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Damage Detection in High-Pressure Storage Cylinders

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1 Introduction

Gaseous fuels stored at pressures up to 700 bar (10,000 psig) have created a need for an on-line damage detection system similar to the on-board diagnostic system for detecting faults in automotive components [1, 2, 3, 4]. The goal was to develop a low-cost system for detecting cuts, holes, and delamination in tanks as shown in Figure 1.

Figure 1: Dual-fuel hydrogen-gasoline truck and storage tank installation.

Electromagmetic, resistive, and ultrasonic methods were investigated. Funding and technical support were provided by Natural Resources Canada, Precarn Inc., Dynetek Industries, the University of Saskatchewan, and General Motors of Canada.

2 Electromagnetic Method

When an electromagnetic wave passes through a carbon fiber/epoxy composite, the incident magnetic field attenuates based on the frequency, conductivity, magnetic permeability, and the thickness of the material [5, 6, 7, 8]. If the composite material is damaged via fiber breakage, or delamination, the local conductivity will change and the amplitude of the magnetic field passing through the material will also change [9, 10]. Monitoring the amplitude of the wave residual passing through the composite can be utilized as a damage indicator.

Piezoelectric sensors made of polyvinylidene difluoride (pvdf) were imbedded into the carbon fiber matrix of storage tanks, as shown in Figure 2. The electromagnetic technique indicated the system was capable of detecting cuts, gouges, delamination, fatigue, heat, and stress rupture well before a leak was initiated. The tests were conducted on forty 33-L, 200-bar (3000-psi) tanks supplied by Dynetek Industries. However, although damage was detected, the receiving signals from the sensors did not show a robust, reliable response to damage.

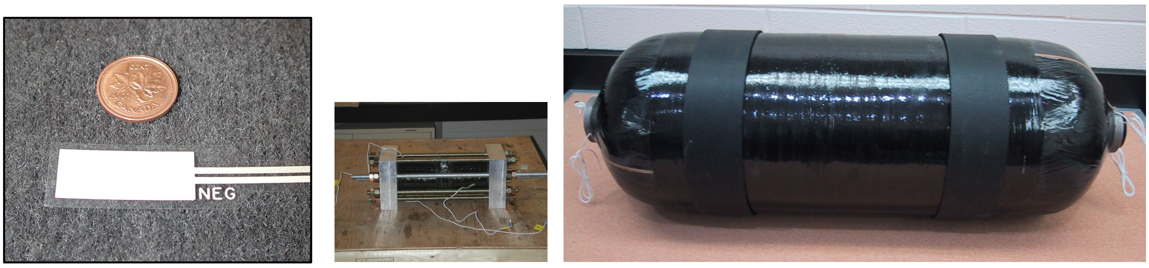

Figure 2: **PVDF sensor, tank modules, and 33-L Dynetek storage tank.**

3 Resistive Measurement

An alternative to the electromagnetic method is to directly measure the resistance of the carbon fiber as a function of resistivity, length, and cross-sectional area of fiber. If a carbon fiber is broken, the resistance of that fiber will become infinite [11, 12, 13]. If it is damaged, the resistance will increase by a finite amount.

The relationship between resistance and damage was first investigated in tank modules wound with carbon fiber, as shown in Figure 2. The results indicated that circumferential measurements were highly sensitive to impact and cut damage. Axial measurements were found to be less sensitive, but more repeatable. When the research was extended to pressurized cylinders, results obtained were similar to un-pressurized results in the axial case, but poor in the circumferential scenario. It was found that the carbon-fiber wrap must be electrically isolated from the aluminum liner, which was difficult to achieve as the tank expanded and contracted due to pressure changes.

4 Ultrasonic Method

Long-range ultrasonic testing is based on the reflection of ultrasound from an area where the sound wave meets a change in wall thickness caused by a flaw, or on the attenuation of the ultrasonic as it is transmitted past such an area, as shown in Figure 3 [9, 10]. In thin shells the ultrasonic wave is guided by the wall surfaces as plate or Lamb waves that penetrate the complete wall thickness.

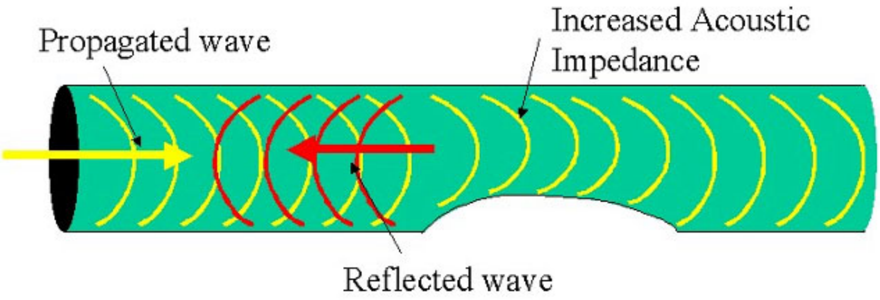

Figure 3: **Ultrasonic wave moving through a tank wall.**

Three types of ultrasonic transducers were evaluated, as shown in Table 1.

Table 1: Comparison of the transducers evaluated for cylinder inspection.

Transducer	Technical Description	Advantages/Disadvantages
Broadband piezoceramic 	0.5-MHz center frequency 0.1 to 1-MHz range 25-mm diameter element 25 x 37.5-mm footprint	Robust Expensive ~ $350/transducer Large footprint – 1.5 x 1” Rigid – requires machining to conform surface Piezoceramic may be damaged by impact
Piezoceramic Disk 	375-kHz radial center frequency 5-MHz thickness center frequency 6-mm diameter	Simple disk embedded on cylinder surface. Relatively inexpensive ~ $10/disk in moderate volumes Straight forward installation procedure Adequate signal-to-noise ratio at low to moderate excitation voltages Rigid – requires machining to conform to surface Piezoceramic may be damaged by impact
Piezoploymer Film 	10-MHz center frequency 110-µm thick 13 mm x 13 mm footprint Copper tape electrodes Wide frequency range	Supplied in large flexible sheets Tough material can survive impact damage Flexible material conforms to surface Relatively inexpensive ~ $400/18”x24” sheet. No adhesive or gel coupling is required Comparably weak transmitter/receiver at the cylinder testing frequencies since 110-µm material has 10-MHz resonance.

A piezoceramic disk sensor installation is shown in Figure 4, along with a sample waveform demonstrating an excellent signal-to-noise (SNR) ratio.

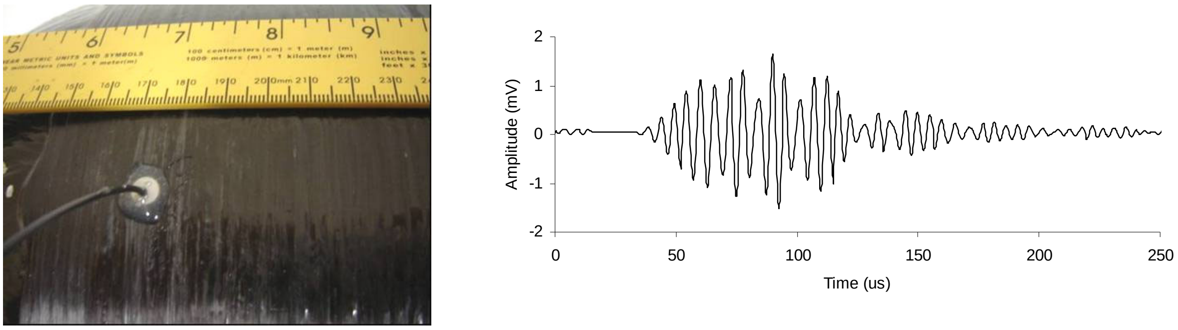

Figure 4: Piezoceramic disk mounted on cylinder and signal-to-noise ratio.

Wave-speed and attenuation characteristics were determined to identify a suitable sensor to generate and receive ultrasound efficiently while mounted on the surface of the tank. It was found that the optimum long-range ultrasound frequency modes were 190 kHz and 322 kHz for axial and circumferencial inspection, repectively. Damage detection tests evaluated the sensitivity of these frequency modes to parallel cuts, perpendicular cuts, small diameter holes, and mechanical impact damage. None of the damage introduced resulted in leakage from the tank.

5 Damage Detection Procedure

While time-of-flight and amplitude are commonly used ultrasonic signal features for defect detection, this work used the cross-correlation coefficient to generate a “signature” or reference waveform immediately after the installation of the sensors. This approach accommodates any changes in the acoustic response of the tank due to manufacturing and installation differences. It is a statistical comparison between the signal in the present state and the signal in the reference state, which is an indication of the damage inflicted on the tank. The reference data set (s_j) is acquired immediately after initial installation of the sensors. All future data (s_k) are compared to the initial data set for damage calculation.

6 Damage Detection Results using Ultrasonics

Transverse cuts and axial notches, 3-mm diameter drilled holes, and impact damage via steel mallet were introduced into a cylinder at various locations. A 1.5-mm thick grinding wheel was used to cut the notches, and a 3-mm diameter drill bit was used to cut a hole 5-mm deep into the carbon-fiber composite material without cutting through.

The damage detection result for impact using a hammer is shown in Figures 5. In this figure the reference waveform acquired before impact is shown as a blue dashed line, and the data acquired after damage is shown as a solid black line which is greatly attenuated. The test setup demonstrates that it is possible to detect damage located midway in the cylinder using sensors on opposite ends of the cylinder.

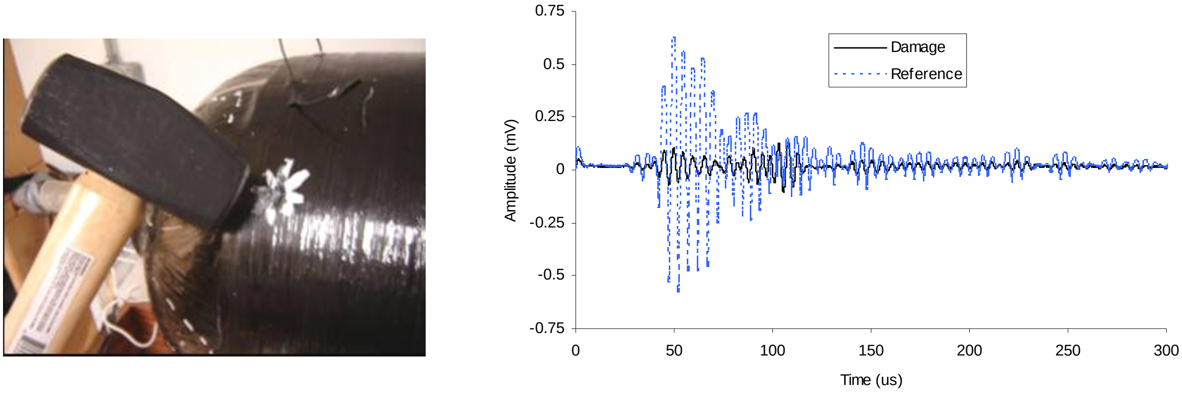

Figure 5: Inflicting impact damage and pre/post wave form.

The results of all the tests in unpressurized cylinders, which are summarized in Table 2, indicate correlation coefficients ranged from 0.93 to 0.44 depending on the type of damage.

A correlation coefficient of one corresponds to no change in the structure compared to the reference case. A correlation coefficient of less than one indicates the structure has changed due to damage. A software program was used to acquire pre- and post-damage data and to automatically calculate the correlation coefficient.

In both the axial and circumferential cases, impact damage resulted in the most significant change in signal. As well, the ultrasound was more sensitive to cuts (notches) oriented perpendicular to the direction of wave propagation than parallel. In the axial direction, for instance, the perpendicular cut (notch) data generated a correlation coefficient of 0.68 compared to 0.83 for the parallel case. Table 3 shows that as the size of cut damage increases, the correlation coefficient decreases.

Table 2: Summary of defect detection results.

Defect Type	Defect Size	Frequency (kHz)	Correlation Coefficient
Axial hole	3-mm diameter, 4.8-mm deep	190	0.83
Axial impact	20-mm x 20-mm on surface	190	0.44
Axial parallel cut	25 (L) x 2 (W) x 2 (D) mm	190	0.83
Axial perpendicular cut	25 (L) x 2 (W) x 2 (D) mm	190	0.68
Circumferential hole	3-mm diameter, 4.8 mm deep	322	0.79
Circumferential damage	20-mm x 20-mm on surface	322	0.69
Circumferential parallel cut	25 (L) x 2 (W) x 2 (D) mm	322	0.93
Circumferential cut	25 (L) x 2 (W) x 2 (D) mm	322	0.85

Table 3: The effect of increasing damage size on correlation coefficient.

Cut Dimensions: L x W x D (mm)	Frequency (kHz)	Correlation Coefficient
17 x 2 x 1	190	0.99
35 x 2 x 4	190	0.78
57 x 2 x 6	190	0.33

7 Discussion

This project investigated ultrasonic, resistive, and electromagnetic techniques for detecting damage in composite cylinders made of carbon fiber with aluminum liners. Ultrasonic techniques appear to have promise as a low-cost method of detecting damage using small piezoceramic disk sensors. Correlation coefficients comparing the tank structure before and after damage was inflicted ranged from 0.93 to 0.44 depending of the type and orientation of damage (cut, hole, impact). The next phase of work should focus on pressure cycling tests to ensure the durability of the sensor and the sensor adhesive, as well as developing a system for installation in a vehicle. It is also important to incorporate damage detection technology into Codes and Standards used to design storage cylinders for compressed gases.

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