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OFS-embedded smart composites: OFDR distributed sensing for structural condition and operation monitoring in spacecraft propellant tank

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ABSTRACT

Spacecraft and launcher development has recently focused on new design concepts employing intelligent propulsion systems, enabled by advanced AI-based paradigms for operations and condition monitoring (OCM) and structural health monitoring (SHM). The main challenge, however, remains providing abundant sensing data points to ensure reliable OCM and SHM processes for effective onboard systems control. This paper presents a case study on a smart spacecraft propellant tank prototype manufactured through carbon fiber filament winding and additive manufacturing of carbon fiber-reinforced polymer, using a Distributed Optical Fiber Sensor (DOFS) system. The optical fiber sensors (OFS) embedding technique is discussed, highlighting methods to optimize temperature isolation from strain variation effects. Composite structure post-processing considerations are also addressed for compatibility with acrylate-coated fibers. Thermal test results, using a high-backscattering OFS interrogated by a Luna ODiSI-6000 OFDR system, are presented.

Keywords: OFDR, Stress-Strain, Temperature Mapping, Space Systems, Intelligent Propulsion, Spacecraft Design.

1. INTRODUCTION

Optical fiber sensors have always synergized well with composite structures and the current advancements in composites manufacturing have opened new opportunities for the employment of distributed fiber sensing in smart spacecraft structures. According to current European space industry requirements [1], a smart propellant tank for spacecraft is generally required to provide continuous monitoring of both the fluid and structural conditions of the tank. Critical parameters sought by spacecraft operators include fluid temperature, pressure, and level. Other requirements, also taken into account in our study, are the environmental operational temperature from -20 °C up to 60 °C, while the propellant temperature is as low as cryogenic temperatures, i.e., circa -190 °C.

The launch vehicle (LV) industry has widely employed carbon composite structures, as in Ariane 6, the new European heavy-lift LV, and Electron LV, one of the successful small-lift launchers; Figure 1 shows the fueling phase with cryogenic liquid oxygen propellant. Proba-2 mission (2009 - present) was one of the earliest demonstrations of optical fiber sensors onboard a small-sized spacecraft, where arrays of FBG sensors were surface-mounted to monitor the structures of several subsystems [2]. —With advancements in manufacturing technologies for composite pressure vessels [3], and additive manufacturing, the embedding and structural integration of optical fiber sensors (OFS) are now receiving growing attention in spacecraft applications [4].

DOFS technology in rocket propulsion applications

Distributed Optic Fiber Sensor (DOFS) systems providing significant high number of sensing points are emerging as a robust and safe sensing technology suitable for thermal mapping in diverse rocket propulsion applications, especially those involved in the operation and condition monitoring of the highly unstable cryogenic propellants [5] [6]. Several sensing principles utilizing optic fibers have been explored and documented for SHM and fluid-level monitoring in various literatures [7] [8] [9]. Nonetheless, the principal challenge, in spacecraft propellant tank applications employing OFS systems, remains the effective structural integration and embedding of optical fibers to accurately provide reliable temperature mapping, local stress-strain detection, and fluid-level monitoring. Several challenges have been addressed in our research through multidisciplinary approaches based on materials science, structural engineering, and composites manufacturing processes [4] [10].

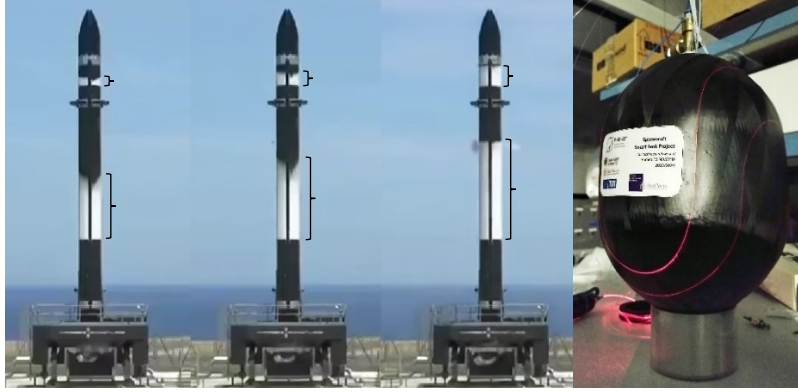


Figure 1. (Left) Rocket Lab’s 18 m high Electron launch vehicle during cryogenic fueling, with visible frost buildup on the structure. (Right) Prototype of a 4-liter smart spacecraft propellant tank developed by the authors, illustrating the serpentine pattern used for OFS embedding; image captured with a long-exposure camera and inspection laser.

2. SYSTEMS DESIGN AND CONCEPTS

The smart propellant tank employs a structural integrated OFS system that’s responsible for: (1) OCM to provide the spacecraft operators with real-time thermal mapping of the tank structure besides the fluid-level monitoring (i.e., propellant gauging); (2) SHM to acquire the local strain value at several predefined points on the structure.

Temperature mapping for operations and condition monitoring (OCM)

DOFS are widely used for effective temperature mapping in structures with high resolution over hundreds of sensing points [5]. The example of pre-flight fueling of a launch vehicle, Figure 1, can be considered as an application for operations monitoring to utilize the OFDR technology for DOFS-embedded composite structures of the propellant storage system. Temperature mapping can provide information to ground operators about the fluid-level gauging and the fluid state, e.g., the liquid and vapor distribution. The well-known OFDR interrogation concept is governed by the characteristic equation:

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta\nu}{\nu} = C_S \Delta\varepsilon + C_T \Delta T \quad (1)$$

$\Delta\lambda$, $\Delta\nu$: wavelength and frequency shift; C_S , C_T : strain and temperature coefficients; $\Delta\varepsilon$, ΔT : strain and temperature variations.

Max principal stress mapping for Structural health monitoring (SHM)

By acquiring the local strain values, we developed a mathematical opto-mechanical model to determine local stress after evaluating the strain transfer from the structure to the optical fiber. Depending on the fiber placement direction, i.e., the embedding orientation, local strain and stress detection will vary between maximum and minimum values, guiding fiber placement to achieve either maximum sensitivity or minimal sensitivity to structural loads. This fiber embedding method was primarily inspired by the classical *Maximum Principal Stress Theory*, widely adopted in structural and mechanical engineering to predict brittle material failure under complex loading. Readers can refer to Section 3 in [10] for the complete derivation of the $\sigma_{(\text{Max Principal})}$ formula as a function of the optical sensor characteristics and material-mechanical properties.

$$\sigma_{\text{Max Principal}} \equiv \sigma_1 = \frac{E\left(\frac{\Delta\lambda}{\lambda} - C_T \Delta T\right)}{(1-\nu^2)\left\{1 + \frac{1}{2}n^2[p_{12} - \nu(p_{11} - p_{22})]\left(1 - \frac{\cosh(kx)}{\cosh(kL)}\right)\right\}} - \frac{(\alpha_{i,c} - \alpha_{i,f})\Delta T\left(1 - \frac{E_f}{E_c + E_f}\right)}{(1-\nu^2)} \quad (2)$$

E : elastic modulus; ν : poisson’s ratio; α : thermal expansion coeff.; n : refr. Index; p_{ij} : strain-optic tensor; k : shear-stress transfer parameter.

3. METHODS: MANUFACTURING AND FOS EMBEDDING

Fiber embedding and cross-sensitivity elimination approaches

The *conventional method* to addressing optical sensor cross-sensitivity involves separately determining the temperature value to enable a closed-form solution for the wavelength shift $\Delta\lambda$ or frequency shift $\Delta\nu$ as a function of strain and temperature variations, as shown in equation (1). Typically, a strain-decoupled optical fiber—housed in a loose tube or capillary—is used to measure system temperature. In this study, a PTFE tube with ~ 0.35 mm thickness was selected and found compatible with both the filament winding process and the composite’s thermal curing cycle. Grooves were machined into the polar bosses and additively manufactured in the tank liner, Figure 2-(a, b), to accommodate the tubes and mitigate pressure during winding and curing; Figures 2-(b, c) show the tri-radial groove pattern at 120° intervals.

Although three tube segments were included for redundancy, this is not strictly required due to thermal stratification in the assumed vertical tank orientation, as shown in Figures 1.

The newly proposed method in our study involved placing the optical fiber sensor, Figure 2-(d, e), in a multi-orientation pattern covering an angular spectrum from 0° to 90° relative to an imaginary central axis along the winding direction. In this configuration, aligned with the minimal principal stress direction indicated by FEM analysis in Figure 2-(f), the mechanical strain contribution to the sensor response is minimized (ideally to zero), enabling isolation and evaluation of the consistency between operational temperature and the sensor signal. The serpentine pattern was found adequate to achieve the required orientation alignment with the maximum and minimum principal stress directions while remaining suitable for embedding during the filament winding process. This unconventional method does not involve using loose tubes or capillaries for structural strain decoupling.

COPV manufacturing and post-processing considerations

The smart tank was manufactured from towpreg Tenax™ 24K 1600TEX with 30% matrix content. The glass transition temperature is between 95 °C and 115 °C and the curing temperature used was 95 °C over eight hours curing time. The reason for selecting the 95 °C was to be slightly below the softening temperature of acrylate and to avoid the melting of the optical fibers connectors that may contain parts of polypropylene plastic and epoxy-based adhesion. This prototype embedded three layers of optical fibers between carbon filament layers 0/1, 4/5, as well as above layer 7 and below the finishing epoxy layer and protective coating. Details about the manufacturing and filament winding can be found in [4].

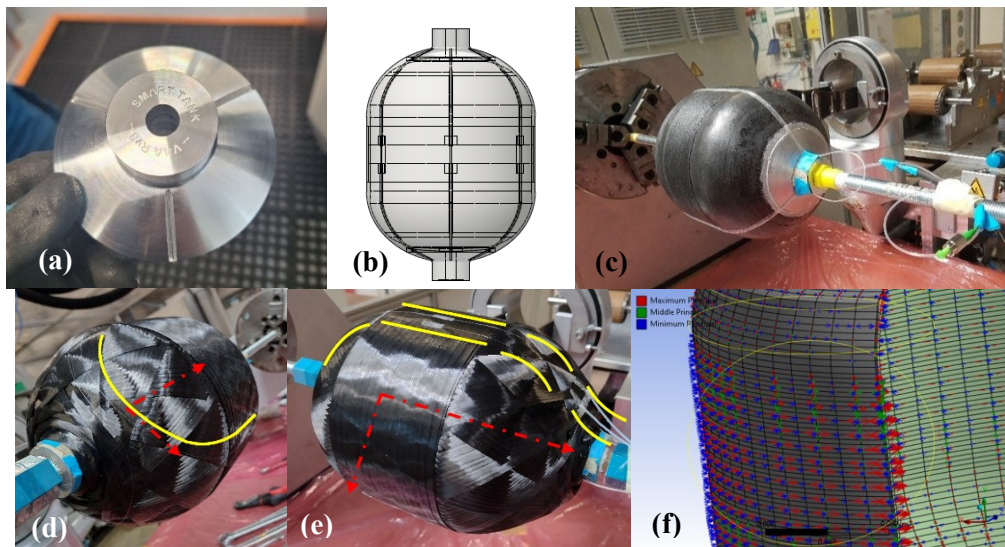


Figure 2. (a) Polar boss with ingress/egress grooves. (b) Teflon tubes $\Phi_{out} = 1.2$ mm / $\Phi_{in} = 0.8$ mm on AM composite liner. (c) 3D printed composite liner mounted on winding machine with strain-decoupled fiber attached to winding axis. (d, e) The optical fiber serpentine pattern & the coordinate system. (f) FEM vector principal elastic strain map [10].

4. TEST RESULTS AND CONCLUSION

Two preliminary thermal variation tests under constant pressure were performed within a climatic chamber over durations of 2.5 hours and 4.5 hours at elevated temperatures up to 85 °C to assess strain variation by inducing thermal expansion of the structure. Figure 3 highlights the thermal test results of the embedded high-backscattering, acrylate-coated fiber.

It was observed during the thermal tests that the locations on the composite tank cylinder aligned with the ‘minimum’ principal stress direction, as in Figure 2- (e, f), were identified by the OFDR and provided accurate and repeatable temperature readings unaffected by the structural internal strain effects due to the thermal expansion. Other positions on the sensor that were aligned with the ‘maximum’ principal stress direction, as in Figure 2-(d), have clearly shown strain variation effects due to thermal expansion, coupled with temperature detection.

Using ODiSI-6001 at 12.50 Hz acquisition rate, 5.2 mm gage pitch, temperature coefficient of -0.638 °C/GHz, the climatic chamber test results showed only missing data-points of 3.72% between the embedded fiber ingress/egress, at indices 235 (1.25 m) and 485 (2.55 m) of a 2.80 m total fiber length. After removing outlier points with Interquartile Range (IQR) method, followed by *NaN* interpolation in the fiber spatial x-axis, Figure 3 heatmap was generated.

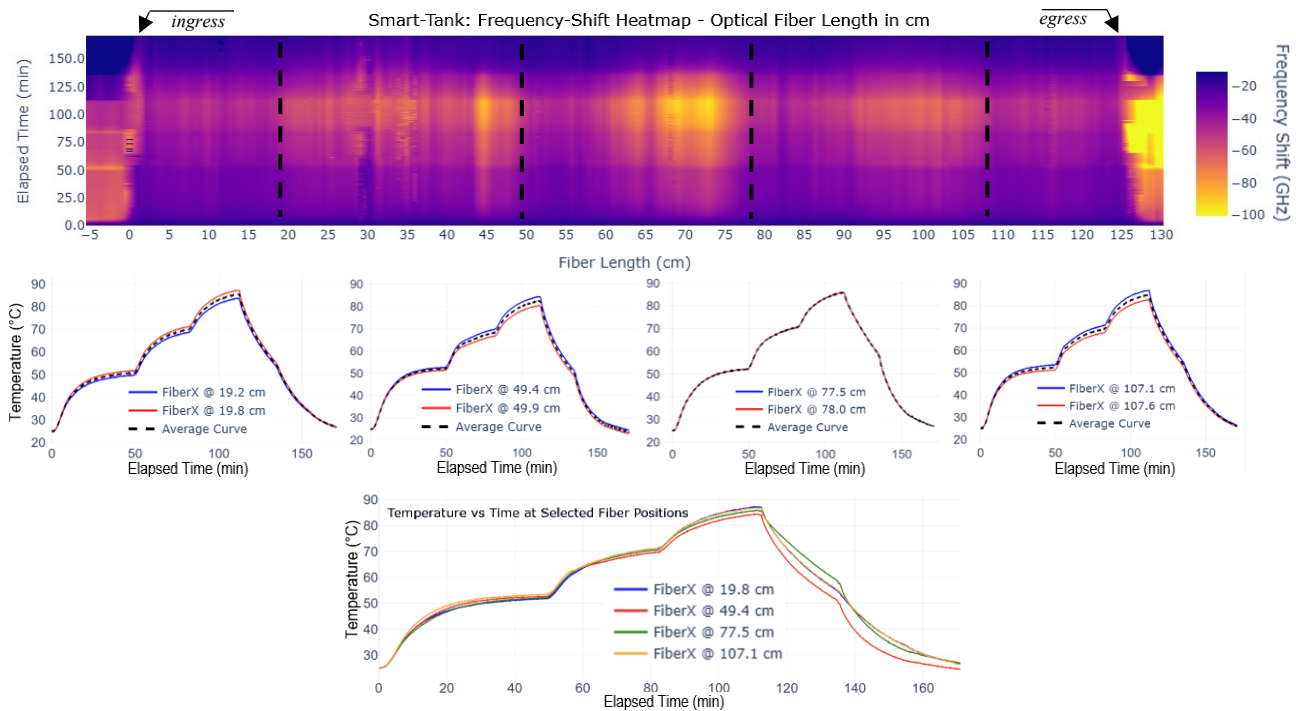


Figure 3. Heatmap and fiber-position curves highlight four regions among the fiber segments aligned with the ‘minimum principal stress direction’ that show clear temperature distinction from strain effects due to thermal expansion; The acquired temperature data coincides with the experiment’s temperature profile [50, 70, 85] °C at pressure 1 atm.

In conclusion, using the newly proposed embedding method to optimize sensor placement, a closed-form solution for the frequency shift governing equations can be achieved by isolating temperature from strain variations in the structure, with a single embedded optical fiber without relying on loose-tubes or capillaries. FEM analysis reliably predicts the direction of stress/strain vectors for any structure under designated loading conditions. Further experimental investigation at varying pressure levels is planned for future tests. The embedding method and results are useful for cryogenic propellant gauging applications in spacecraft composite tanks, especially those with additively manufactured components.

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