

IMPROVED MATERIAL CHARACTERIZATION OF COMPOSITES USING PLATE WAVE DISPERSION DATA

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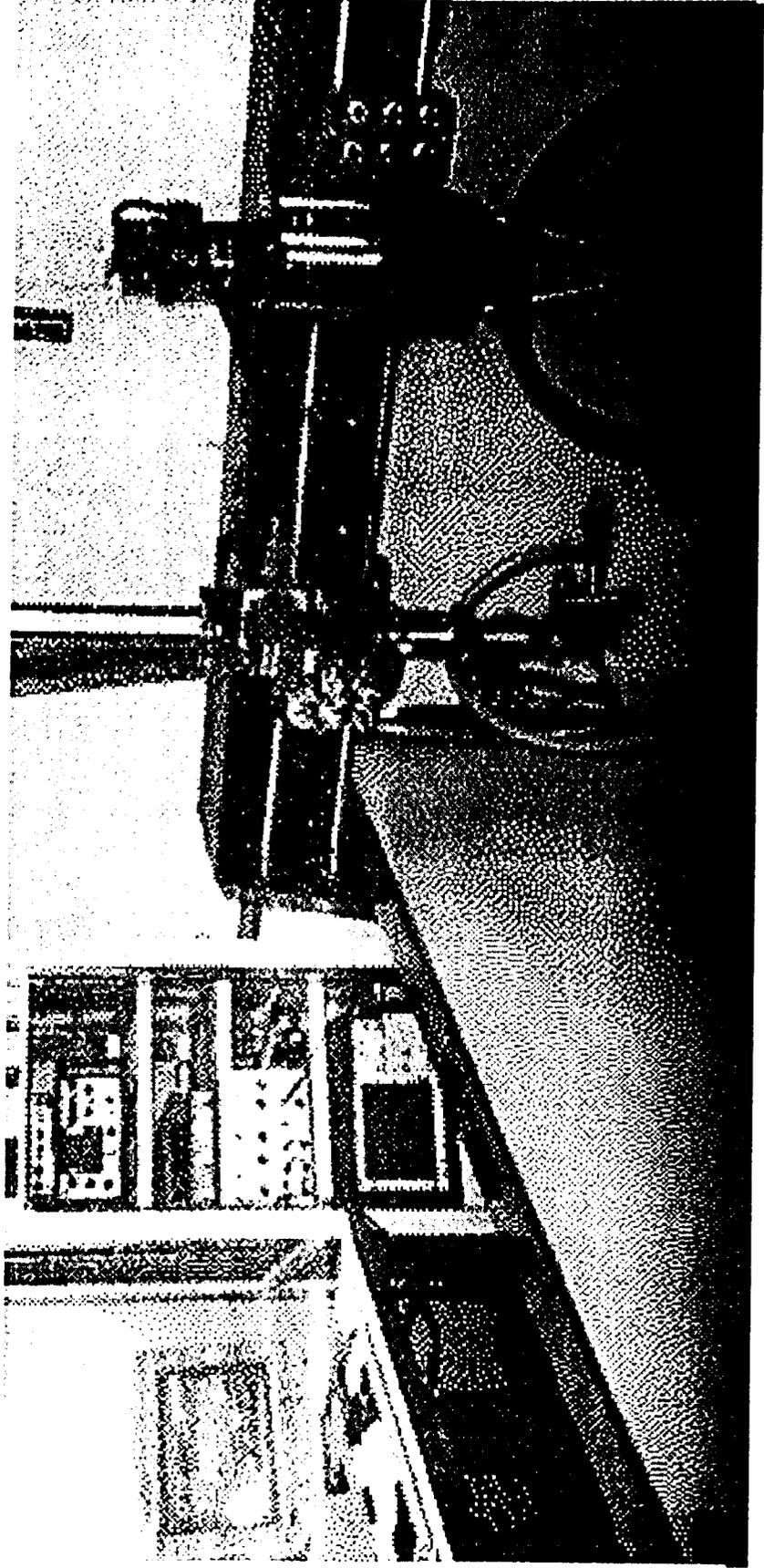
Leaky Lamb Wave NDE of Composites

Background

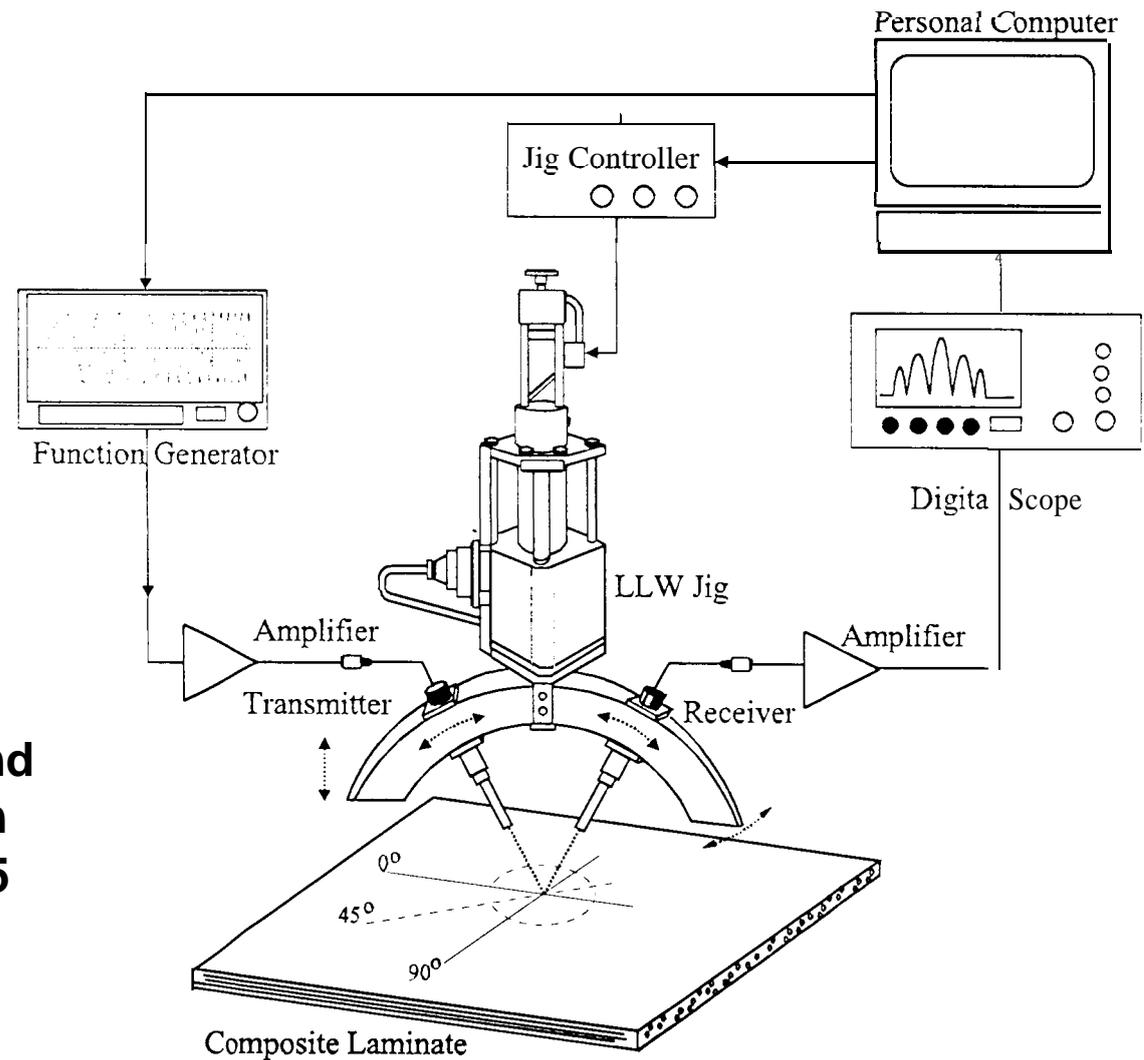
- Phenomenon discovered in 1983 *
- Very good agreement between theoretical analysis and experimental data
- An efficient setup was developed for data acquisition
- Inversion algorithms were developed to allow determination of the elastic constants
- Method was applied to NDE of defects imaging and characterization

* Bar-Cohen & Chimenti

LLW TEST SETUP



LLW SCANNER AND TEST SYSTEM



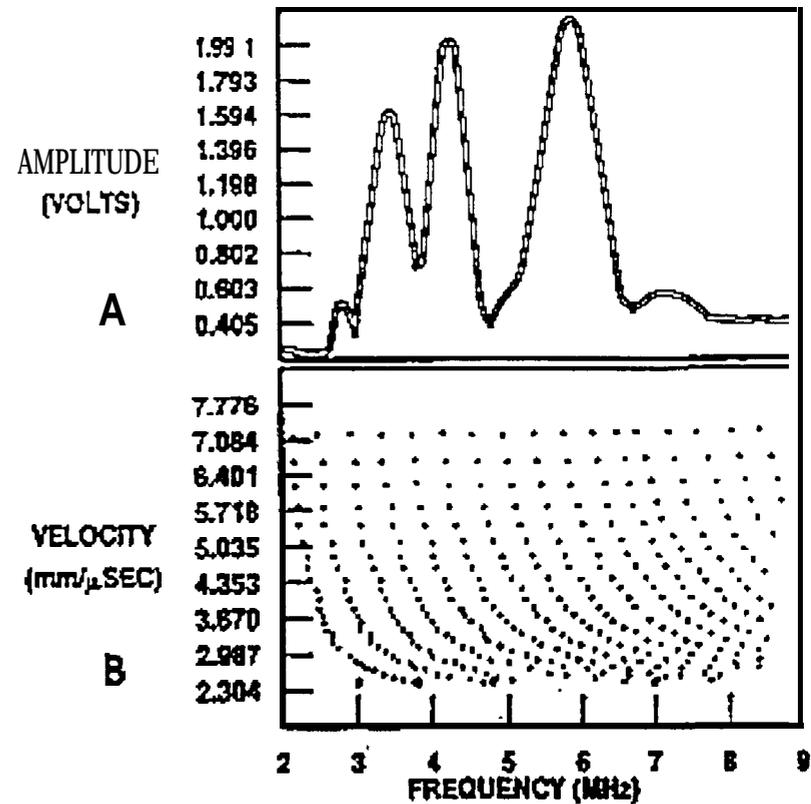
The LLW scanner is computer controlled and the dispersion data can be obtained at about 45 seconds

LLW DISPERSION DATA

Data Acquisition Process - Computer Display

Spectra at a given angle being acquired first and modes are search by the computer

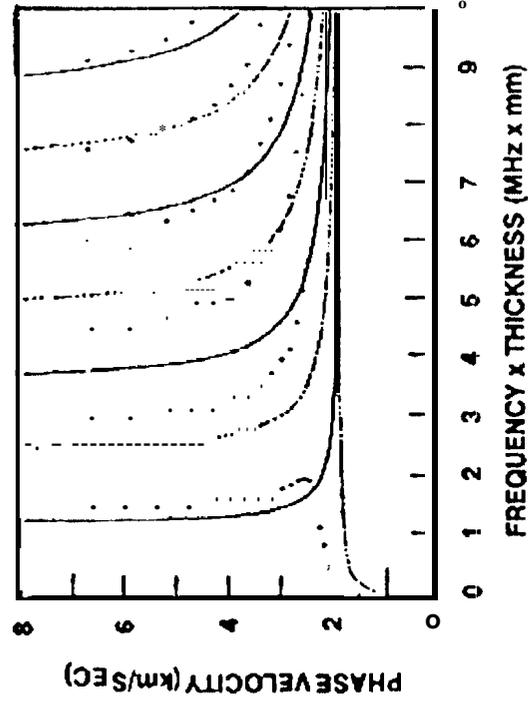
Dispersion curve is formed as an accumulation of the all the acquired modes



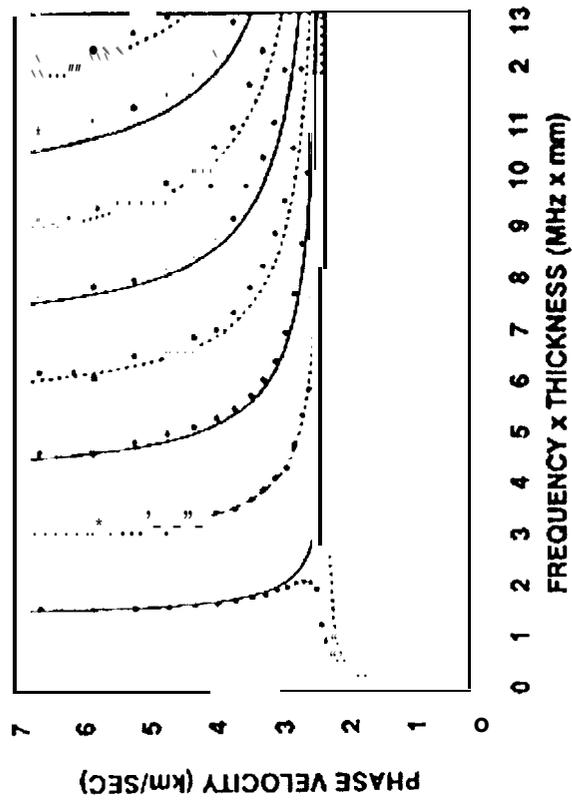
LEAKY LAMB WAVE (LLW) DISPERSION CURVE

$[\frac{0}{90}]_8$ Gr/Ep Laminate along the fibers

a. ASSUMED ELASTIC PROPERTIES



b. INVERTED ELASTIC PROPERTIES



DISPERSION EQUATION FOR COMPOSITE MATERIAL AS ORTHOTROPIC MEDIA

The dispersion equation for composite material can be expressed as

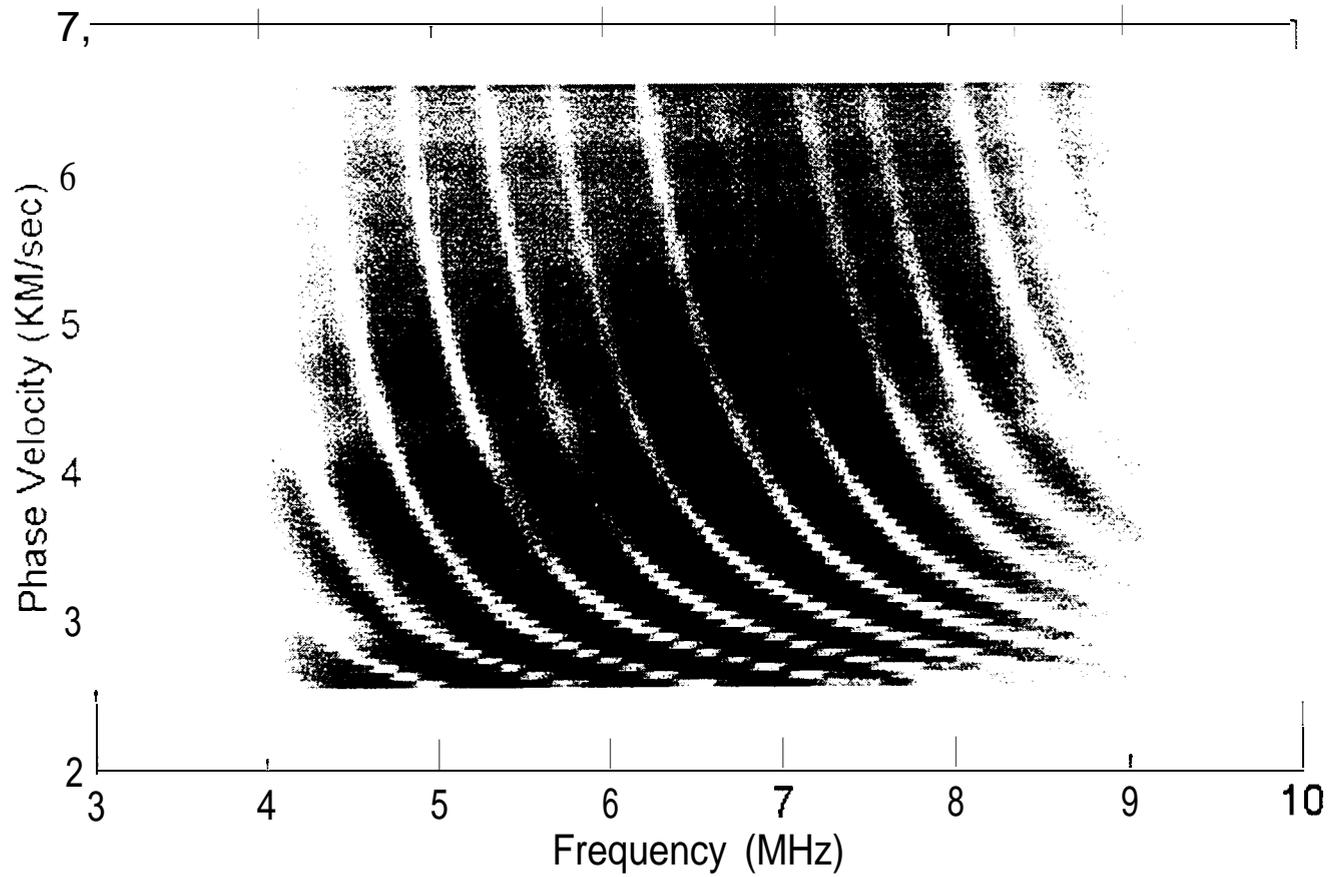
$$\Delta_1 \cot(\zeta_1 \omega H / 2) + \Delta_2 \cot(\zeta_2 \omega H / 2) + \Delta_3 \cot(\zeta_3 \omega H / 2) = 0$$

for symmetric mode, and

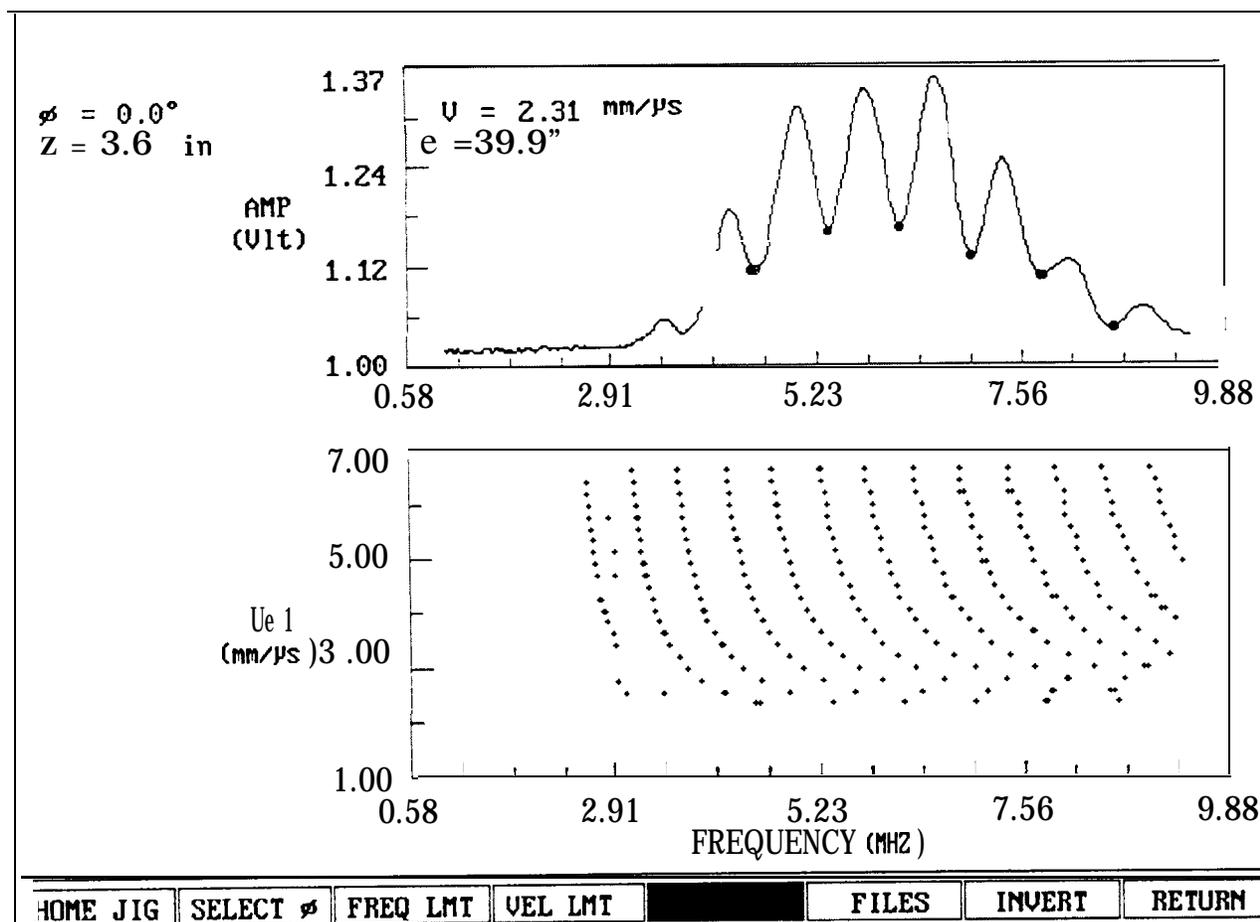
$$\Delta_1 \tan(\zeta_1 \omega H / 2) + \Delta_2 \tan(\zeta_2 \omega H / 2) + \Delta_3 \tan(\zeta_3 \omega H / 2) = 0$$

for anti-symmetric mod. Where H is thickness of the plate and the parameters A_i, ζ_i are functions of the elastic constants c_{ij} , and the density of the composite materials, respectively. Thus, the related material constants can be inverted for the experimental data through above equations.

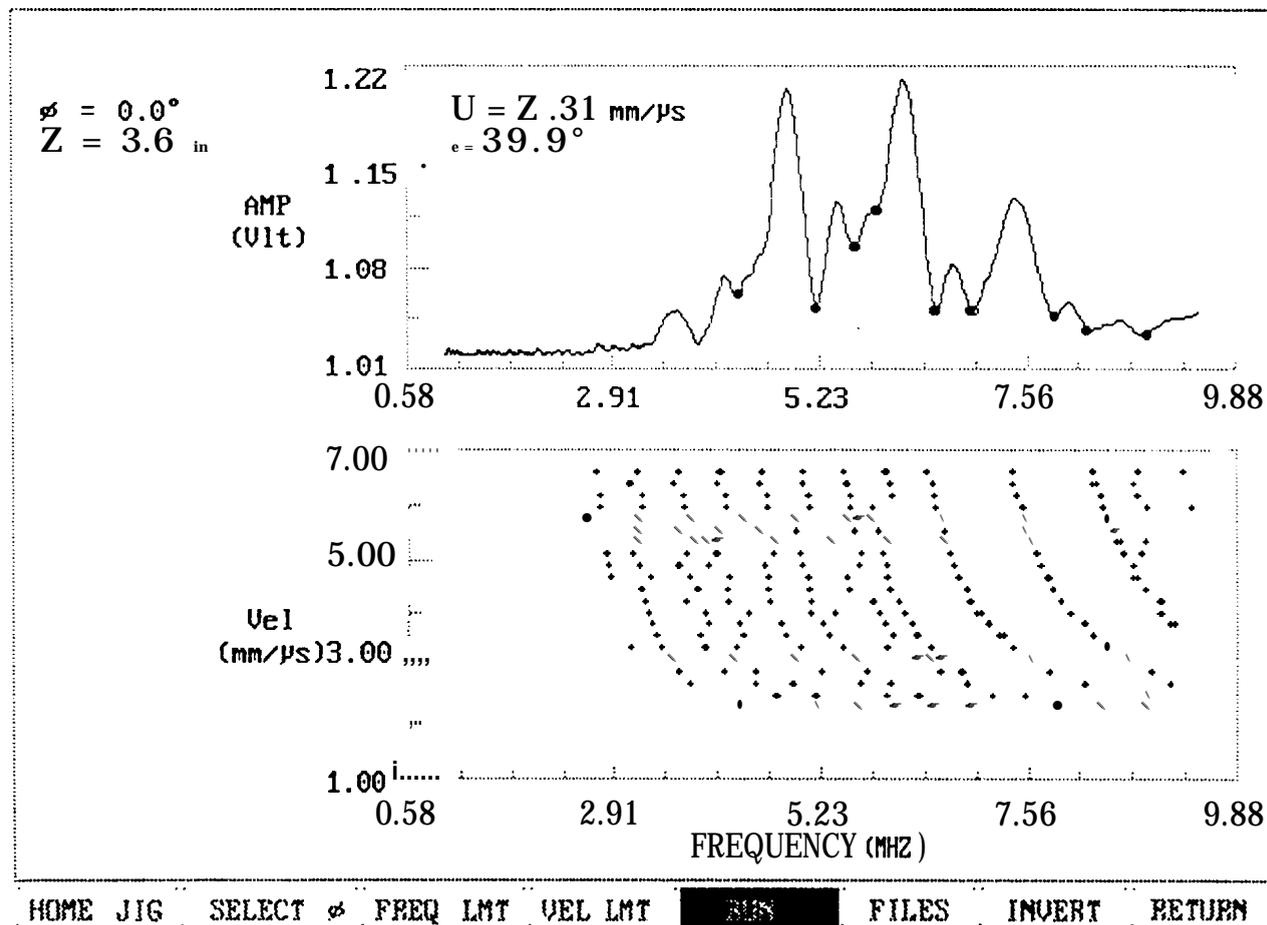
DISPERSION CURVE EXPERIMENTAL DATA



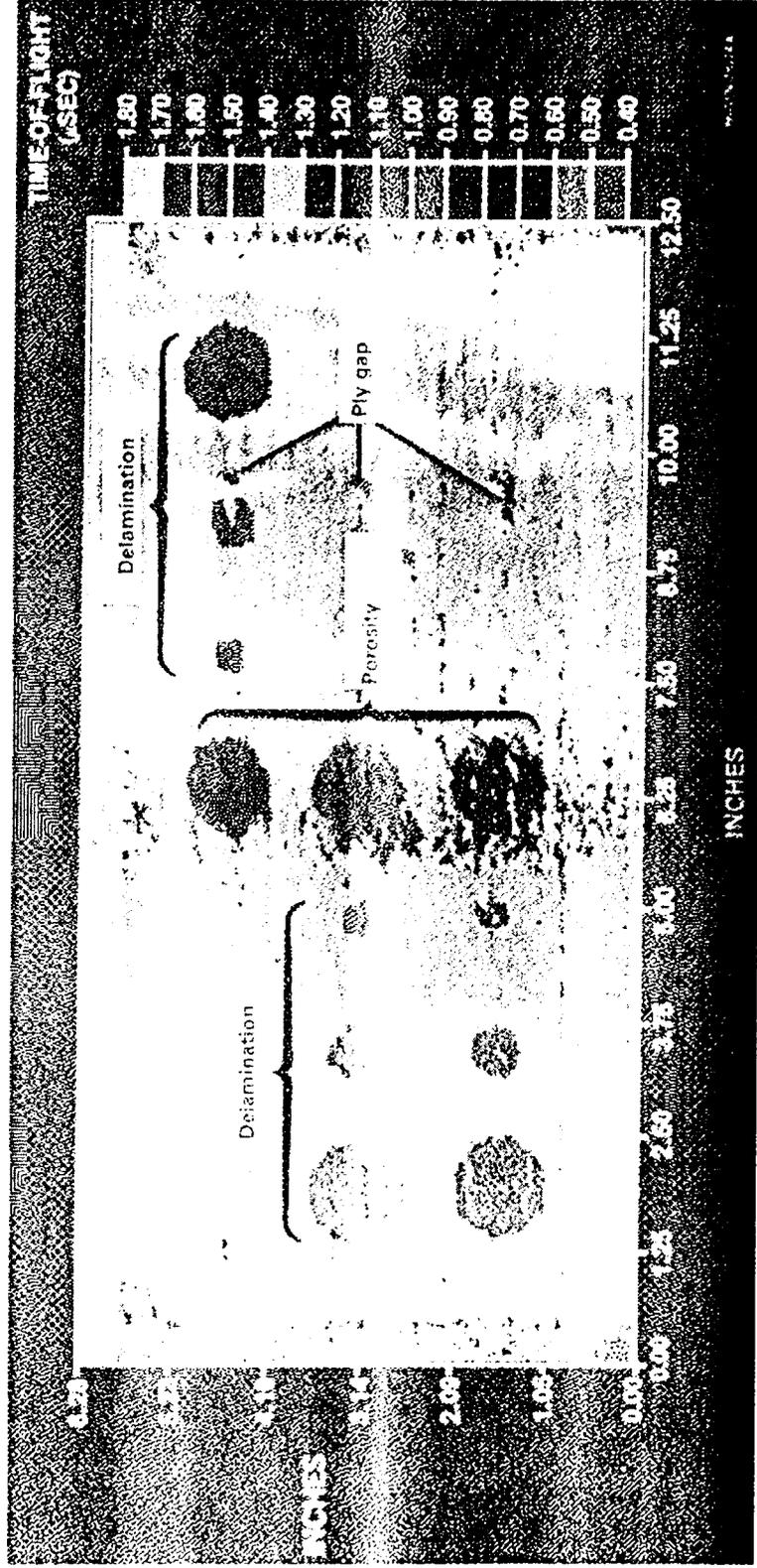
DISPERSION DATA AND REFLECTION AT 39.9° FOR Gr/Ep [0]24 LAMINATE



DISPERSION DATA FOR POROSITY AT THE MIDDLE LAYER OF [0]24 Gr/Ep LAMINATE



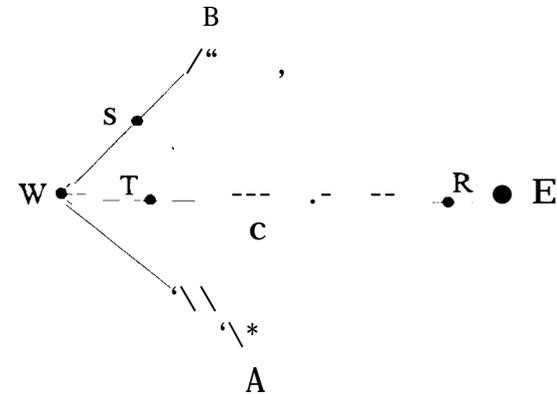
W C-scan of σ_8 Gr/Ep Laminate



SIMPLEX ALGORITHM

(Using two-variable problem as an example)

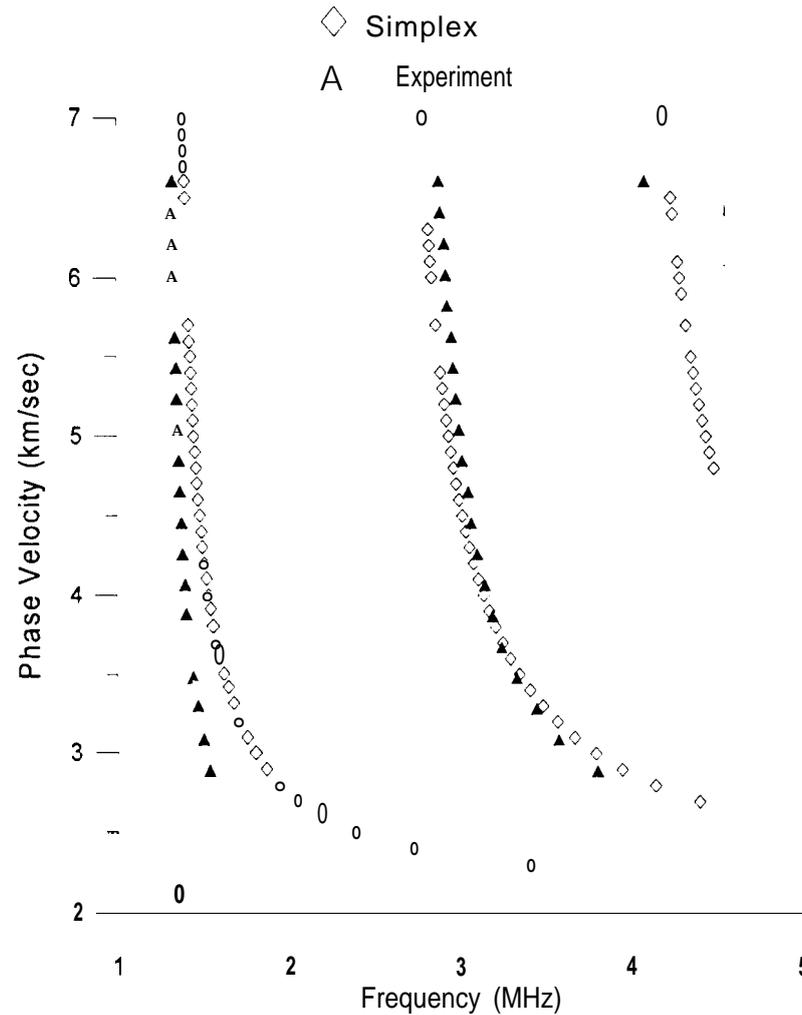
- consider each set of the two variables as a point in a space of dimension two. The point is called a vertex.
- A Simplex is a geometrical figure that consists of three vertices, as shown in the figure.
- To best fit the experiment data, the Simplex is moved according to the following rules:
 - (a) Find the best and worst vertices.
 - (b) Replace the worst vertex by another vertex according to one of the four mechanisms: reflection, expansion, contraction, and shrinkage.
 - (c) Continue the process until “satisfactory” result is obtained.
- In the figure, B is the best vertex, W is the worst vertex, A is the third vertex; C is the center of AB, R is the reflected vertex, E is the expanded vertex, S is the shrunken vertex, and T is the contracted vertex.



SIMPLEX APPROACH

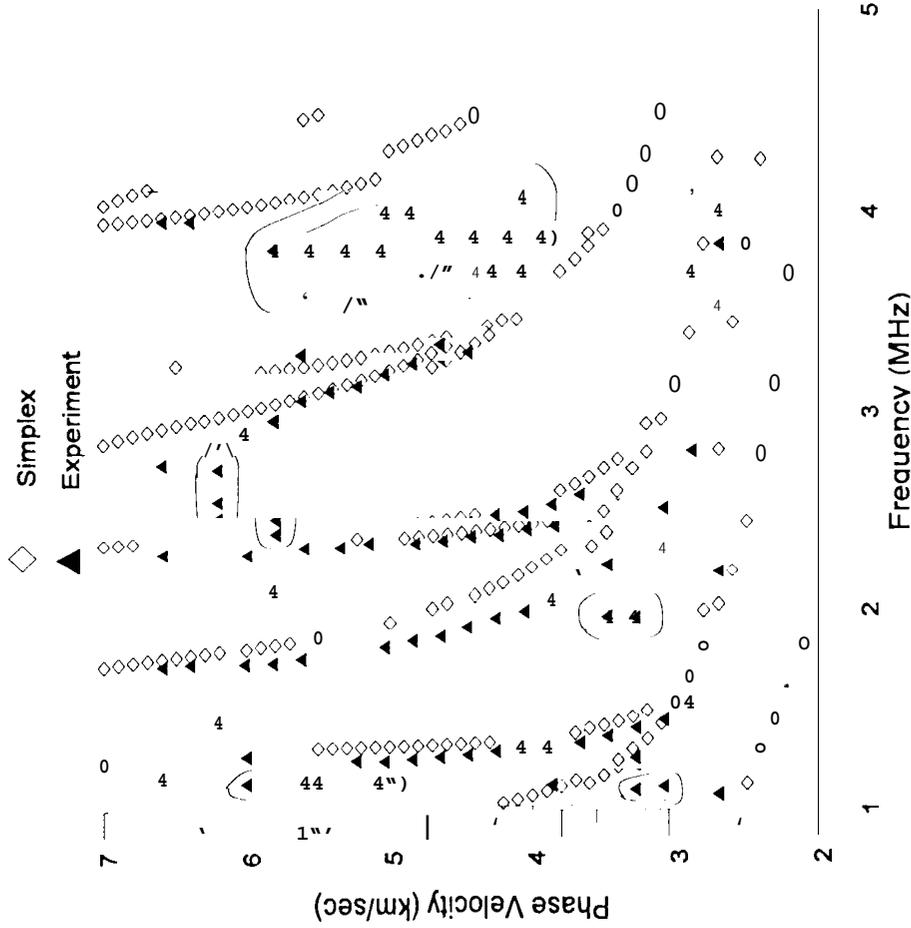
- Use the Simplex to derive a set of material constants which best fit the original experiment data.
- . Use the material constants to construct the dispersion curves and compare with the original experiment data.
- Remove the experimental data that are noise or experimental error.
- Use the Simplex again to derive a set of material constants for the modified experiment data.

EXPERIMENTAL CORROBORATION OF THE SIMPLEX ANALYZED DISPERSION CURVE FOR A UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATE (ALONG THE FIBER ORIENTATION)



Thickness = 1.19-mm, $\rho = 1.588\text{-g/cc}$,
 $C_{11} = 161.34\text{-GPa}$, $C_{12} = 6.78\text{-GPa}$, $C_{22} = 17.75\text{-GPa}$, $C_{23} = 6.88\text{-GPa}$, $C_{55} = 7.76\text{-GPa}$.

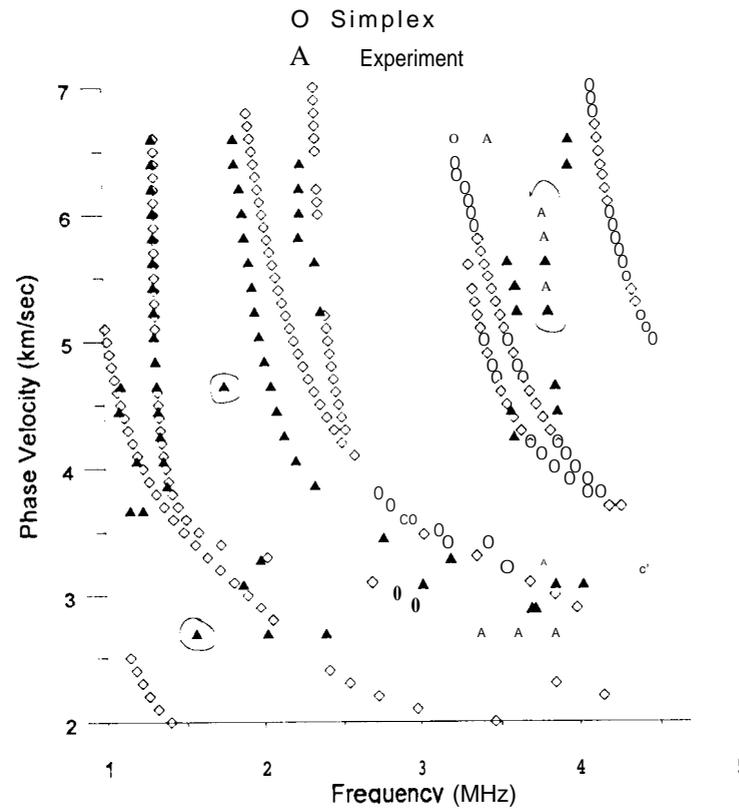
EXPERIMENTAL CORROBORATION OF THE SIMPLEX ANALYZED DISPERSION CURVE FOR A UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATE (ALONG THE 45° POLAR ANGLE)



Thickness = 1.19-mm, $\rho = 1.588\text{-g/cc}$,
 $C_{11} = 161.34\text{-GPa}$, $C_{12} = 6.78\text{-GPa}$, $C_{22} = 7.75\text{-GPa}$, $C_{23} = 88\text{-GPa}$, $C_{33} = 7.76\text{-GPa}$

Note: Circles indicate the data points excluded when using the Simplex algorithm.

EXPERIMENTAL CORROBORATION OF THE SIMPLEX ANALYZED DISPERSION CURVE FOR
A UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATE (ALONG THE 90° POLAR ANGLE)



Thickness = 1.19-mm, $\rho = 1.588\text{-g/cc}$,

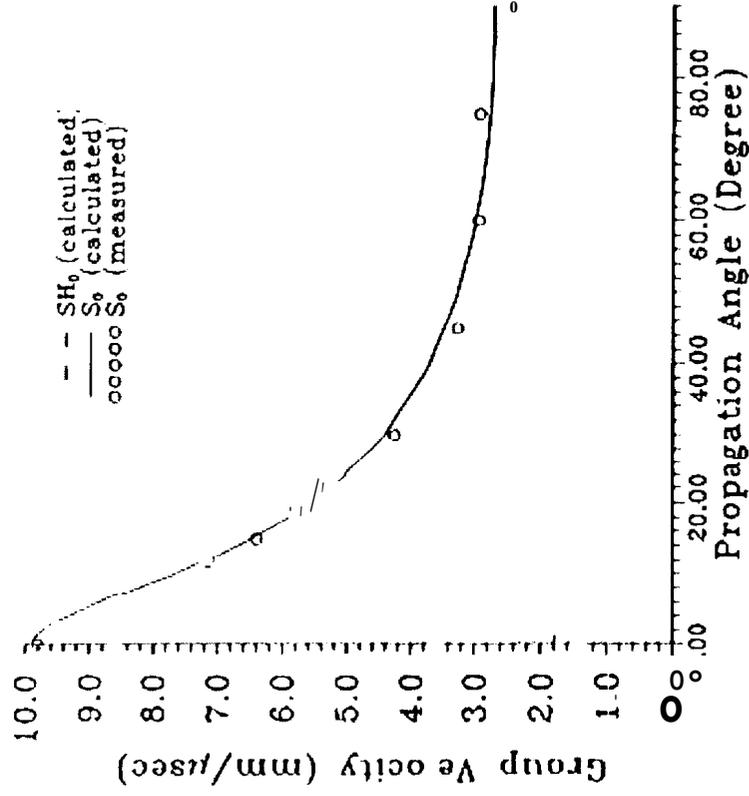
$C_{11} = 161.34\text{-GPa}$, $C_{12} = 6.78\text{-GPa}$, $C_{22} = 17.75\text{-GPa}$, $C_{23} = 6.88\text{-GPa}$, $C_{55} = 7.76\text{-GPa}$.

Circles indicate the data points excluded when using the Simplex algorithm.

Application of LLW Data inversion of Elastic Properties: Fire Damage Assessment

- Fire damage to composites is causing initially material degradation and as the damage becomes more severe, physical flaws appear.
- Repair of aerospace structures exposed to thermal damage or removal of all the infected sections.
- Practical NDE methods are unable to indicate thermal infection unless physical damage already occurred (cracking, delamination, etc.)

Measured & calculated group velocity for the extensional mode Ξ_3 propagating at 0° to 90° with the fibers in a unidirectional G^R & 3.175-mm thick plate.

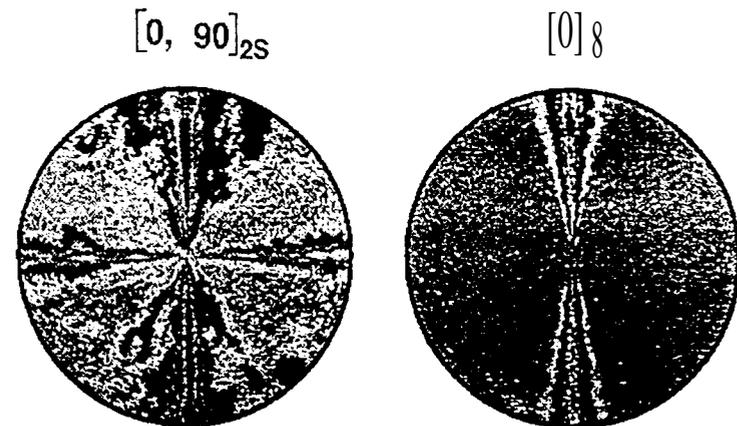


AUTOMATION OF THE LLW SYSTEM CALIBRATION

Setting up a LLW experiment requires the alignment of the sample plane in relation to the LLW transducers in terms of the beam-crossing height as well as the polar angle.

- HEIGHT SETTING - ^{adjustment} The height is being set by optimizing the relation between the maximum reflection amplitude and the LLW minima height. An algorithm was coded to allow such setting. ^{Sample}

- POLAR ANGLE SETTING - Using the polar backscattering technique the maximum scattering amplitude is searched to identify the direction of the first layer.



Concluding Remarks

- LLW measurements allow assessment of the matrix dominated properties.
 - At high frequencies the model requires analysis of the influence of the individual layers.
 - Low frequency analysis can provide global laminate properties.
 - LLW data inversion can be used to gauge the material degradation due to manufacturing (e.g., porosity, excessive resin) and service (e.g., fire) causes.
- All five constants of a composite laminate can be determined using pitch-catch pulse experiments.
- The recent enhancement of dispersion curves acquisition speed makes the characterization of defects using LLW an effective NDE tool