

MONITORING COMPOSITE MATERIAL PRESSURE VESSELS WITH A FIBER-OPTIC/MICROELECTRONIC SENSOR SYSTEM

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ABSTRACT

We discuss the concept of an integrated, fiber-optic/microelectronic distributed sensor system that can monitor composite material pressure vessels for Air Force space systems to provide assessments of the overall health and integrity of the vessel throughout its entire operating history from birth to end-of-life. The fiber optic component would include either a semiconductor light emitting diode or diode laser and a multiplexed fiber optic sensing network incorporating Bragg grating sensors capable of detecting internal temperature and strain. The microelectronic components include a power source, a pulsed laser driver, time-domain data acquisition hardware, a microprocessor, a data storage device, and a communication interface. The sensing system would be incorporated within the composite during its manufacture. The microelectronic data acquisition and logging system would record the environmental conditions to which the vessel has been subjected during its storage and transit, e.g., the history of thermal excursions, pressure loading data, the occurrence of mechanical impacts, the presence of changing internal strain due to aging, delamination, material decomposition, etc. Data would be maintained in non-volatile memory for subsequent readout through a microcomputer interface.

INTRODUCTION

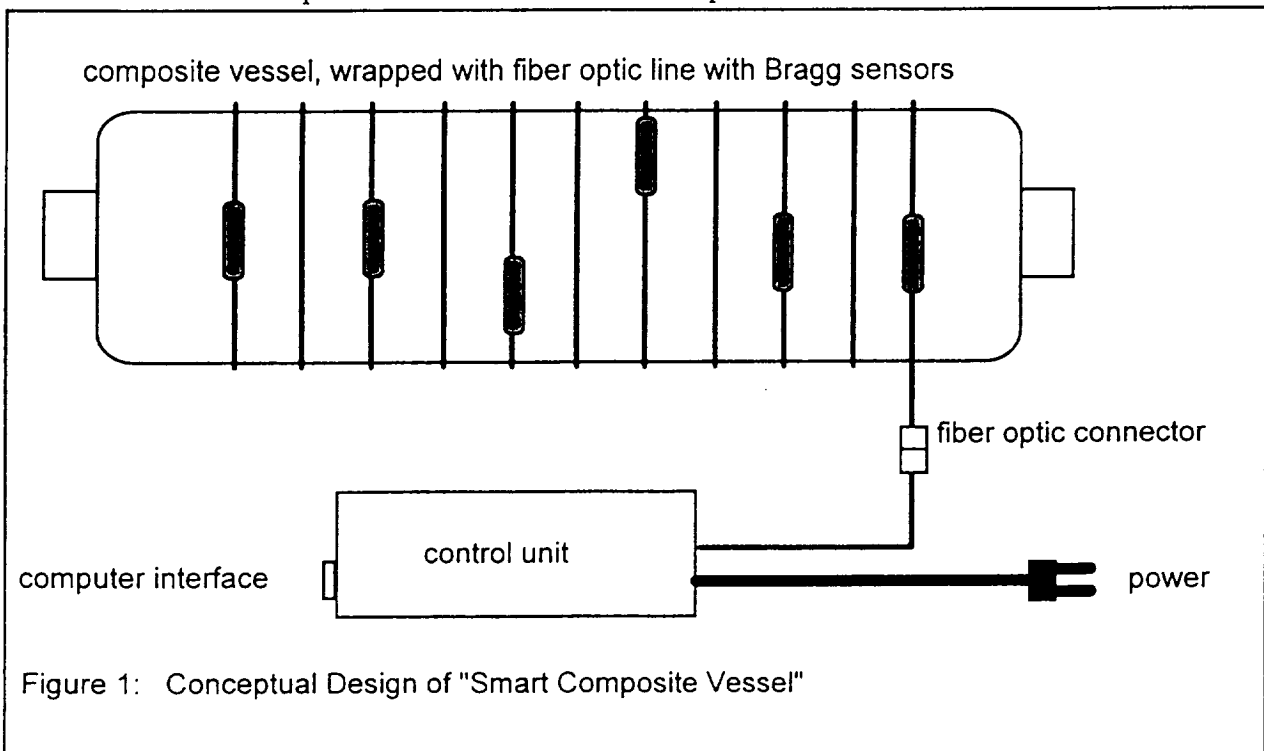
Fiber reinforced composites are the structural material of choice for fabricating high pressure vessels suitable for spacecraft applications. The superior specific properties of these materials greatly benefit systems for which weight minimization is a paramount concern. However, composite materials possess poor impact performance, a consequence of their limited ability to undergo plastic deformation. Much of the kinetic energy of an impacting mass is dissipated through the creation of large areas of fracture, resulting in a significant reduction in both the strength and stiffness of the composite (1). Even relatively low velocity impacts ($\cong 10 \text{ ms}^{-1}$) can cause delamination and matrix cracking with little or no evidence of exterior damage. In a documented instance a 50 % loss in the strength of a composite rocket motor casing resulted from an impact that produced damage at only the threshold of visibility (2). Rough handling at the factory or during transport are potential sources of damage. Furthermore, exposure of the vessel to excessive temperatures or internal pressure during testing and storage can also produce invisible damage that may result in a significant reduction in the burst strength of the vessel. To prevent failures, one could employ non-destructive testing methods to evaluate structural integrity by inspecting for damage just prior to deployment. Alternatively, one could maintain strict control and surveillance of the vessel at all times after manufacture, ensuring that all thermal, pressurization, and impact events are diligently logged for a subsequent assessment of structural integrity. Both of these options are costly, requiring access to either elaborate off-line instrumentation or the implementation of painstaking control and documentation procedures.

This paper discusses the concept of a fiber-optic/microelectronic sensor system for composite pressure vessels that will automatically detect and record the occurrence and magnitude of damaging environmental stresses suffered by the vessel. Fiber optic sensors would acquire data on both accidental

and intentional stresses experienced by the vessel during storage, transit, and operation. This data would be logged and evaluated with an on-board microprocessor that incorporated non-volatile storage for subsequent readout. This fiberoptic/microelectronic sensing system constitutes an application-specific integrated microinstrument (ASIM) that would enable the manufacture of smart composite pressure vessels that permit damage assessment via an on-demand capability of reporting critical life-stress history.

CONCEPT OVERVIEW

The environmental stress events that must be recorded are the occurrences of impacts, overpressurization, and exposure to high temperatures. These phenomena can be measured with a multiplexed array of optically-interrogated fiber optic strain and temperature sensors. A schematic illustration of the overall system is shown in Figure 1. It includes several fiber optic sensors attached to the external wall of the pressure vessel. The sensors are bonded at appropriate locations onto the surface of a composite vessel prior to adding the final protective overwrap. External attachment avoids perturbation of the composite matrix by the fiber optic waveguide and ensures that the sensors themselves do not compromise the intrinsic strength of the material. If necessary, the network can be mounted after the completion of the high temperature cure to preclude the possibility of thermal damage to the sensing network. The sensors are interconnected via standard fiber optic waveguide which is coupled to an electrooptic control unit via a fiber optic connector. The control unit contains an interrogating near infrared light source, a photodetector, and other optical and microelectronic components that are required for detecting and demultiplexing the signals arising from each of the sensors. A microprocessor manages data acquisition, demultiplexing, and the conversion of the individual sensor responses to localized strain and temperature data.

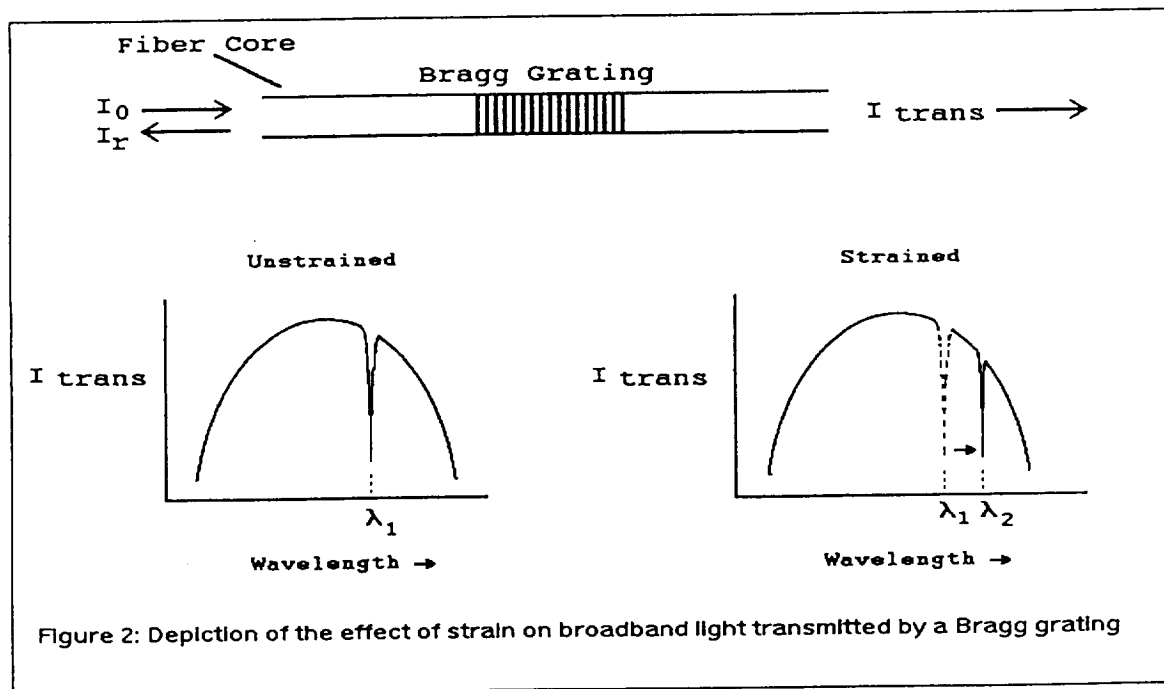


This integrated sensor/microelectronic system would operate continuously and record data in non-volatile memory if preset thresholds of temperature or strain were exceeded. Data processing would be used to differentiate between static and dynamic strain effects. The DC response of a fiber optic strain sensor would be used to determine the steady-state strain resulting from pressurization while its AC

response would be used to detect vibration following a mechanical impact. In the latter case the transient ringing produced by the normal vibrations of the vessel would be detected by strain sensors positioned at the mechanical antinodes of the vessel. Wall temperature would be determined with a DC-coupled fiber optic temperature sensor.

Fiber Optic Sensing System:

Strain and temperature will be detected with fiber optic Bragg grating sensors (FOBGS). A FOBGS is a moderately short gauge length sensor ($\cong 1$ cm) fabricated within the core of photosensitive optical fiber by producing a periodic spatial modulation of the core index of refraction with a UV laser. Permanent modulation can be produced by either lithographic (3) or holographic exposure techniques (4). The resulting grating acts as a narrow-band reflector, with a central wavelength that is determined by the grating spacing. Since light transmitted by the grating will be missing those wavelength components that have been reflected, then the grating also behaves as a narrow bandwidth notch filter. Changes of strain or temperature modify that spacing to produce a detectable shift in the center wavelength of the reflection (notch). Transmitted signals arising from a FOBGS that is interrogated by a broadband LED light source are illustrated in Figure 2. The notch wavelength is directly proportional to the grating spacing and hence the absolute strain and temperature at the site of the grating. Sensing is accomplished by measuring the wavelength of the retroreflected light with a suitable spectral technique. Resolutions of 1°C (temperature) and $5 \mu\epsilon$ (strain) are easily achievable. Differentiation between the effects of temperature and strain can be performed by encapsulating some sensors in strain-free manner within a housing so that these sensors respond only to temperature changes and are unaffected by strain. Alternatively, a dual-wavelength techniques employing superimposed grating sensors could be used (5).



Control Unit Subsystem:

Several Bragg gratings will be multiplexed on a fiber optic network that will be interrogated with a broadband NIR LED light source. The LED will be contained within an externally mounted electrooptic module that includes signal acquisition, demultiplexing, and all data processing, storage, and readout electronics. This module will interrogate the strain and temperature sensors and demultiplex the signals reflected by the Bragg sensor array. Numerous demultiplexing techniques exist that are based upon wavelength or combined time and wavelength decoding that permit extraction of the temperature and strain data from these reflected signals. In time-division demultiplexing, one utilizes pulsed interrogation of the sensor array and performs time-domain signal processing to infer sensor location from the arrival order of the reflected pulses. In wavelength-division demultiplexing, one utilizes spectral decoding of the returns from sensors that have been fabricated with unique central wavelengths that serve to identify the sensor location. Numerous wavelength demodulation options are available, including a fiber coupled CCD spectrometer, a fiber Fabry-Perot etalon, an acousto-optic tunable filter, and a matched Bragg grating demultiplexer array (6-8). Combined time and wavelength division methods may be employed if it is necessary to increase the number of sensors beyond that which can be demultiplexed by wavelength alone.

The selection of a specific demultiplexing scheme is dependent upon many factors including: strain and temperature resolution, the number of sensors, response time, the mechanical and thermal behavior of the composite, cost, and tolerable system complexity. A detailed requirements analysis that considers all these factors must be performed prior to selecting the optimum scheme.

A signal processing module will separate and process the temperature, steady state strain, and vibration components of the electrooptic module output signal, determine if preset alarm thresholds have been exceeded and generate digital output for storage in non-volatile memory. A non-interruptible power supply will provide continuous power service during momentary power failure. A self-check module will be incorporated that generates system diagnostics for storage at a predetermined periodicity.

Development Roadmap:

Structural Analysis

As noted above, a thorough evaluation of the mechanical and thermal behavior of the composite is necessary for designing a suitable demultiplexing system. The normal modes of the vibrating vessel must be determined and the points of maximum vibration amplitude must be identified for several different types of excitation. A measurement of the relationship between the deposited shock energy and the resulting vibrational amplitude is necessary. If not already available, an alarm threshold for shock energy must be determined from a measurement of the damage induced at different shock energy levels. This will allow us to establish alarm thresholds for vibrational amplitude. Likewise, alarm thresholds for steady state strain and temperature must be determined from previously known data or new measurements.

Sensing and Control Unit Subsystems

The principle parameters of the sensing subsystem that must be determined are the number of strain and temperature sensors required to achieve our objectives, the interrogating light source, the design wavelengths for each of the multiplexed sensors, and the spacing between sensors. Several issues related to sensor attachment must also be addressed including determination of the manufacturing point at which the sensors will be incorporated within the vessel, the identification of bonding methods that assure good thermal and compliant mechanical coupling, selection of sensor protective overwrap, and the design of fiber ingress and egress ports.

The demultiplexing technique incorporated within the electrooptic module must be designed, fabricated and tested assuring that sensitivity, dynamic operating range, signal to noise ratio, and response bandwidths match system requirements. The signal processing module that receives analog input from the electrooptic module and provides digital output for storage must also be designed, fabricated, and tested. The diagnostic parameters of the self-check module must be defined and the module designed, fabricated, and tested. Finally, commercially available power supplies and non-volatile memories suitable for this application must be identified.

CONCLUSION

A conceptual solution for automatically monitoring and logging environmentally-induced overstress on composite high pressure vessels has been described. A roadmap for determining the system requirements has been developed that summarizes the mechanical properties that must be experimentally determined and the design issues that must be met to achieve this objective.

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