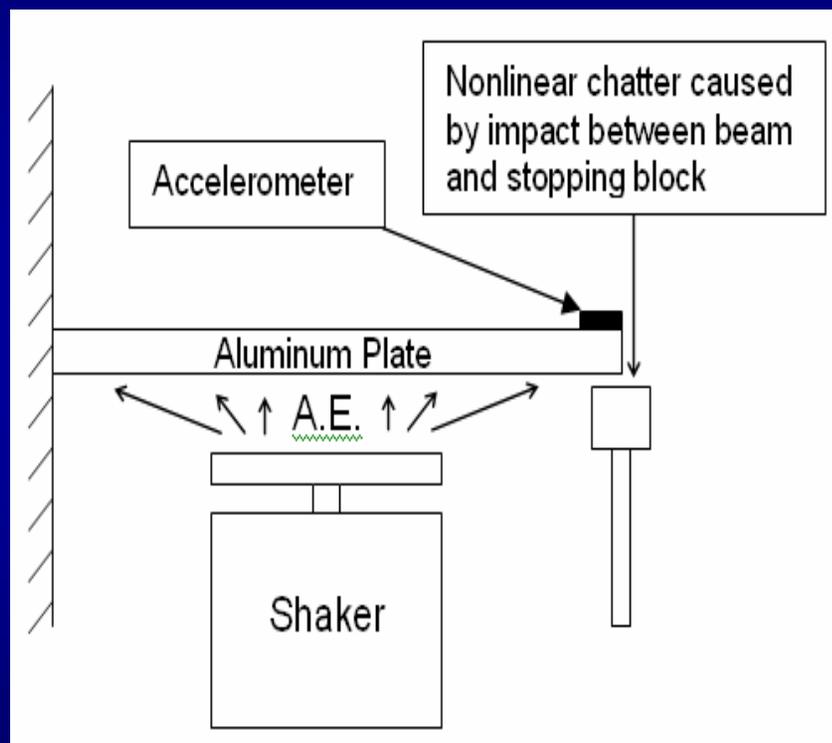
# Nonlinear systems excited by a frequency, $f$ , will output a combination of frequencies $nf$

The output frequencies,  $nf$ , where  $n = 2, 3, 4 \dots$  are called harmonics



Given inputs  $f_c$  and  $f_m$ , the output will also contain the sum and difference of harmonics

# A simple experiment was proposed to show that chatter between two surfaces causes harmonics

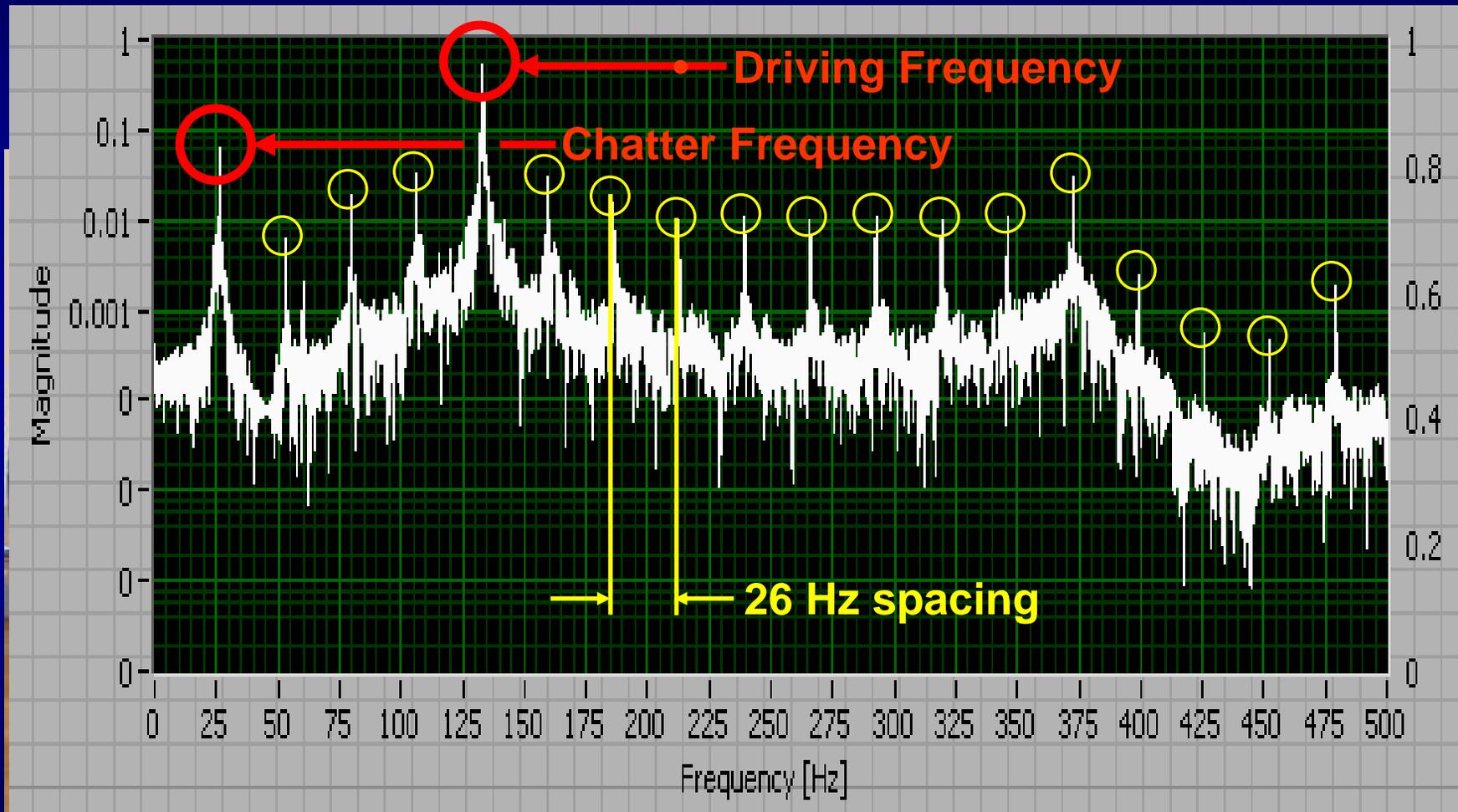


Sound waves emitted from shaker excite the thin beam

Plate would impact the stopper causing chatter

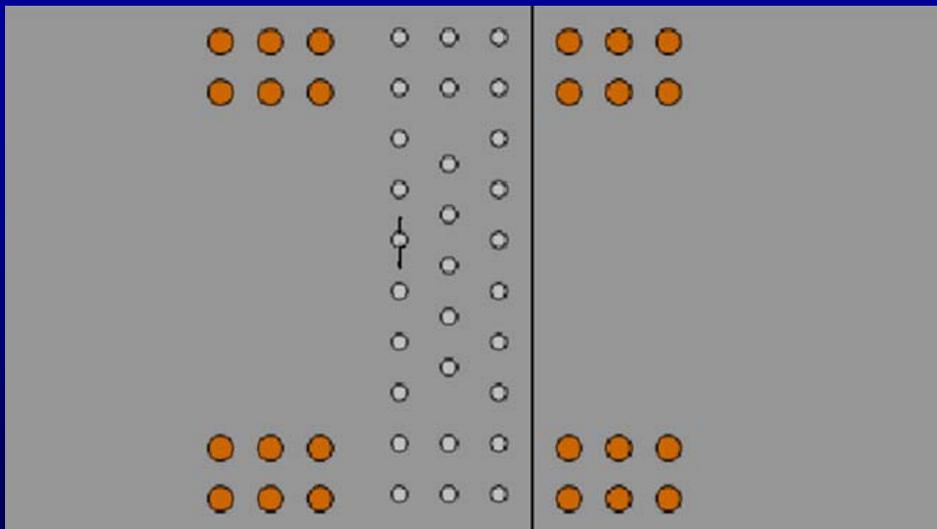
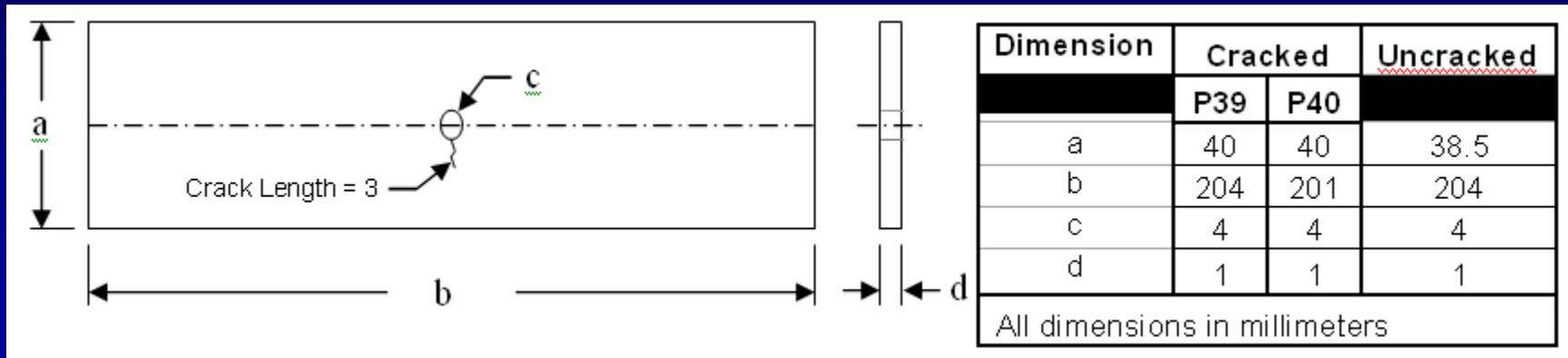
Harmonics expected to appear in the frequency response

# The frequency response for the test contained harmonics spaced by the frequency of plate chatter



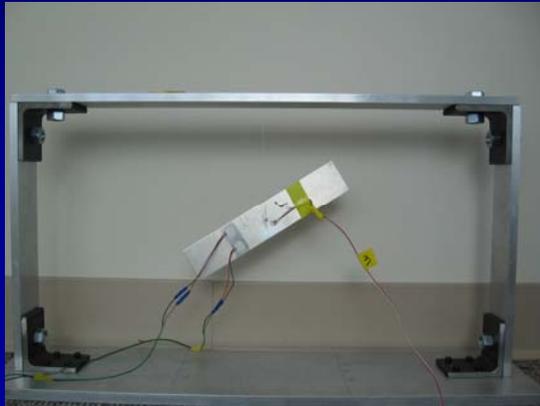
[Anton]

# Three small plates and a lap-joint were provided by the Aging Aircraft Facility at Sandia National Lab



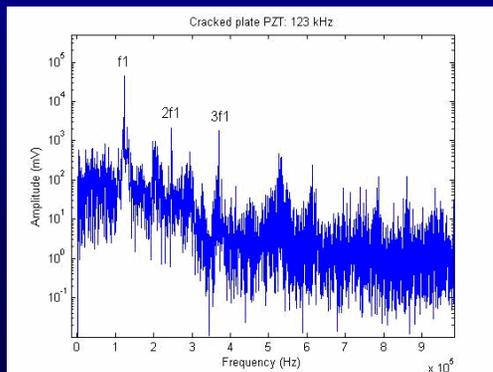
The lap-joint is representative of that found on a Boeing 737

# Various experimental strategies were employed in exploring the small aluminum plate samples



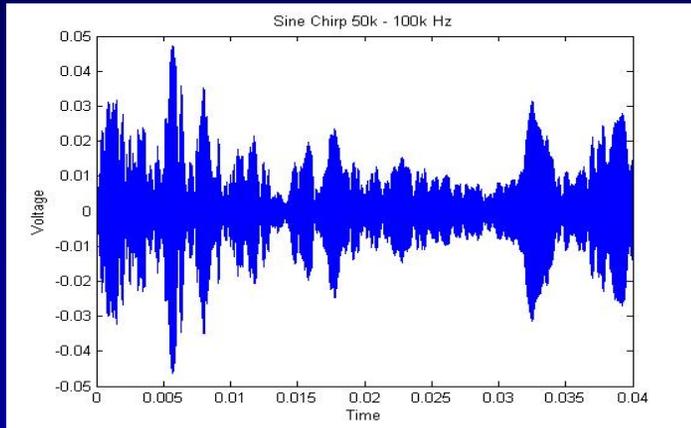
Single frequency actuation via PZT

Dual frequency excitation



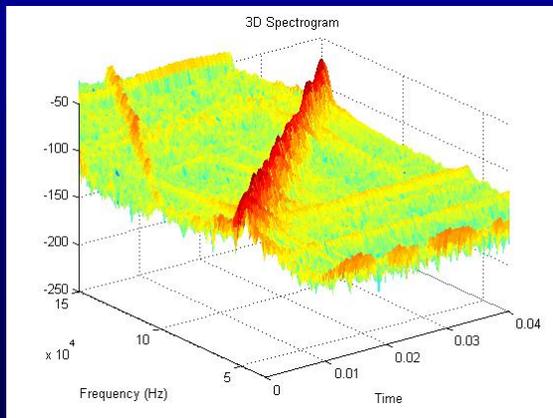
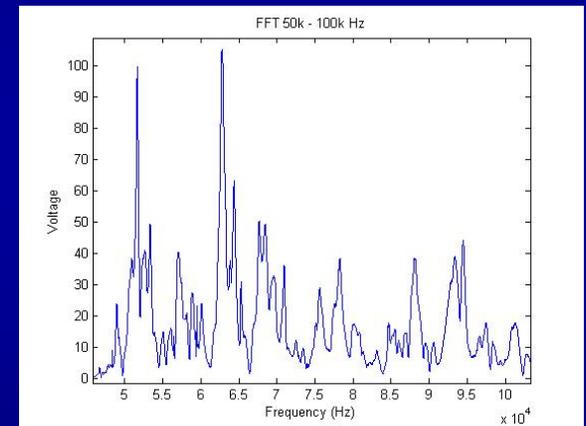
Results and analysis

# Numerical and experimental modal testing was conducted to find resonant frequencies



A PZT excited a sine chirp over various frequency bands in the plate

The Fourier Transform of the time data was taken to view frequency content

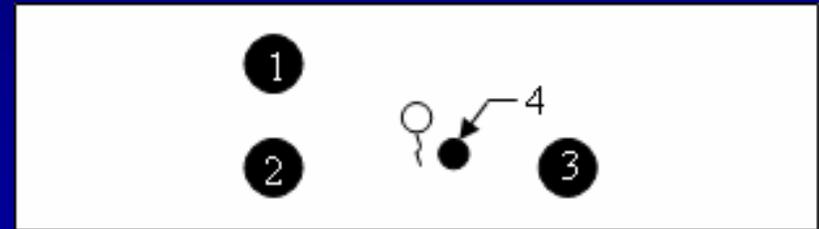


A spectrogram combined time and frequency data visible plot

# Single frequency actuation was utilized to detect nonlinearities from the fatigue crack



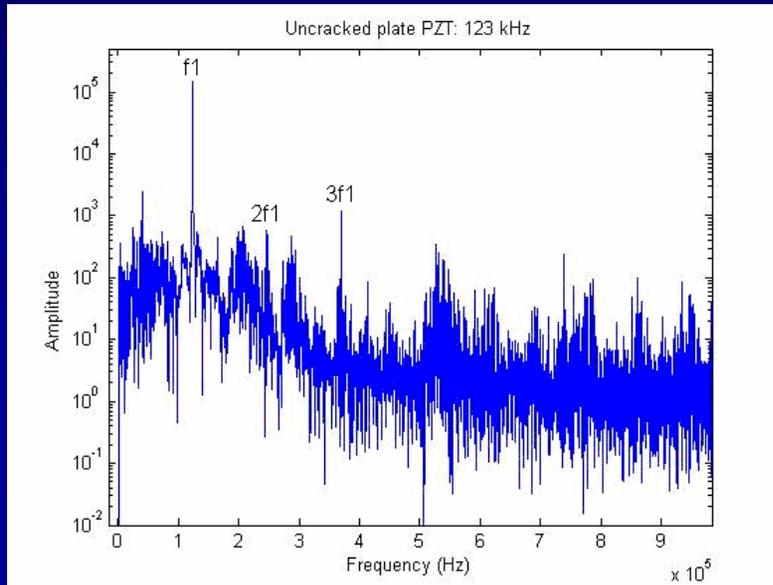
Overall set up



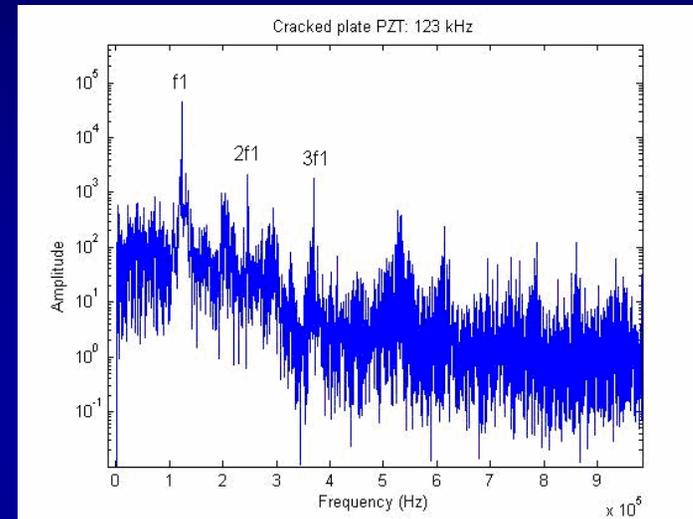
Pitch catch setup

PZT 1 actuating while  
PZT 4 senses

# The response of the single frequency actuation showed nonlinearities

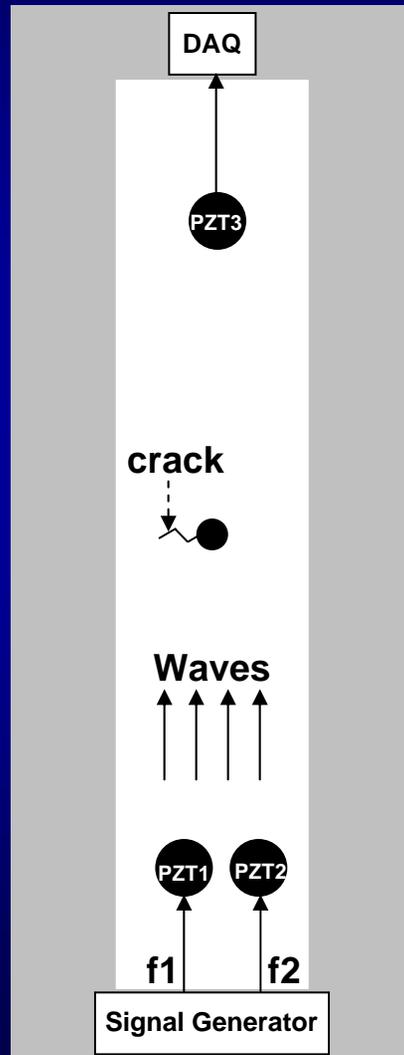


Unfortunately the frequency response of the uncracked plate showed harmonics as well



Exciting one PZT resulted in harmonics of the driving frequency in the cracked plate

# Actuating with two frequencies should reveal more nonlinearities

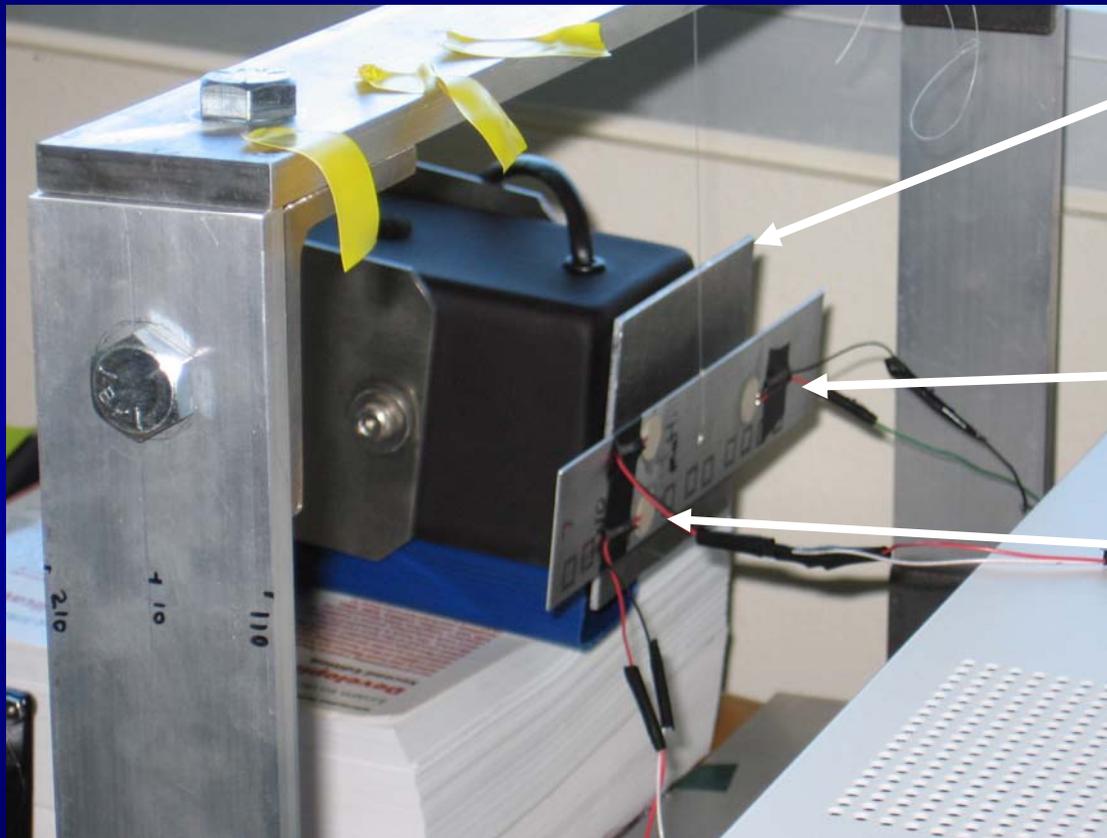


PZT1 actuates at a low frequency ( $f_1$ )

PZT2 actuates at a high frequency ( $f_2$ )

PZT3 acts as the sensor

# Actuating with two frequencies should reveal more nonlinearities

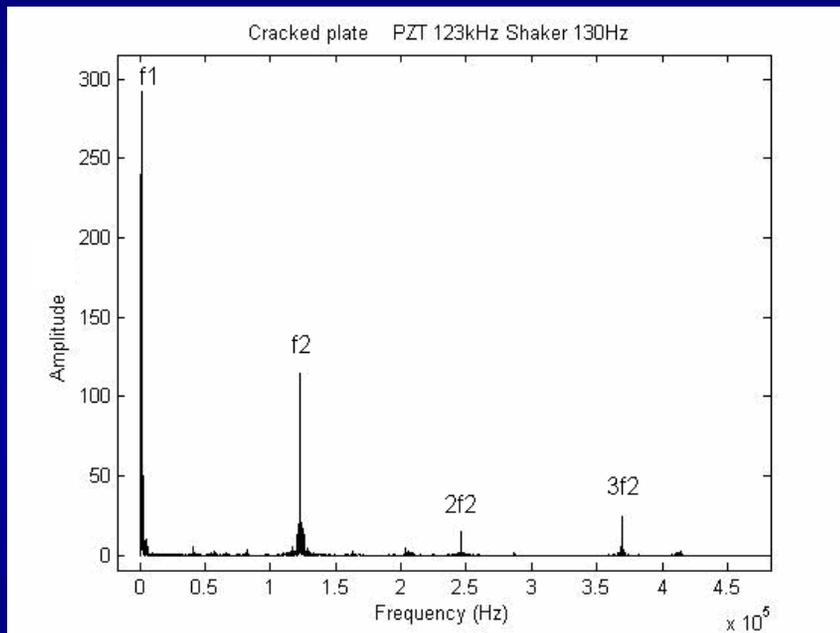


Shaker used to excite a lower frequency ( $f_1$ )

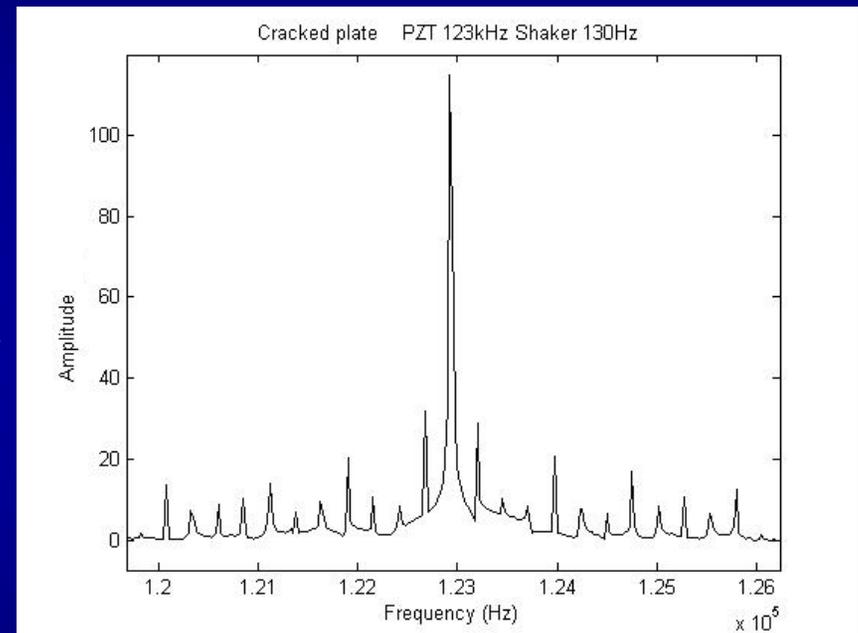
PZT 3 used as a sensor

PZT 1 actuates a higher frequency ( $f_2$ )

# Excitation with a shaker and a PZT was used in order to see other nonlinear responses

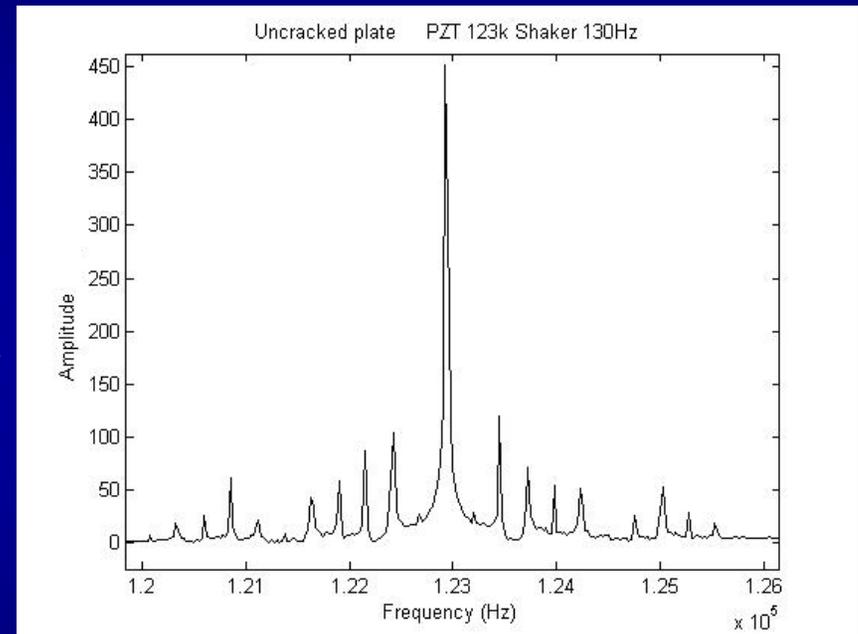
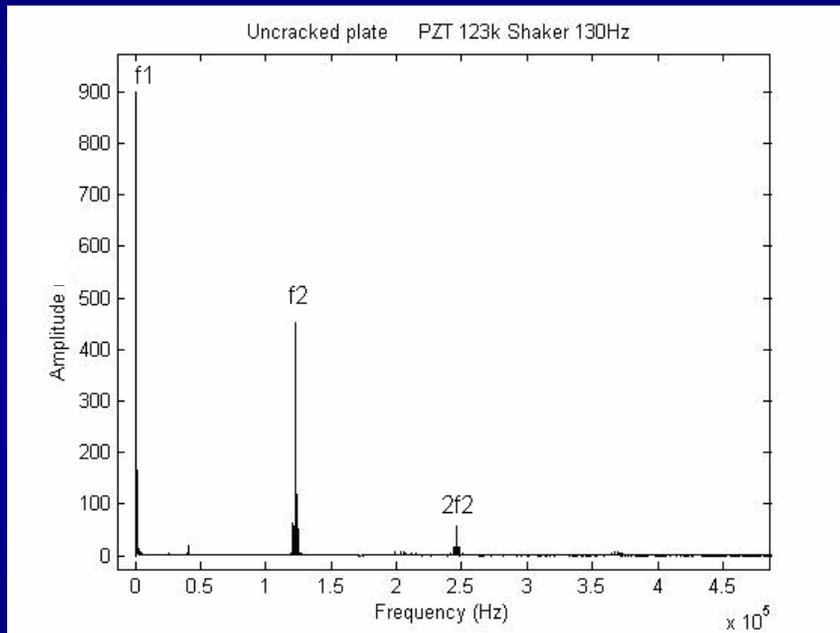


FFT of response revealed harmonics



A close up at 123 kHz revealed sum and difference frequencies

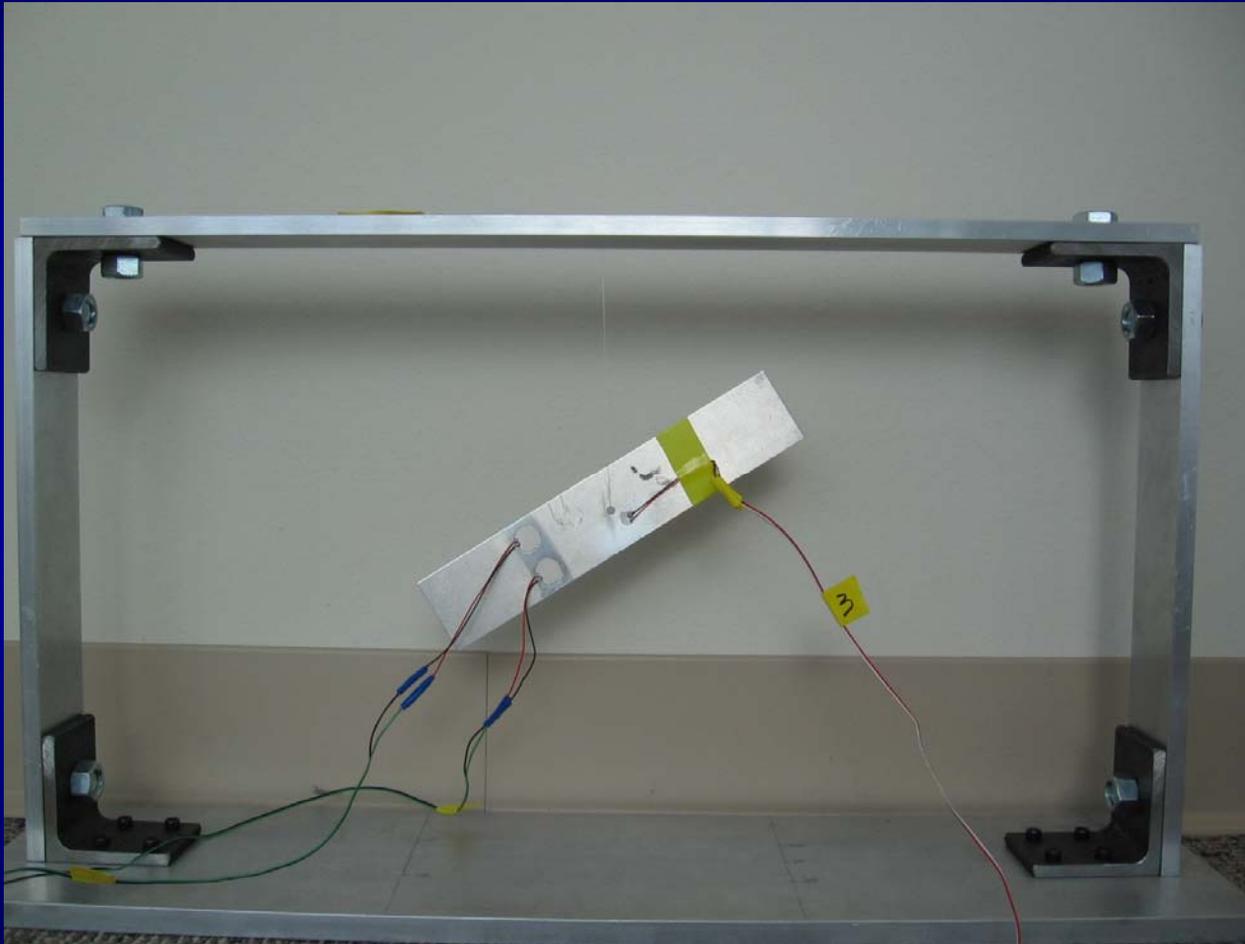
# Excitation with a shaker and a PZT was used in order to see other nonlinear responses



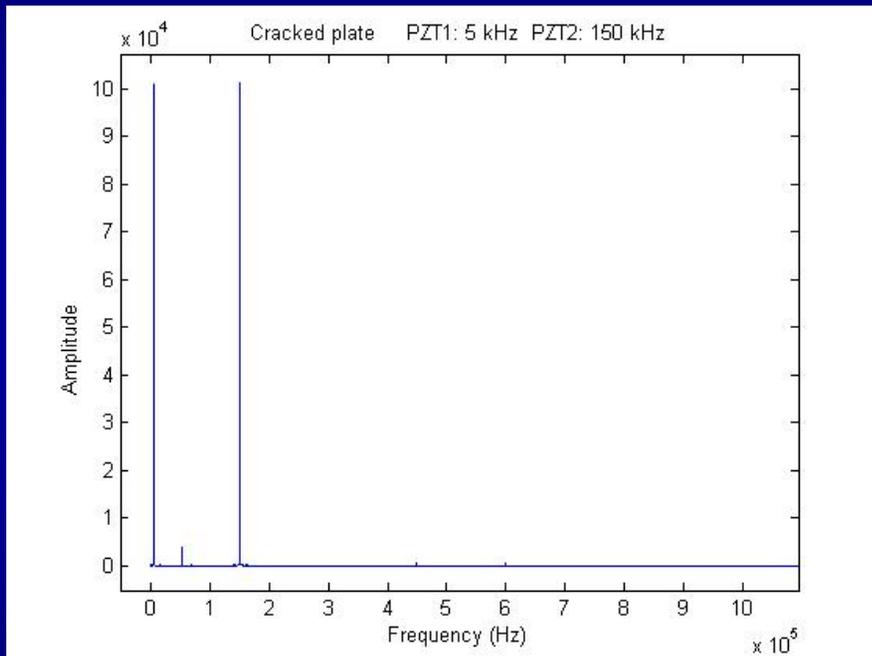
The FFT of the uncracked plate showed less pronounced harmonics

But a close up showed similar sum and differences

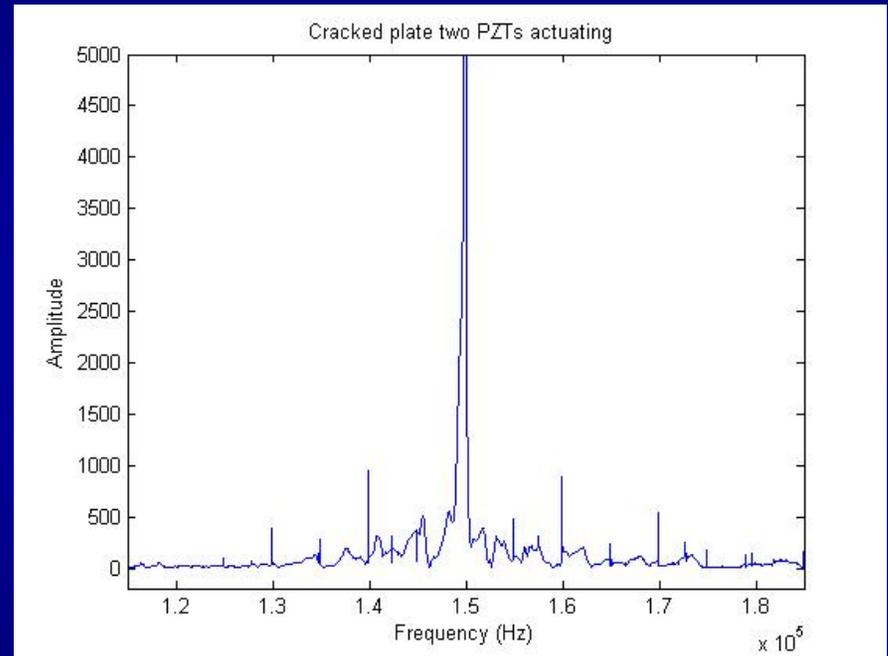
**Dual actuation with two PZTs was undertaken to see more conclusive results**



# Dual actuation with two PZTs was undertaken to see more conclusive results

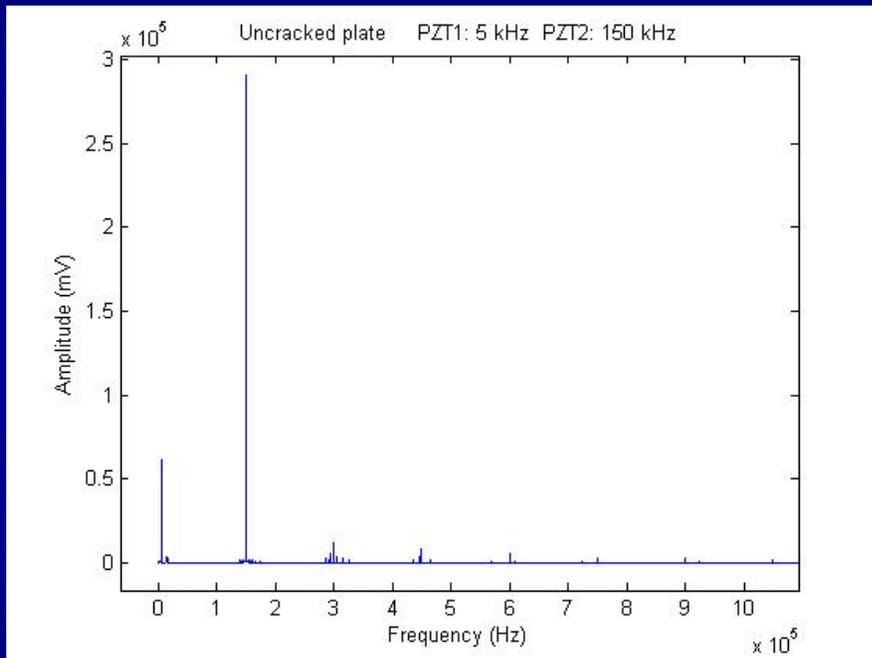


FFT of cracked plate showed very little harmonics

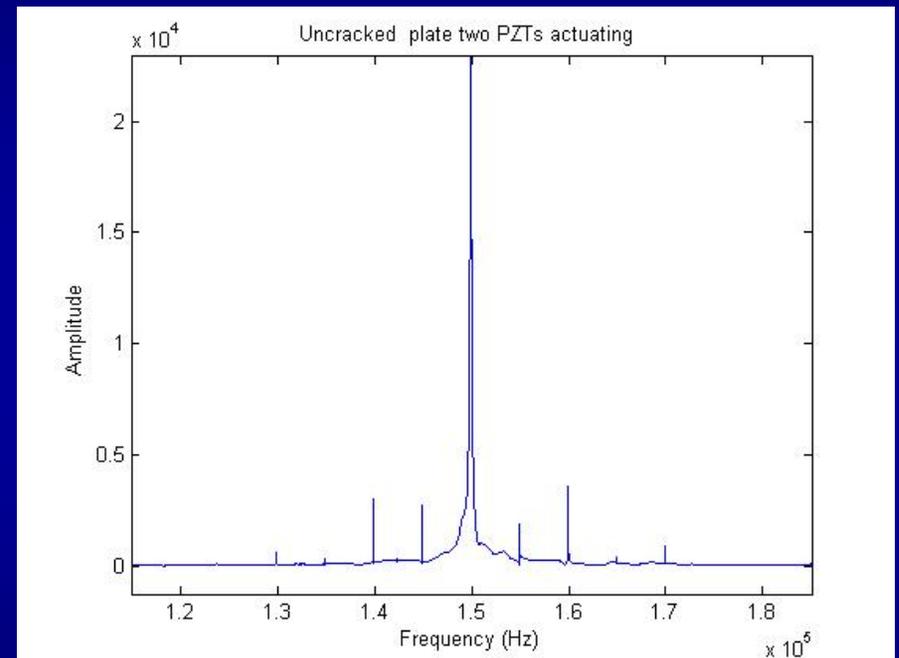


Close up showed sum and difference frequencies

# Dual actuation with two PZTs was undertaken to see more conclusive results



FFT of uncracked plate showed more pronounced harmonics

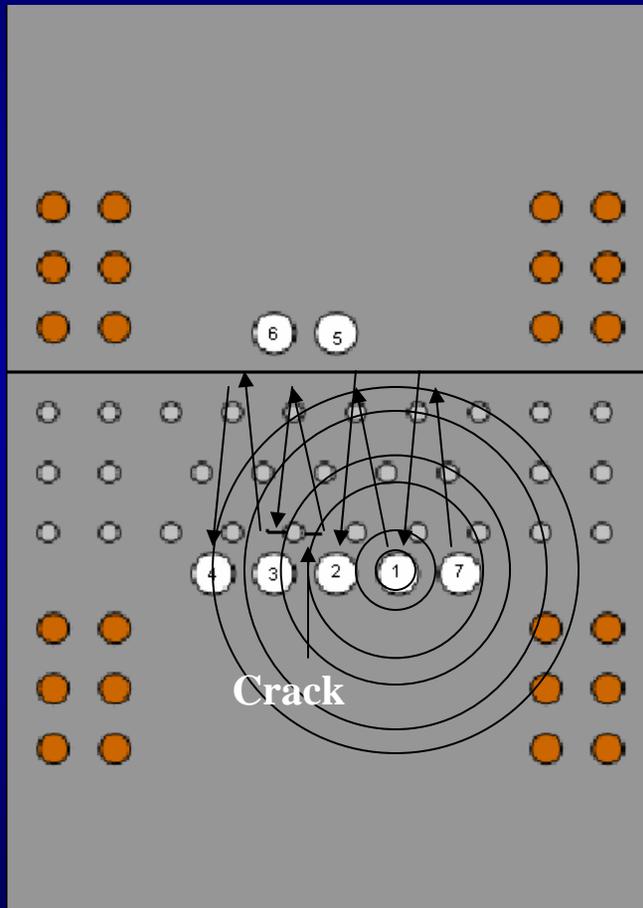


But the sum and difference frequencies were less prevalent

## Analysis of the aluminum plate experiments showed areas that need to be addressed

- Clipping issues encountered need to be dealt with
- Sources of nonlinearities must be identified
- A DAQ code tailored to the project particular requirements needs to be written
- Bigger fatigue cracks would be a better starting point

**The crack present on the lap joint was larger and should generate nonlinearities more readily**



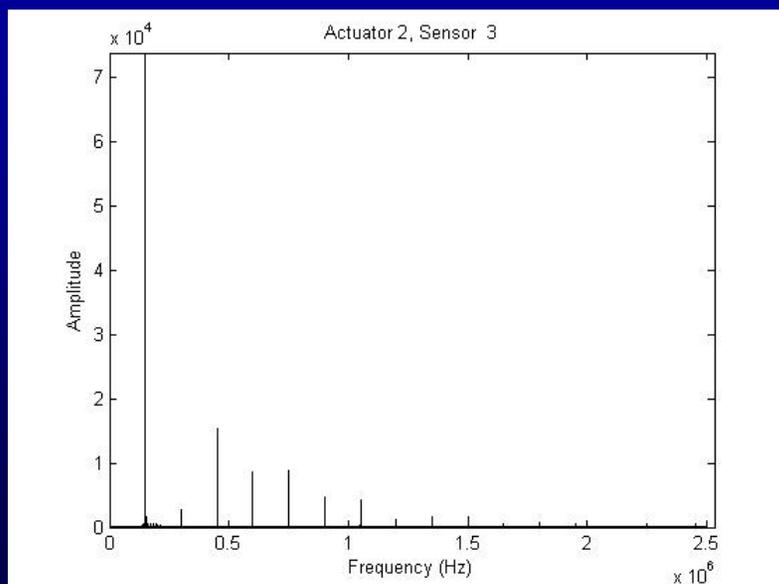
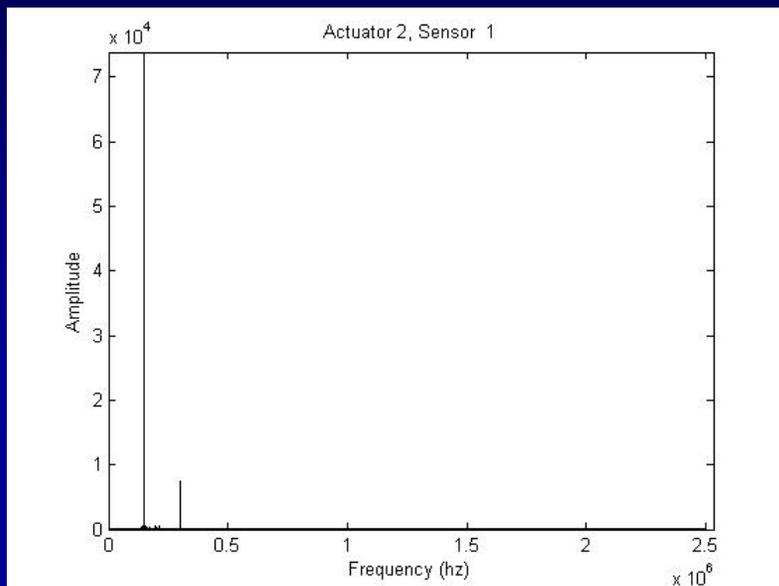
**Crack measures 10mm on either side of hole**

**Multiple pitch-catch**

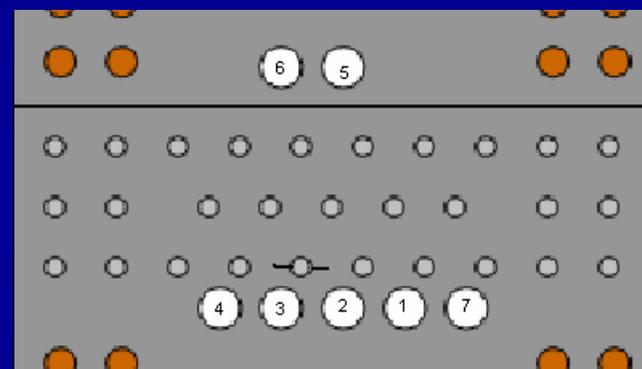
**Adjacent paths**

**Two frequency excitation**

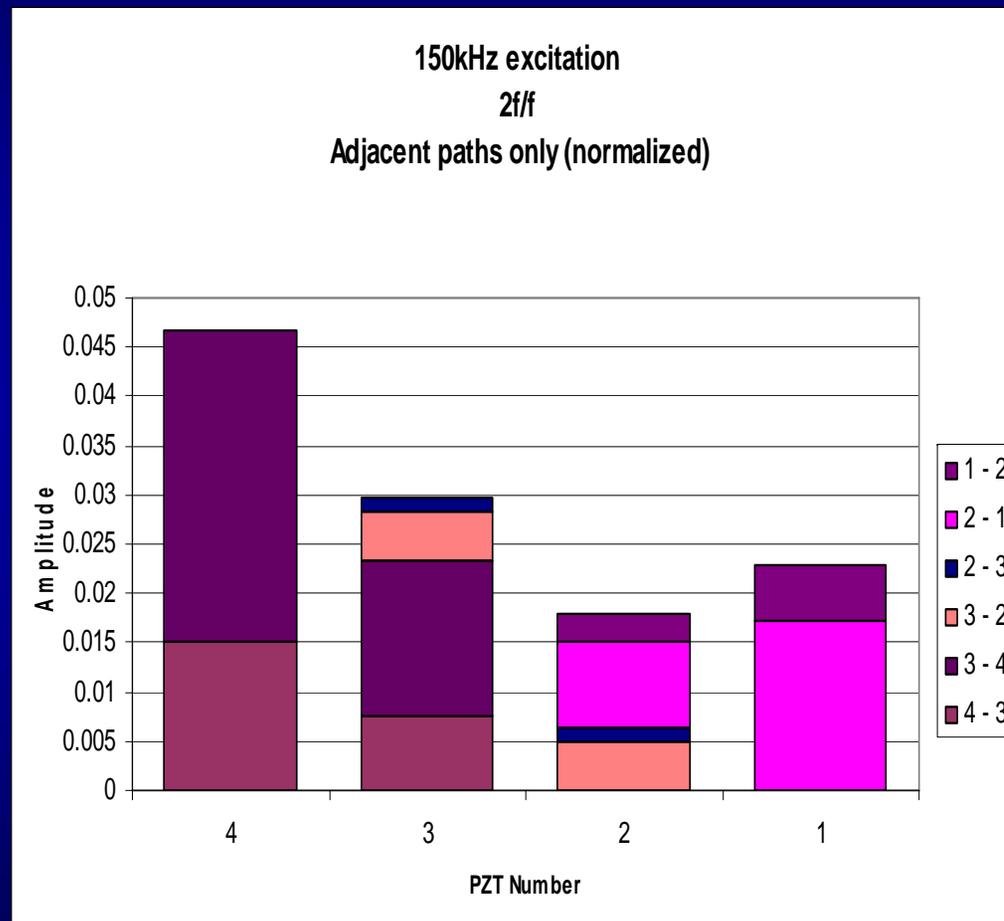
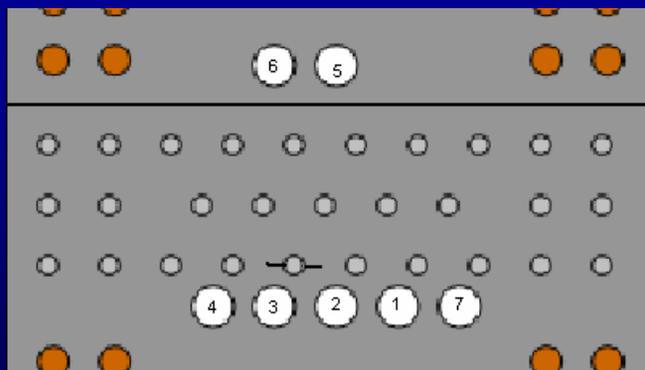
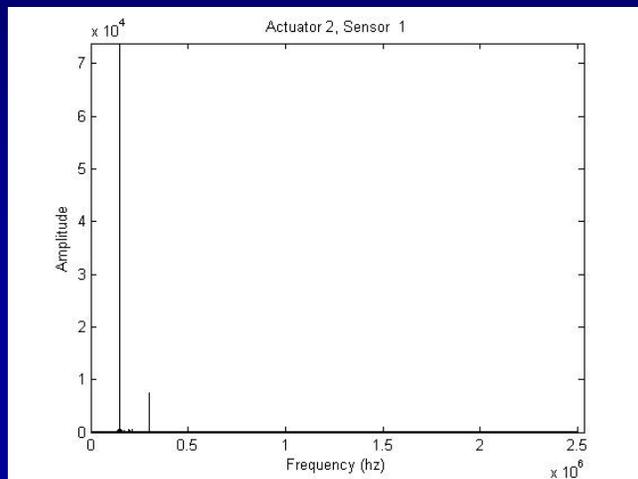
# Increased harmonic amplitude appears in paths that directly interact with crack



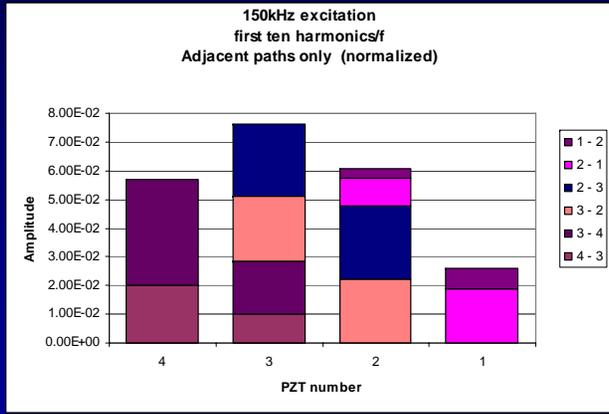
Excitation with a 150 k Hz sine wave



# The ratio of drive frequency to first harmonic amplitudes was explored as a method for crack location

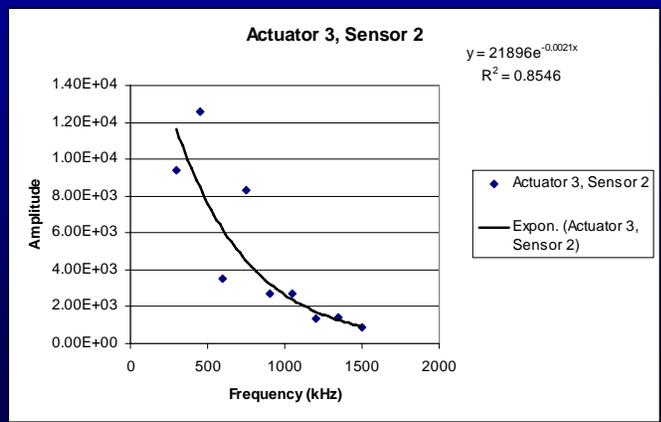
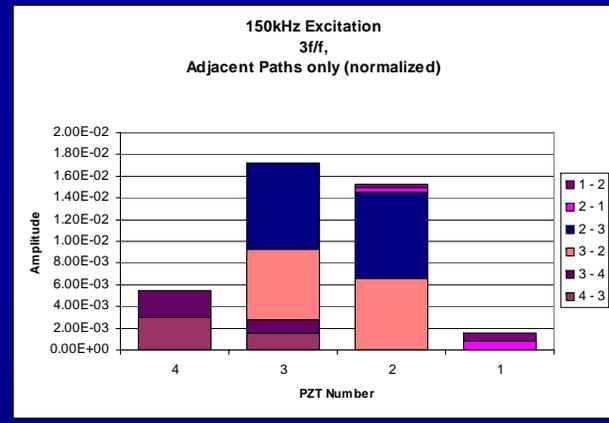


# Several methods of locating the crack were explored



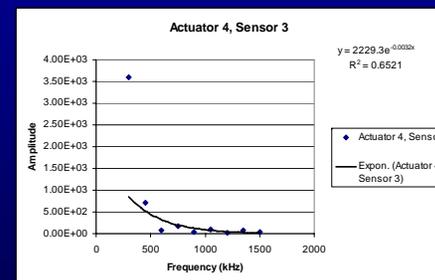
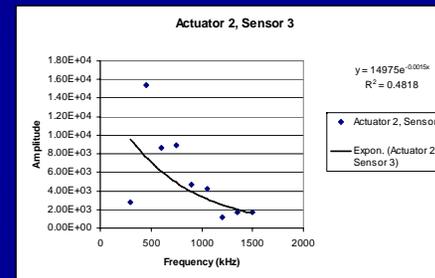
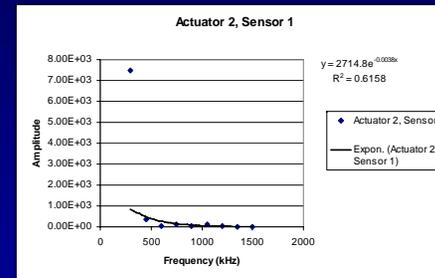
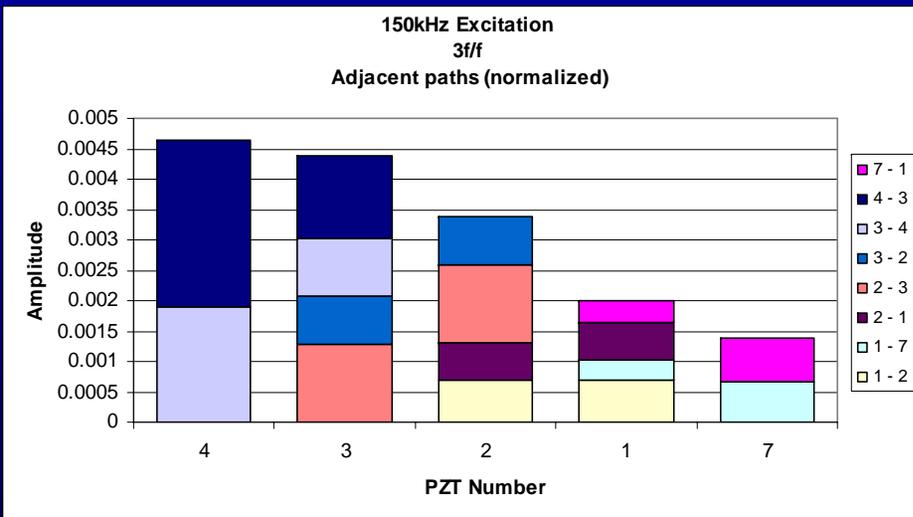
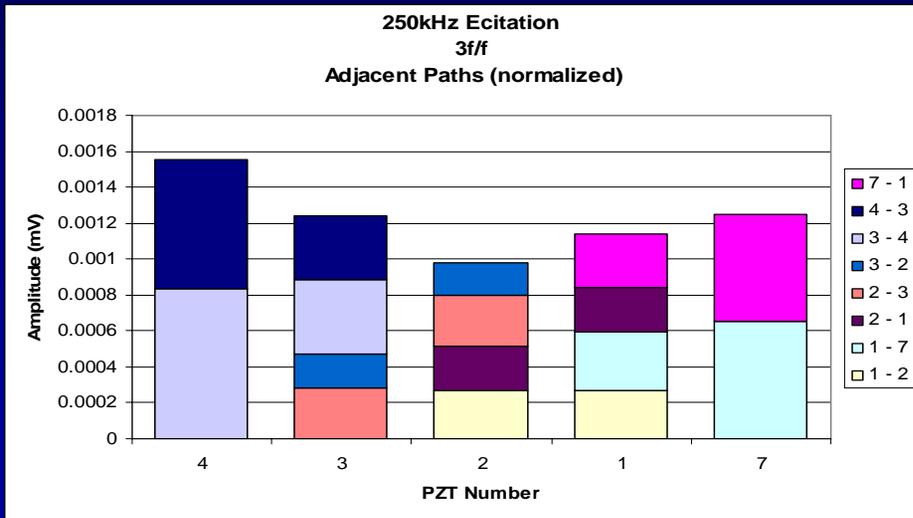
Sum of the amplitudes of the first ten harmonics divided by the amplitude of the driving frequency

Amplitude of the of the second harmonic (3f) divided by the amplitude of the driving frequency

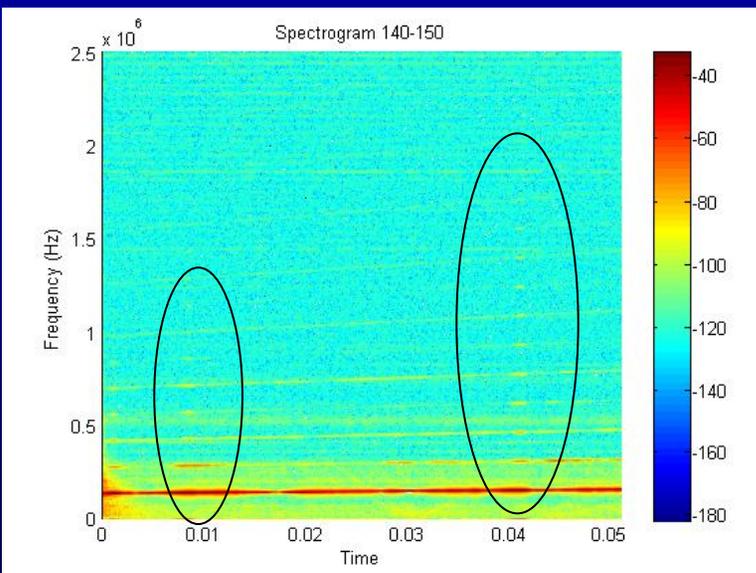
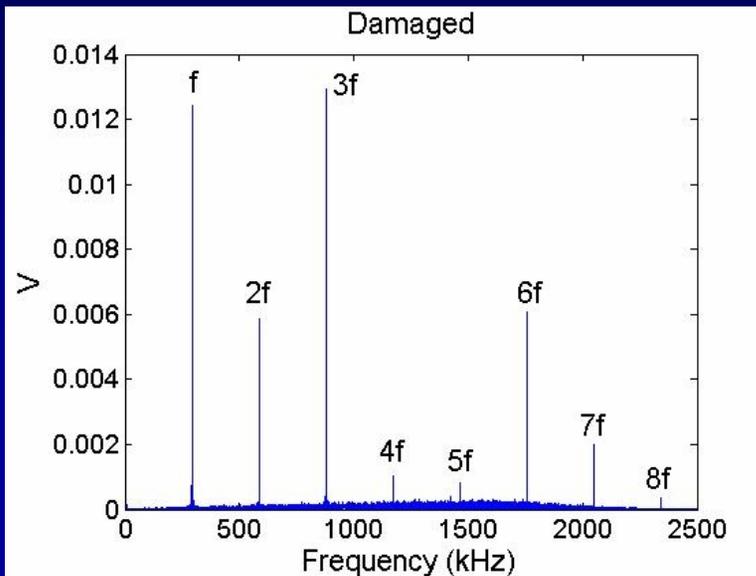


Exponential curve fit of harmonic amplitudes

# A consistent method of locating the crack was not found



# Detection of fatigue cracks with nonlinear acoustics is worth further study



**Nonlinearities exist in the cracked plate**

**Other sources of nonlinearity:  
Clipping  
Electronics**

## We would like to acknowledge:

1. The Los Alamos National Laboratory - University of California Engineering Institute for hosting the Los Alamos Dynamics Summer School
2. Funding support from Los Alamos National Laboratory
3. Mike Bode and Sandia National Laboratory for providing the plates
4. Vibrant Technologies (MeScope software)
5. The Mathworks, Inc. ( Matlab, Simulink, XPCTarget)
6. ABAQUS, Inc. (ABAQUS finite element analysis software)
7. The support from our mentors Anthony Puckett, Gyuhae Park, Laura Jacobs, Charles Farrar, Miles Buechler, TJ Ulrich, Pete Avitabile
8. Steven Anton (Labview help)

## References

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