SMART LAYER AND SMART SUITCASE FOR STRUCTURAL HEALTH MONITORING APPLICATIONS

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ABSTRACT

Knowledge of integrity of in-service structures can greatly enhance their safety and reliability and lower structural maintenance cost. Current practices limit the extent of real-time knowledge that can be obtained from structures during inspection, are labor-intensive and thereby increase life-cycle costs. Utilization of distributed sensors integrated with the structure is a viable and cost-effective means of monitoring the structure and reducing inspection costs. Acellent Technologies is developing a novel system for actively and passively interrogating the health of a structure through an integrated network of sensors and actuators. Acellent's system comprises of SMART Layers™, SMART Suitcase™ and diagnostic software. The patented SMART Layer™ is a thin dielectric film with an embedded network of distributed piezoelectric actuators/sensors that can be surface-mounted on metallic structures or embedded inside composite structures. The SMART Suitcase™ is a portable diagnostic unit designed with multiple sensor/actuator channels to interface with the SMART Layer™, generate diagnostic signals from actuators and record measurements from the embedded sensors. With appropriate diagnostic software, Acellent's system can be used for monitoring structural condition and for detecting damage while the structures are in service. This paper enumerates on the SMART Layer™ and SMART Suitcase™ and their applicability to composite and metal structures.

Keywords: Structural Health Monitoring; SMART Layer™; SMART Suitcase™; built-in/embedded sensors, piezoelectric, sensor network

1. INTRODUCTION

Safety and reliability are critical factors in the usage of in-service structures. Existing invisible damage has the potential to grow and lead to catastrophic failures, loss of human life and decrease in economy. Real-life examples of structural failures are present in airline crashes, space shuttles explosion, building and bridge collapses. In order to minimize the possibility of failure, structures have traditionally been designed with safety factors. However, this may be insufficient since the service conditions that different structures operate under vary. Over time, the effect of these small variations can accumulate resulting in a significant difference in their safety level and their residual life. One possible method of ensuring structural safety is to inspect structures frequently and keep abreast of their structural condition. Unfortunately, regular usage of current structural inspection practices can be expensive and labor-intensive. Current techniques such as x-ray, ultrasound, c-scan, and thermal imaging that are commonly used for inspection are time-consuming, expensive, and rely heavily on human interpretation. Furthermore they cannot be applied to inaccessible structural areas and in some cases may require entire structural disassembly. Quite often, the inspection equipment is available only at specialized facilities requiring the structure to removed from service and sent to these facilities for inspection thereby further increasing operating costs.

Recent advances in sensor technology, material processing, damage modeling, and system integration have enabled new developments in structural evaluation/inspection technologies to overcome the shortcomings of existing inspection systems. Among them is the concept of structural health monitoring using a built-in structural diagnostic system. A built-in monitoring system would consist of three major components: sensors/sensor network, integrated hardware, and software to monitor in-situ the “health” condition of in-service structures. An important part of the system is the proper integration of the sensors and actuators with the structure. Although sensors can be integrated individually with a structure a novel and cost-effective method would be to integrate a *network* of sensors with the structure. This sensor network when combined with more sophisticated data acqusition systems and diagnostic software can drastically reduce the cost of inspection, allow for more frequent maintenance schedules and reduce the likelihood of catastrophic structural failures.

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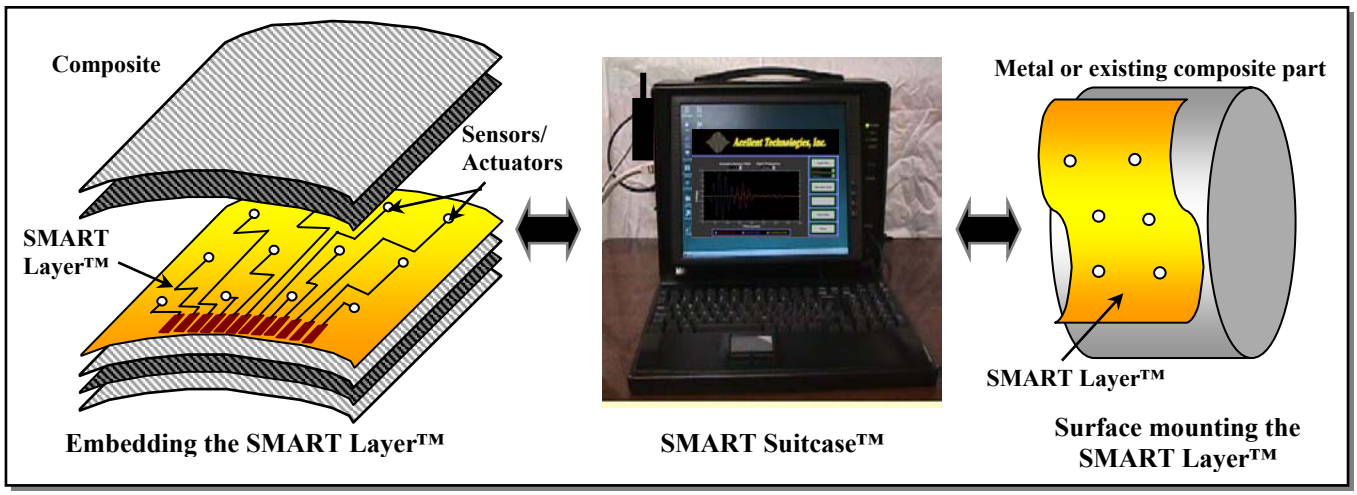


Figure 1: Acellent's SMART Layers™ and SMART Suitcase™.

Acellent Technologies, Inc. is developing an integrated sensor network system that utilizes a network of distributed piezoelectric sensors/actuators embedded on a thin dielectric carrier film called the SMART[1] layer™, to query, monitor and evaluate the condition of a structure. Diagnostic signals obtained from a structure during monitoring through wired or wireless means are processed by a portable diagnostic unit called the SMART Suitcase™. With appropriate diagnostic software, the signals can be analyzed to ascertain the integrity of the structure being monitored. The SMART Layer™ technology and has both active and passive sensing capabilities using piezoelectric sensors (PZT) for structural health monitoring purposes.

2. THE SMART LAYER™

The SMART Layer™ with an integrated network of distributed piezoelectric (PZT) transducers has been developed to efficiently integrate a network of sensors onto structures [4]. The SMART Layer™ fabrication process is based on the flexible printed circuit technique used in the electronics industry, with modifications to accommodate the composite manufacturing process. The major processing steps involve printing and etching a conductor pattern onto a dielectric substrate, laminating a dielectric cover layer for electrical insulation, and mounting arrays of piezoceramics on the circuit. The SMART Layer™ is treated as an extra ply that can be placed between composite plies during composite layup process. After co-curing in an autoclave, the resulting composite structure would have an integrated network of piezoceramics that can be used to send and receive diagnostic signals for monitoring the structure. A schematic description of the SMART Layer™ and its integration concept is shown in figure 1.

The SMART Layer™ can also be surface mounted on a variety of structures including both metallic structures and composite structure. For metallic structures, the SMART Layer™s are bonded onto metal surfaces using a secondary adhesive such as epoxy. The epoxy can either be elevated temperature cured or room temperature cured for field application. The SMART Layers™ manufactured by Acellent come with an epoxy film adhesive added onto one side of the layer for bonding to metals. Users simply peel off the backing film and attach the SMART Layer™ onto their structure. For composite structures, one option is to embedd the SMART Layer™ into the structure itself during the manufacturing stage. Since the SMART Layer™ has temperature tolerance in excess of 400^{o}F, it can be co-cured with a wide range of composite materials. Embedding and co-curing with the structure itself can fabricate a highly integrated multifunctional SMART structure. The process of embedding a SMART Layer™ inside composite materials does not alter the composite manufacturing process.

[1] SMART™ stands for **S**tanford **M**ulti-**A**ctuator-**R**eceiver **T**ransduction. This technology is recognized as a leading candidate for health monitoring applications and has several advantages over other current health monitoring technologies.

Several SMART Layers™ have been fabricated at Acellent and embedded inside Gr/Ep composite laminates and surface mounted on metal parts successfully. Quality testing has shown that the piezoceramics embedded using this SMART Layer™ approach function properly and provide signal uniform response for the entire network. The fabricated embedded-composite panels are being used to develop and demonstrate structural health monitoring applications.

SMART Layer™ design:

Acellent Technologies has pioneered the techniques of manufacturing SMART Layers™ in a variety of sizes, shapes and complexity. Examples of the SMART Layers™ of various shapes made by Acellent are shown in figure 2. The size of the SMART Layers™ that can be fabricated range from a couple of inches up to several feet. The SMART Layers™ vary in complexity going from a simple 2-sensor flat strip to a complex 30-sensor 3-D shell. They can be fabricated in different shapes for integrating with different contours of structures. Basic shapes include rectangular, long slender strips, circular, and three-dimensional shell.

Rectangular Circular 3-D

Figure 2: Examples of SMART Layers™ in various shapes.

For structures with multiple-curvatures and complex geometry, SMART Layers™ can be custom designed with special shapes and cutouts to provide a perfect fit. An innovative method of designing the flexible SMART Layer™ such that it can hold its shape upon fabrication has been developed at Acellent. Figure 3 depicts the designing process. This method called the "cut-out method" allows the different layers that together make the SMART Layer™ be cut in a pre-specified geometry. The layers when collectively cured produce a SMART Layer™ with the required shape.

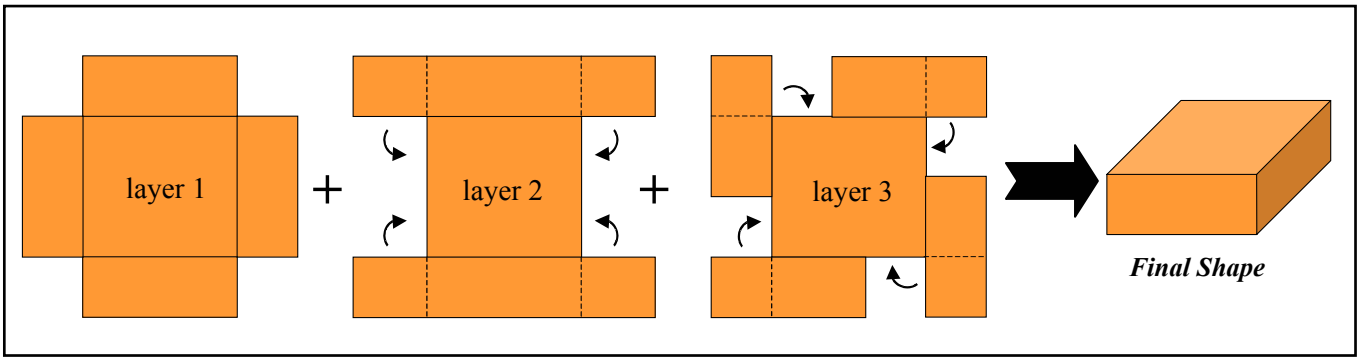


Figure 3: Fabrication method for facilitating the SMART Layers™ to hold their shape

An alternate method of fabricating three-dimensional complex shaped SMART Layers™ such that they hold their shape, is to use mechanical locks at pre-selected locations and then shape the layer based on the required geometry. Upon cure, the layer will hold its shape. A schematic of this concept is presented in figure 4.

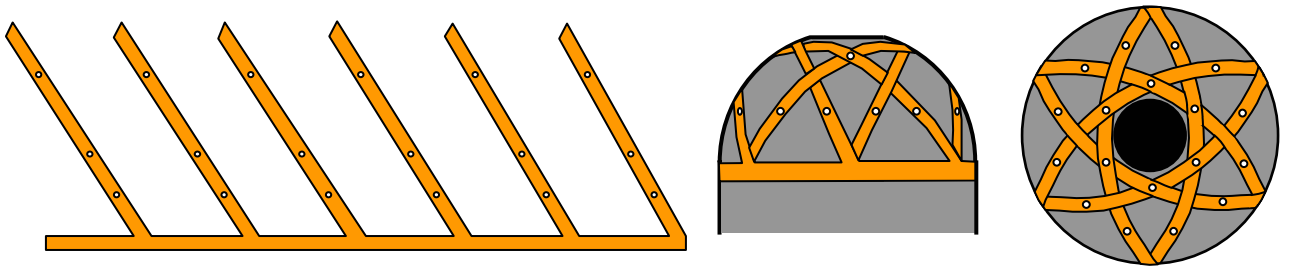


Figure 4: Alternate method for fabrication of 3-D SMART Layers™[2]

Testing:

Mechanical tests on composite coupon specimens with and without embedded SMART Layers™ were conducted to assess the change in structural integrity due to inclusion of the SMART Layer™. Static loading and impact tests were performed on woven graphite/epoxy coupon specimens with a lay-up $[0_4/90_4/0_4]$. SMART Layers™ were placed at the lower 0/90 interface. Results of 3-point bending tests conducted on these specimens are presented in figure 5. The test results indicate that the presence of the SMART Layer™ does neither noticeably affect the strength of the host composite structure nor promotes delamination.

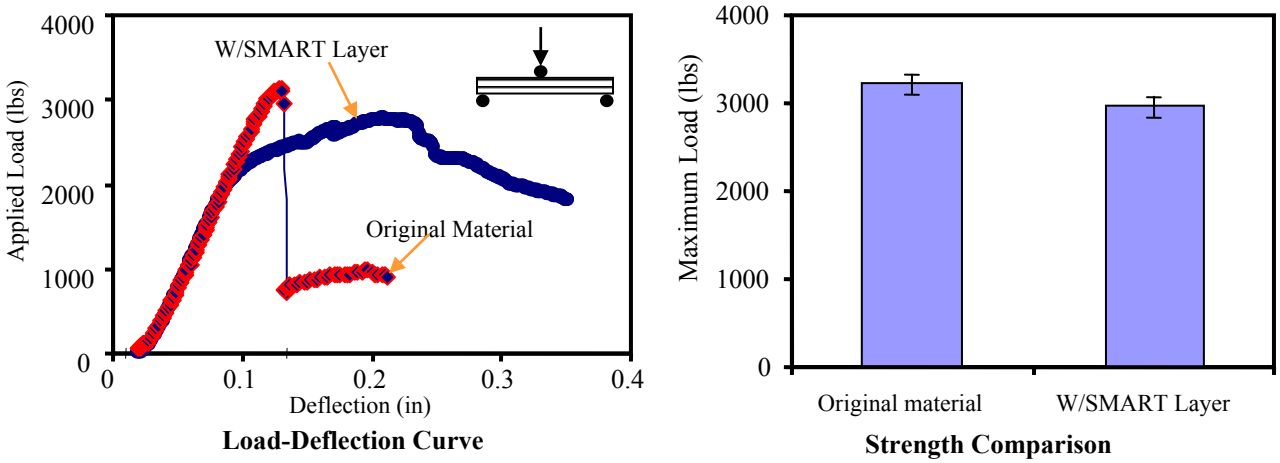


Figure 5: Mechanical test results of specimens with and without embedded SMART Layer™

An examination of the cross-section of the specimens corroborates these findings. Magnified views of the cross-sections of the specimens are shown in figure 6. It is clear that delamination in the specimens without the embedded SMART layer occurs at the lower 0/90 interface as expected, due to the high interfacial shear stress at the ply-group interface. However, in the specimens with an embedded SMART layer at the lower 0/90 interface, there is no delamination. The actual delamination occurs one or two plies away from the interface, indicating that the SMART layer does not promote delamination but rather defers it.

The tolerance of the SMART Layer™ when exposed to environmental aging due to prolonged exposure to varying temperature and moisture conditions has also been investigated. The tests were carried out on flat plate woven composite/epoxy specimens with embedded (at center ply) and surface mounted SMART Layers™. The specimens with a

[2] Data taken from report no. AFRL-PR-ED-TR-2000-0025,
"A Built-in Active Sensing Structural Diagnostic (BASSD) system for Rocket Motors", Acellent Technologies, Inc.

lay-up of 8-ply [0/90/±45]s were all co-cured with the SMART Layers™. The signals obtained at periodic intervals were compared to reference signals obtained prior to the start of the test. Figure 7 depicts these results for a specimen with surface mounted SMART layer™ for all possible signal paths. The % variation in maximum signal amplitude of the output signals as compared to the reference signals during the specified test time period is plotted in the graph. The results of the test data collected and analyzed over a period of 3 months indicate that the SMART Layer™ shows good tolerance to environmental conditions and records no significant change in signals during this time except for a one-time signal change that occurs during the initial part of the test. This change is likely due to the initial settling effect of the piezos in the layer after manufacture.

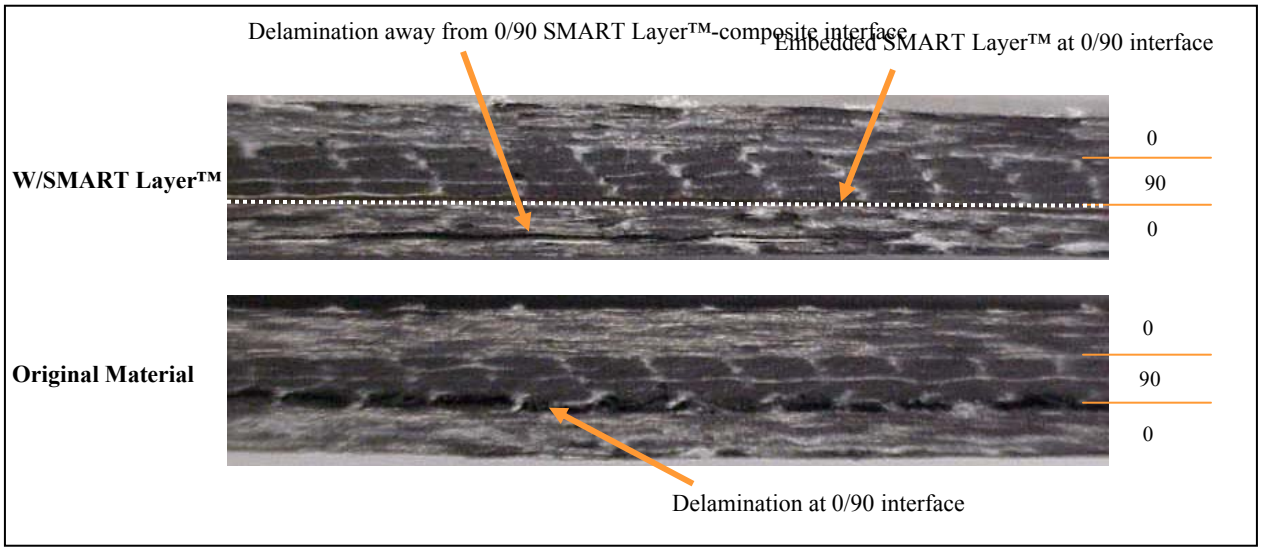


Figure 6: Magnified cross-sectional view of test specimens

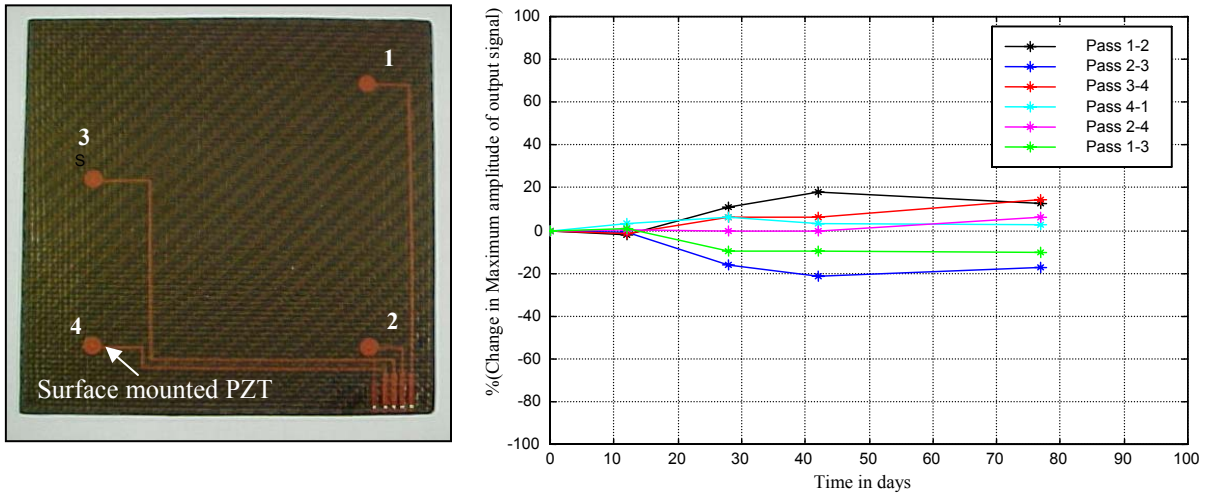


Figure 7: SMART Layer™ tolerance to natural aging effects[3]

[3] Data taken from final report submitted to BMDO, # DASG60-00-M-0109
"Development of Intelligent Composites using Integrated SMART layer Technology", Acellent Technologies, Inc.

3. THE SMART SUITCASE

The SMART Suitcase™[4] is a portable diagnostic instrument that has multiple sensor/actuator (I/O) channels to interface specifically with the SMART Layer™ (Figure 8). It has the built-in capability to drive the piezo actuators embedded on the SMART Layer™ and record measurements from adjoining piezo sensors. It can store the sensory data and perform real time data analysis. The current SMART Suitcase™ model has capability to interface with up to 30 piezo actuators/sensors. It drives the piezo actuators with a specific pre-programmed diagnostic waveform, while recording the output from neighboring piezo sensors.

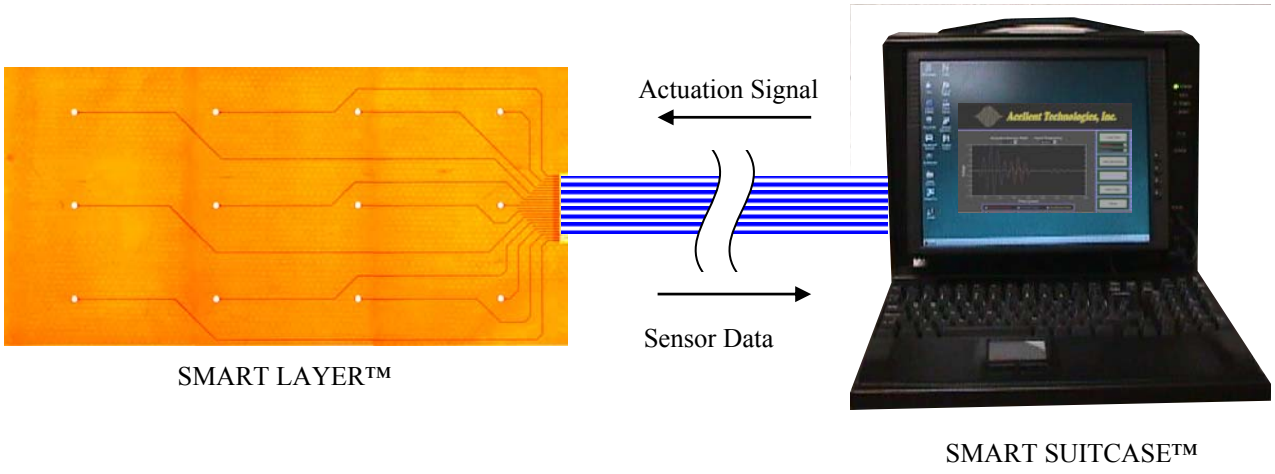


Figure 8: SMART Layer™ interfaced with the SMART Suitcase™

The SMART Suitcase™ is designed as a PC-based portable instrument that has the built-in capability to generate a specific waveform for structural diagnostic, collect sensor data with high sampling rate and resolution, and multi-channel capability to accommodate *a network* of piezos. The components of a SMART Suitcase™ system are shown in figure 9. They include a diagnostic waveform generator, an actuator power amplifier, a multi-channel switching matrix, a sensor signal filter and amplifier board, a sensor data acquisition board, and devices for data storage and processing. Selected specifications of the SMART Suitcase™ components are listed in table 1.

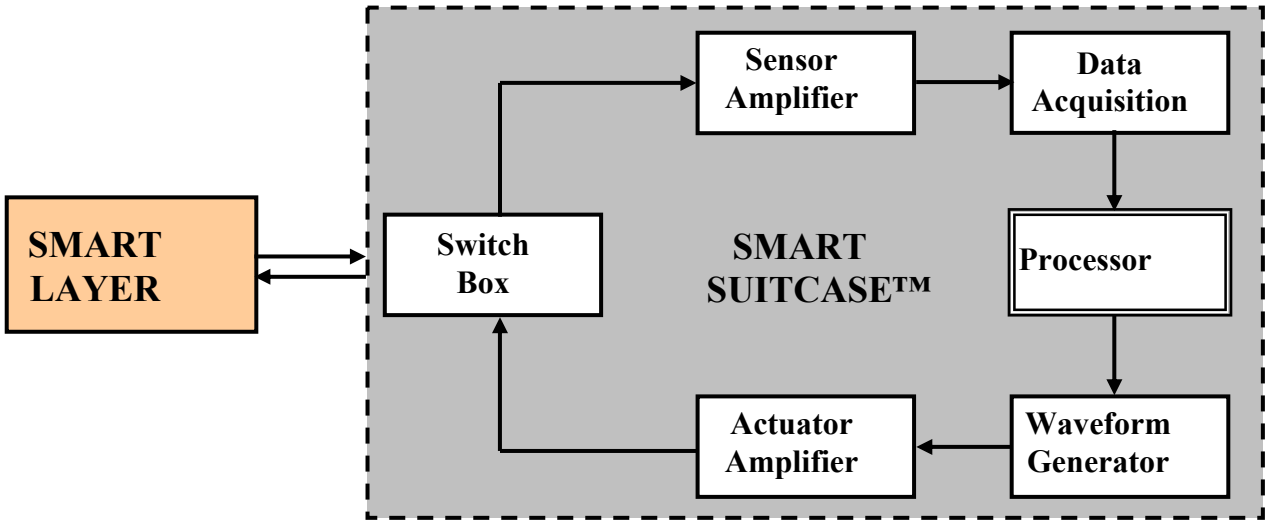


Figure 9: Components of the SMART Suitcase™

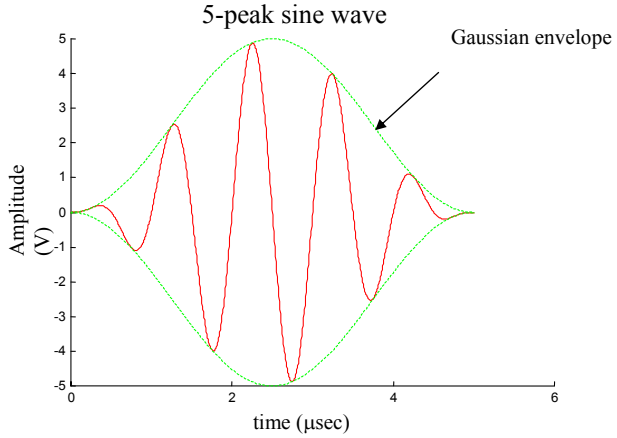
[4] Developed during a Phase II contract with the U.S. Army Missile Command. Contract no. DAAH01-00-C-R019.

Table 1: Specification of SMART Suitcase™

PROPERTY	SPECIFICATION
Physical Dimensions	15.7”W x 11.7”H x 7.7”D. Weight: 21 lbs.
Processor	Intel Pentium III
Operating System	Microsoft Windows with custom users environment
I/O channels	30 piezo channels
Signal Generation	Programmable Arbitrary Waveform Generator (DAC)
Actuator Amplifier Output Power	34 Watts, 200 Vpp max
Output frequency range	61 μHz to 10 MHz
Data Acquisition	High-speed Data Acquisition Board (ADC)
Sampling Rate	60 MSample/sec
Input Bandwidth	25 MHz
Sensor Amplifier Gain	10
Environmental	Operating Temp: +32^{o}F to +113^{o}F. Storage Temp: -4^{o}F to +149^{o}F. Relative Humidity: 20 to 80%, non-condensing.

The components inside the SMART Suitcase™ include both OEM PC boards and custom boards made by Acellent. Integration of these individual components produces a unique portable instrument that can be used with the SMART Layer™ to monitor the condition of in-service structures. Special software drivers are installed on the SMART Suitcase™ to allow the various components to communicate and synchronize their operation.

The diagnostic waveform output by the SMART Suitcase™ to drive the piezo actuators is a 5-peak sine wave modulated by a cosine (gaussian) envelope. This particular waveform has been chosen due to its narrow band signal that contains only a few frequency components, versus a wide band signal that contains a wide spectrum of frequencies. The less the frequency components in the diagnostic signal, the smaller the amount of distortion to the waveform due to dispersion effect of wave propagation. Therefore using a diagnostic signal with the 5-peak sine-wave waveform produces sensor data that are easier to interpret. The data generated in this fashion from the SMART layer™ and SMART Suitcase™ can be analyzed in a variety of ways [5,6].



$$A = \frac{1}{2}\sin \omega t \left[1 - \cos\left(\frac{\omega t}{5}\right)\right] \quad (1)$$

where $\omega = 2\pi f$
and f is the center frequency of the waveform in Hz

Figure 10: Diagnostic signal waveform used by the SMART Suitcase™ to drive piezo actuators

4. APPLICATIONS

The SMART layer™ along with the SMART Suitcase™ can be used to generate and receive ultrasonic waves on structures. The ultrasonic wave can be used for different purposes, one of which is to interrogate the condition of structures. With the *network* of actuators and sensors on the SMART layer, diagnostic signals can be sent from any actuator in the network to any neighboring sensor in the network, in many combinations forming various unique paths that cover the entire structure. This concept is illustrated in Figure 11, which shows an example of the diagnostic signal generated by the SMART layer™ and recorded by the SMART Suitcase™. The structure shown is a composite sandwich beam mounted with two SMART layer™ strips that are used to send and receive diagnostic signals. Depending on the application, various waveforms can be used for the diagnostic signal. The signal recorded by the SMART Suitcase™ can be analyzed with signal processing techniques to interpret the information.

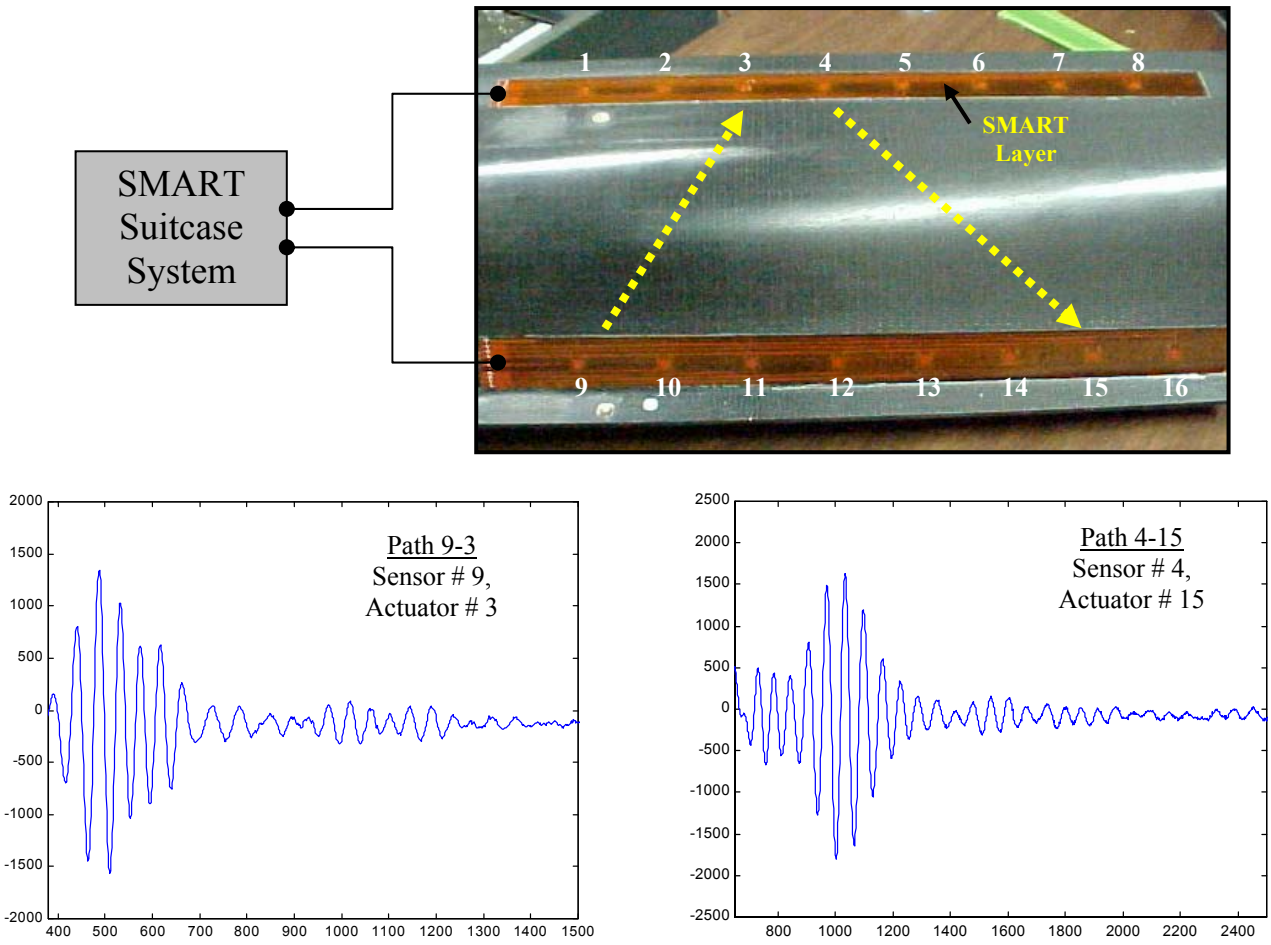


Figure 11: Example of diagnostic wave generated on a composite sandwich beam using SMART layers™.

By using different signal processing techniques to process the diagnostic signals, information concerning the structure can be obtained for a variety of purposes. The diagnostic signals can potentially be used to detect structural damage, monitor in-service condition of structures, measure structural behavior, record environmental condition, characterize material degradation and monitor manufacturing processes. To perform these various tasks using the diagnostic signal generated by the SMART layer™ and the SMART Suitcase™, software algorithms need to be developed. Currently, researchers at Acellent are using the SMART layer™ and SMART Suitcase™ to generate experimental data for this purpose. With the assortment of application-specific signal processing algorithms that are developed, it will be possible to assess the condition of in-service structures quickly and efficiently.

5. SUMMARY

This presentation summarizes the activities at Acellent Technologies on the development of the SMART Layer™ sensor network and the SMART Suitcase™ portable instrument for built-in structural diagnostics. Information about the major components of the system, specifically the SMART Layer™ and the SMART Suitcase™, are presented in the paper. SMART Layers™ offer an efficient and economical method of integrating a network of distributed piezoelectric transducer onto structures. This method can be used for both metallic and composite structures. The SMART Layers™ can be fabricated in a variety of shapes and sizes to conform with the shape of the host structure. Various mechanical and environmental aging tests were done to characterize the effect of embedding a SMART Layer™ inside composite materials and its tolerance to external environmental conditions. For the materials tested, the results showed that embedding a SMART Layer™ does not degrade the integrity of the host material. A description of the SMART Suitcase™ portable diagnostic instrument's major capabilities and some selected technical specifications are also given. The SMART Suitcase™ offers a convenient solution for on-site data collection and analysis of in-service structures. The SMART Suitcase™ provides the necessary actuation and data collection functions required to interfaces directly with the SMART Layer™. It also provides a platform for real-time data analysis when interfaced with appropriate application software. Acellent's system can be used for structural diagnostic and health monitoring purposes. Overall, the built-in structural diagnostic system that's being developed represents a new approach to structural inspection that has the potential to reduce the time, labor, and cost associated with current available techniques. Through better knowledge of structure integrity in service, improvements in structural safety and reliability can be achieved.

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