HIGHER ORDER NONLINEARITY MEASUREMENT TECHNIQUES IN THIN ADHESIVE LAYER

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INTRODUCTION

In a recent paper [1] a nonlinear method was suggested to evaluate adhesive joint quality and it was pointed out that nonlinear measurements are more directly correlated to mechanical strengths than linear ones. In that paper a new dynamic acousto-elastic measurement technique was introduced and shown to be sensitive enough to measure both first and second order nonlinearities at load levels of 15% of the ultimate strength. At this stress level special geometry of the adhesive joint sample is required in order to adopt the sample to a high power loading machine. Lower stress levels however can be generated by low frequency high power ultrasonic transducer which would replace the loading machine and make the technique truly a nondestructive one. The objective of this paper is to introduce a more sensitive measurement technique to measure both first and second order nonlinearities in a thin adhesive layer at stress level of 1-2% of the ultimate strength.

FIRST AND SECOND ORDER NONLINEARITIES

Nonlinearities enter in at least two ways into acoustical measurements. either through harmonic generation of finite amplitude ultrasonic wave or through the propagation of an infinitesimally small amplitude ultrasonic wave in a stressed solid. The so-called nonlinearity parameter [2] (may be called as first order nonlinearity parameter) can be obtained by measuring the amplitude of the second harmonic as function of frequency distance and fundamental amplitude. Nonlinearity parameter can also be obtained from acousto-elastic measurements, i.e. from stress dependent sound velocities [3]. For thin adhesive layers, the harmonic generation method would require very high frequency which is not suitable because of the extremely high attenuation. Acousto-elastic measurements however can be adapted by measuring the sound velocities in the adhesive joint as a function of uniaxial compression and tension. One may write the sound velocity in terms of stress as

$$C(\sigma) = C_0 + C_1\sigma + C_2\sigma^2 \qquad (1)$$

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Here C_0 is the sound velocity in the unstressed solid C_1 which may be called the first order acousto-elastic constant related to the first order nonlinearity parameter of the material and expressed in terms of second and third order elastic constants. C_2 may be called the second order acousto-elastic constant related to a second order nonlinearity parameter of the material and can be expressed in terms of second, third and fourth order elastic constants. Depending on the direction of the stress with respect to the polarization of the ultrasonic wave C_1 and C_2 may have different forms. In order to determine C_1 and C_2 one can either use extremely high stresses to have second order term is large enough or try to eliminate the first order term by some means. For a tensile-shear lap joint of the adhesively bonded plate (Fig. 1) which is considered here the problem is rather complicated for two reasons. First because both shear and normal stresses are present and because the stress distribution is not uniform, e.g. the shear stress is much larger at the edge of the joint

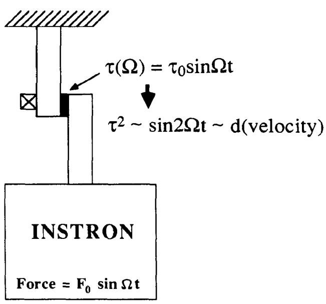


Fig. 1. Schematic Diagram of the Dynamic Acousto-Elastic Measurement in an Adhesive joint.

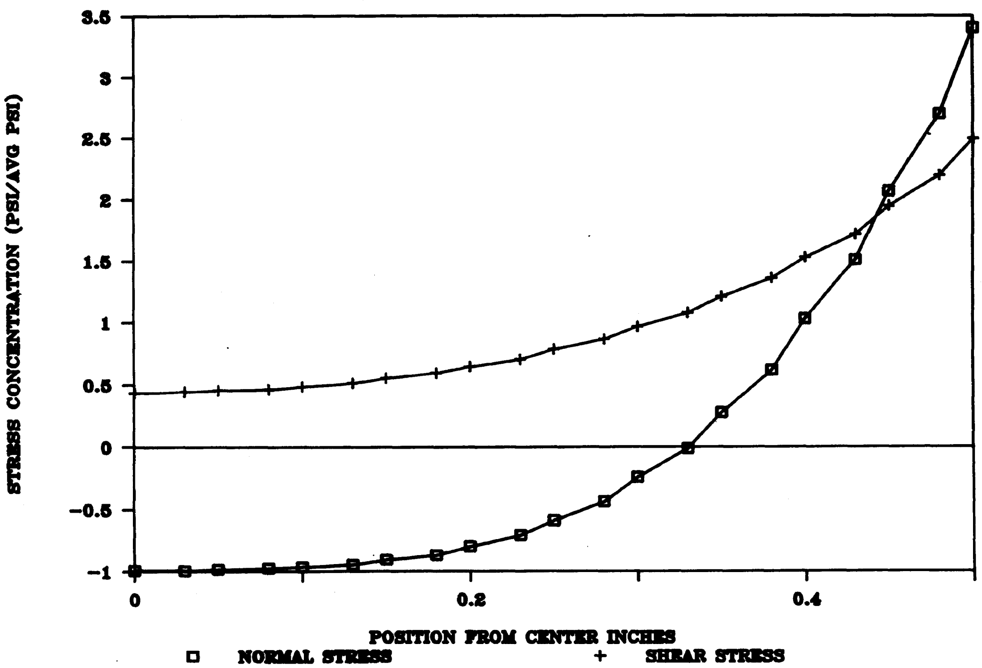


Fig. 2. Calculated Shear and Normal Stress Distribution in a 1" adhesive lap joint

than at the center. In Fig. 2, the shear and normal stress distributions are shown. The normal stress will contribute to both first and second order nonlinear effect, but the second order term is very small for moderate stresses and can be neglected and the shear stress will contribute only to the second order stress square term because of symmetry [1]. Based on the stress distribution which is shown in Fig. 2 the measurements at the center will provide the first order nonlinear term, i.e. C_1 and measurements at the edge (where the normal stress crosses zero) will result in the second order term C_2. This separation of the two nonlinear effects was demonstrated earlier [1].

SAMPLE DESCRIPTION

The adhesively bonded samples were prepared by Northrop Corp. An FM300 structural adhesive of approximately 200 μm thick was applied per manufacturers specifications (American Cyanamid). The adherends were two aluminum plates of 3/8 inch thick. These were machined into symmetric single lap tensile shear specimens shown in Fig. 3.

Both geometry and material properties (of the adhesive adherend) play a role in the stress distribution in the adhesive joint. Based on a model introduced by Goland and Reissner [4], the stress distribution for a .35" lap is shown in Fig. 4. We have shown earlier in Fig. 2 the same calculations for a 1" overlap.

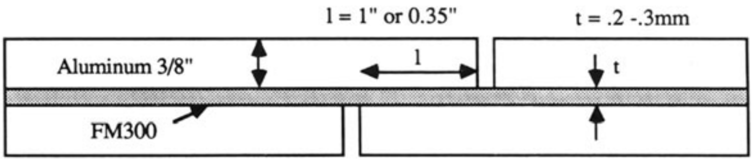


Fig. 3. Sample Geometry.

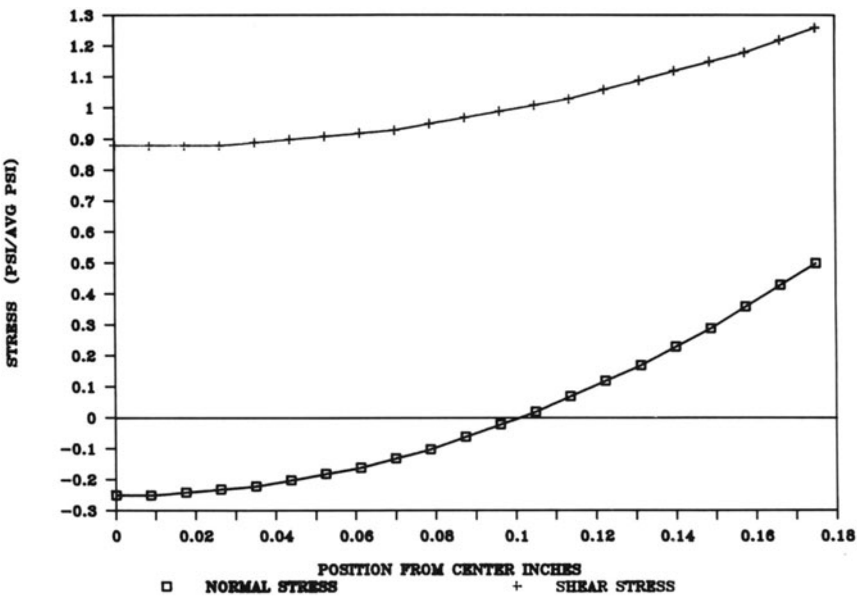


Fig. 4. Calculated Shear and Normal Stress Distribution in a .35 Inch Adhesive Lap Joint.

To determine the stress level within the aperture of a .25" transducer the stress and stress squared were integrated over the transducer face area for various positions. The results are summarized in Table 1. Note the small change in transducer position from .32" causes a significant change in the shear stress squared for a 1" lap.

TABLE I

Integrated Stress & Stress^2 for a 1/4" Sensor & 1 PSI Average Shear Stress

Lap Length	Postion from Center	Shear Stress (PSI)	Shear Stress^2 (PSI^2)	Normal Stress (PSI)	Normal Stress^2 (PSI^2)
1"	0"	0.462	0.213	-0.979	0.958
1"	0.06"	0.485	0.237	-0.960	0.923
1"	0.30"	1.010	1.087	-0.115	0.308
1"	0.32"	1.128	1.362	0.137	0.454
0.35"	0"	0.923	0.855	-0.153	0.033
0.35"	0.05"	0.953	0.916	-0.095	0.040

APPARATUS

The equipment used to make velocity variation measurements is shown in Fig. 5. A mechanical actuator, a servo hydraulic Instron, responds to a 10 Hz sine wave oscillator to provide a harmonic load on the specimen. At the center of the specimen two cuts transform the tensile load into stress in the adhesive. An ultrasonic transducer is coupled to the adhesive layer. The transducer also receives the returned echoes which travel to a preamplifier. The preamplifier output is split to the box car averager and the oscilloscope. The oscilloscope waits a set delay time after pulser synchronization pulse is received. Then the oscilloscope arms itself to trigger on a zero crossing of the front adhesive surface echo output of the preamplifier. When the oscilloscope triggers it outputs a gate pulse to a delay. The delay, a second oscilloscope, outputs a gate pulse to the boxcar averager trigger after the adjustable delay time. The boxcar averager then samples the preamplifier's output voltage over a short portion of a single ultrasonic cycle. This sample is amplified and held in an analog output buffer until the next trigger arrives from the delay. A 50 Hz low pass filter smooths the boxcar's buffer voltage and outputs the resulting signal to the lock in amplifier input. The lock in amplifier measures the component of the signal in phase with the 10 Hz oscillator. The lock in amplifier also measures the 20 Hz signal component in phase with the square of the 10 Hz oscillator signal.

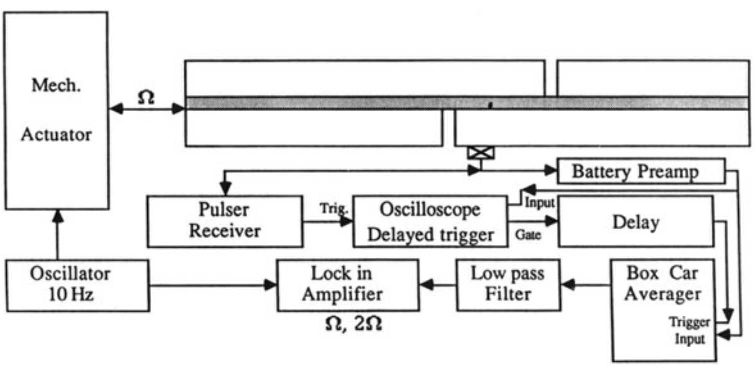


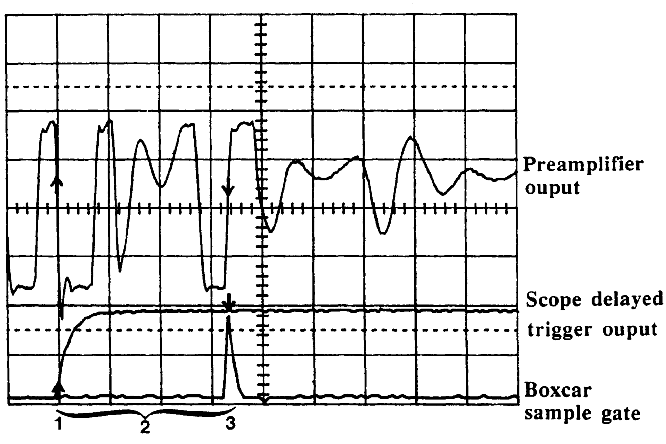
Fig. 5. Experimental System.

Time Domain Measurement

In general time domain methods are simply a measurement of the travel time between echoes. For relative change in velocity only the variation of that time is required. For high sensitivity instead of clocking the time between zero crossings we (1) trigger on a zero crossing of the front adhesive surface echo, (2) set a time delay equal to the delay between the trigger and a zero crossing of a (we used the second) back adhesive surface echo, and (3) measure the voltage when the zero crossing should occur. (Fig. 6)

Since a sine wave is a straight line as it crosses zero the voltage is proportional to the change in travel time. The only calibration required is the slope of the signal as it crosses zero. Very high sensitivity requires a large slope. To achieve high resolution very low noise is required on the signal as it crosses zero. The boxcar amplifier integrates a gated portion of a back wall echo as it crosses zero. The delay is set to give a zero average for the voltage measurement. If the velocity changes slightly a large shift in the sampled voltage near that zero crossing occurs. The delay is maintained constant with little time jitter. Jitter in delay circuits of the triggering scope, the delay circuit (a second oscilloscope) and the boxcar averager were minimized. The delay oscilloscope was selected because of its low jitter. The jitter of the boxcar amplifier's delay was minimized by using its minimum delay and augmenting this delay with the delay scope. The boxcar outputs the last gated signal average and holds it until the next pulse. A low pass filter averages these outputs, while a lock in amplifier determines the components of the velocity which vary in phase with the load and load squared.

Calibration is relatively simple. The delay is varied by 2 ns being careful to keep the box car amplifier's gate in the linear portion of the zero crossing while the change in signal output of the boxcar is determined. This ratio times the gain of the lock in gives the sensitivity.



1. **Trigger on a zero crossing of front adhesive echo.**
2. **Start delay that ends at a zero crossing of a back surface echo under a no load situation.**
3. **Measure the voltage at the end of the delay under dynamic load conditions.**

Fig. 6. Ultrasonic Echoes Amplified and Gated from an Adhesive Joint.

RESULTS AND DISCUSSION

Typical Output

Figure 7 shows two possible results for the change of spectral amplitude during the loading of a lap joint. Generally a combination of these first and second harmonics of load will superimpose. The large sine wave is the load, 500 lbs. peak, from the load cell. The first harmonic spectral output is seen when the 1/4" transducer is centered on a 1 inch lap and samples high compressive load on the sample but low shear loads. The second harmonic is visible when the transducer is positioned near the edge where high shear loads exist but the compressive load swings through zero to tension. (Fig. 2)

To make the specimen subject to almost pure shear the lap length was reduced. Initial data [1] showed how sensitive the experimental method must be to measure the variation in velocity at twice the frequency of the applied mechanical stresses (See Table II).

TABLE II

Shear Stress Relative to Ultimate Strength Vs. Relative Change in the Velocity

Shear Stress (% of 6 KSI Ultimate)	Change in Velocity dV/V (PPM)
15	300
10	130
5	33
3	12
1	1.3

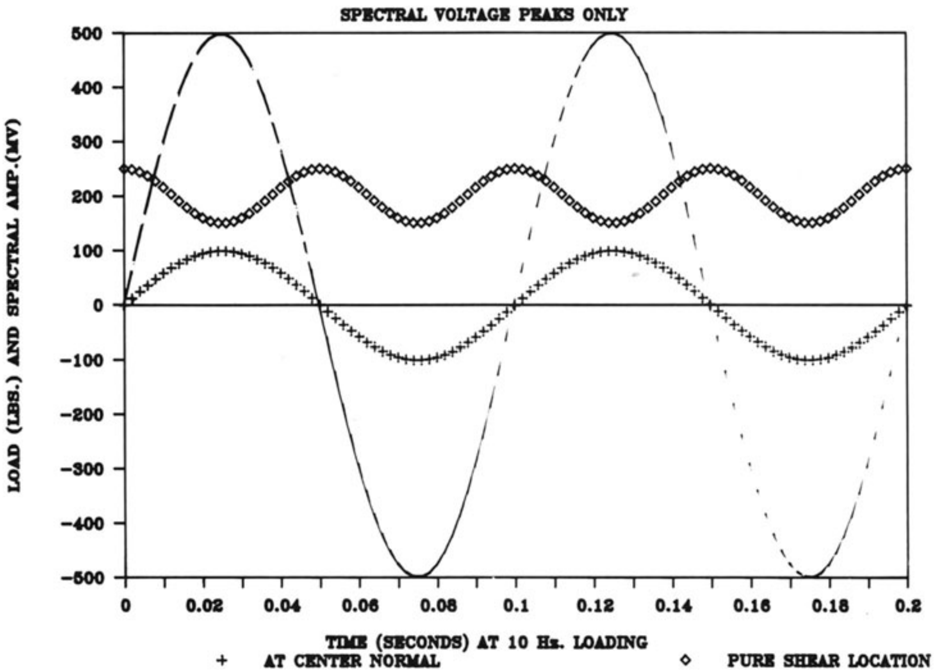


Fig. 7. Time Domain Outputs of the (a) Load, (b) First Harmonic, and (c) Second Harmonic of the Boxcar Amplifier.

The data measured between 5% and 15% of the ultimate stress was measured using the spectral method, and below 5% using the time domain technique [1]. The change in apparent velocity due to the thickness correction, is calculated for 2 cases: normal stress and shear stress. Both the apparent velocity and the thickness corrections are shown in Figs. 8 and 9. The thickness correction for the apparent velocity change is 40% under normal stress (Fig. 8); whereas the thickness correction under shear stress is only 4%. The shear thickness correction is in the opposite direction from the nonlinear material softening indicated by the apparent velocity change.

Figure 9 is plotted on a log log plot in Fig. 10. A straight line fit implies the same 2nd order acousto-elastic constant is observed at stresses between 5% and 15% of ultimate (top 3 clusters) as is measured between 1.5% and 3% (bottom 2 point clusters). The top three clusters of points were measured using the spectral method, while the bottom 2 clusters were measured using the time domain method. The time domain resolution in terms of equivalent noise bandwidth was 1.1 picoseconds or 1.7 parts per million (ppm) of the velocity. This is a significant improvement over the 60 ppm resolution of the spectral method.

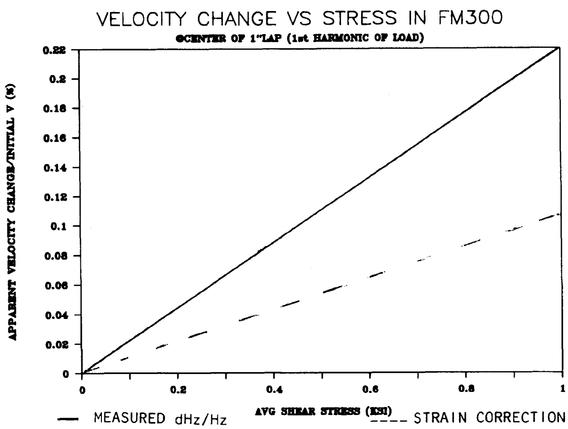


Fig. 8. Change of Velocity & Adhesive Thickness as a Function of Normal Stress

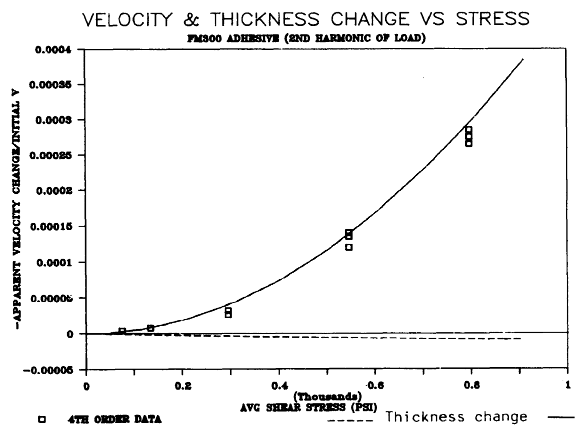


Fig. 9. Change of Shear Velocity in an Adhesive Joint and Adhesive Thickness as a Function of Shear Stress.

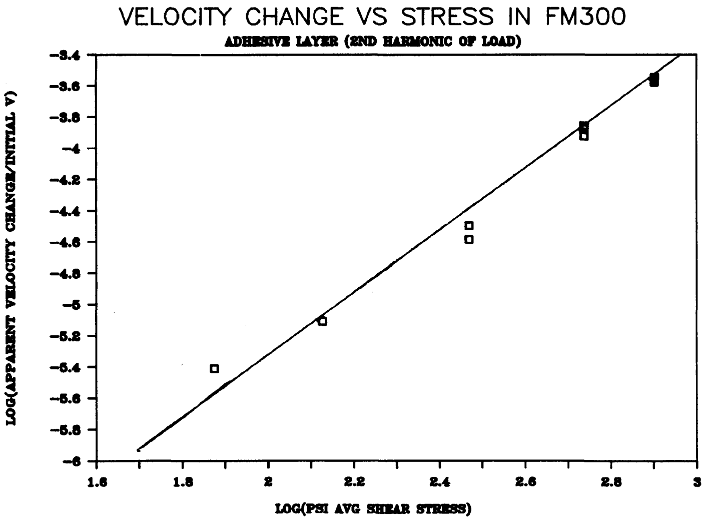


Fig. 10. Change of Shear Velocity in an Adhesive Joint as a Function of Shear Stress (Log Log Plot).

CONCLUSIONS

A modified version of a dynamic acousto-elastic measurement [5] to measure acoustic nonlinearities in an adhesive joint was introduced. This technique which is based on the time domain measurement of velocity variation under an applied stress is sensitive to measure first and second order nonlinearities in the adhesive joint at 1-2% of the ultimate strength of the adhesive joint. Velocity measurements are obtained at 1.7 part per million. Experimental results indicate that second order nonlinearities at that low stress levels are well correlated to earlier data measured [1] at 15% stress level of the ultimate strength. At these low levels of the external stress the dynamic acousto-elastic technique does not require any special geometry and can be used as a real NDE technique.

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