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Integrated Health Monitoring Approach for Reusable Cryogenic Tank Structures

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Reliability, safety, and economic feasibility of future space transportation systems rely not only on their technical and operational improvements but also as a key task on implementation of health monitoring systems with innovative sensor and diagnosis technologies. The application of such systems provides the possibility to reduce significantly the maintenance costs and turnaround time for future reusable launch vehicles. Current development tasks and activities are described in the field of integrated health monitoring/management for reusable launch vehicles, in particular, for large reusable cryogenic tank structures. Integrated health monitoring refers both to in-flight monitoring and on-ground verification phases. The dedicated engineering tasks are addressed including identification of critical components and conditions, selection of measurable parameters, detailed tradeoff and definition of candidate sensors, their adequate accommodation, diagnostic expert systems, and data analysis. Special emphasis is given to innovative onboard sensors such as fiber optic sensors and acoustic emission sensors as well as nondestructive inspection techniques such as infrared thermography and laser shearography as the most promising methods for inspection of cryogenic tank structures subsystems and components. Finally, the importance of applying telerobotic inspections in restricted tank areas is highlighted.

Introduction

THE objectives of this paper are to highlight and to discuss the necessary development tasks and activities in the field of integrated health monitoring/management (IHM) with the emphasis on reusable cryogenic fuel tank structures. Reusability at low cost is the key requirement for future crewed space vehicles considering the immense cost constraints of space transportation today. In comparison to the space shuttle, this goal only can be achieved when operational costs and expenditure can be reduced to civil or military aircraft operation conditions. This imposes more stringent and increased requirements on vehicle subsystem and component design in terms of reusability. Reusability can be achieved through increased durability or increased knowledge about subsystem and component condition (health). The first issue is linked with a considerable weight penalty and the second with sensor instrumentation and nondestructive inspection (NDI) methods to verify structural and functional integrity and health of reusable launch vehicles (RLV) both in-flight and on-ground. A new approach (described in this paper) to meet these requirements is the implementation of IHM allowing the prolongation of component usage and improvement of maintenance operations. The advantages of IHM are especially important in terms of aspects arising from the requirement of the launch reusability.

IHM Development Tasks for Reusable Cryogenic Tanks: Background

Several innovative projects launched by national and international space agencies (DLR, German Aerospace Research Center; ESA; NASA), such as the Future European Space Transportation Investigation Program (FESTIP) system and technology studies, Technologien fuer zukuenftige Raumtransportsysteme (TETRA), X-33, X-34, and X-38/crew transport vehicle (CTV), include as an essential part the design the development and practical application of health monitoring systems (HMS) based on intelligent sensors instrumentation. The main goal of advanced HMS is to provide complete tests and to check all structural elements and subsystems of the RLV and to verify their safety and operational capability. This is especially true in regard to rocket/airbreathing engines, reusable cryogenic tanks, and hot structures (thermal protection system, nose cap, hot flaps, etc.).

Integrated HMS implemented in RLV have to provide enduring knowledge about the local critical conditions and operational parameters of the monitored structure (integrity, wear, aging, load history, etc.). This problem includes inspection of all critical hardware of the RLV during manufacturing, joining, and assembly, as well as application of sensor technologies during prelaunch, mission, maintenance, and turnaround.

The main focus in the development of the cryogenic tanks that are being developed for future space transportation systems in the ESA program FESTIP is their reusability. With respect to reusability, one of the most important tasks is to minimize the number of inspections between flights and, correspondingly, to decrease sufficiently the life-cycle cost of the launching system. In general, it may be achieved in two ways.

1) Provide robust, damage tolerant design and structural integrity margins of the cryogenic tank to avoid its disassembly and to eliminate additional inspection procedures by preventing potential failures during the expected lifetime cycle of tank usage.

2) Evaluate and apply the most appropriate automated HMS including embedded sensors and advanced NDI methods to detect defects and damages that may occur during the flight.

It is obvious, however, that even with the successful development of robust structural design and an improved technology performance level, some forms of monitoring and inspection will be necessary to identify external threats to the structural and functional integrity of the tank and to evaluate the influence of damages sustained during operation. The optimum solution is to combine system robustness and integrity margins with cost-effective IHM technologies.

The relevant HMS will improve the inspectability of advanced structures and lightweight materials proposed for use in cryogenic tank design such as Al-Li alloys, carbon fiber-reinforced polymers, and ceramic composite materials (C/C, C/SiC). HMS will provide better understanding of the structure behavior by simplification of defects and damages determination and localization.

The integrated health monitoring concept for reusable cryogenic tanks refers to real-time in-flight monitoring and between flights ground verification phases. This requires both novel smart onboard sensorics and data processing units as well as advanced ground-based NDI methods suitable for effective inspection of the whole assembled tank and its subsystems during postflight maintenance and turnaround phases. Thus, the availability of integrated HMS in various areas with different physical measuring tasks is the key

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factor in the development of an operational and reliable reusable cryogenic tank.

IHM Concept

To create an effective IHM concept the development tasks can be divided into several steps, namely, 1) identification of critical components, conditions, and failure modes; 2) selection of operational parameters; 3) detailed tradeoff and selection of sensors; 4) diagnostic measurements and sensor data analysis; and 5) system diagnostics and failure mode recognition.

IHM development logic is presented in Fig. 1. Such a development plan will provide IHM design and identify parameters that have to be monitored/managed during operation of the tank.

The first step is connected with the evaluation and identification of all of the critical components, conditions, and expected failure modes on the basis of the cryogenic tank specification and design. The FESTIP Technology Study—Structures has proposed two alternative cryogenic tank concepts, metallic and composite. For both concepts, a novel fully reusable thermal protection system (TPS) based on carbon matrix compound (CMC) materials has been developed.[1]

With respect to FESTIP metallic/composite tank structural design, the main potential failure modes that can cause degradation in the integrated tank wall/cryogenic insulation/TPS are the following: cracks, corrosion, and stress corrosion cracking (for metallic tank wall); delaminations, voids, and inclusions (for composite tank wall); joint failures and disbonds between various parts of the tank, for example, cryogenic insulation/tank wall, liner/composite skin, etc.; impact damages in TPS; and cryogenic fuel leakage. Definition and identification of potential structural defects and failure modes is supported by analytical methods such as (failure modes effects and criticality analysis), which examines all conceivable failures and their effects on the tank structure.

The next steps include the selection of operational parameters (measurands) that have to be detected and monitored as well as the tradeoff and detailed definition of sensoric candidates and principles. A network of sensors is intended to monitor tank operational loads and flight parameters and to inform if they are within the operational range.

The selection procedure represents broad possibilities to combine failure modes, measurands, and measurement technologies. The choice of operational parameters has to fulfill the basic principles of

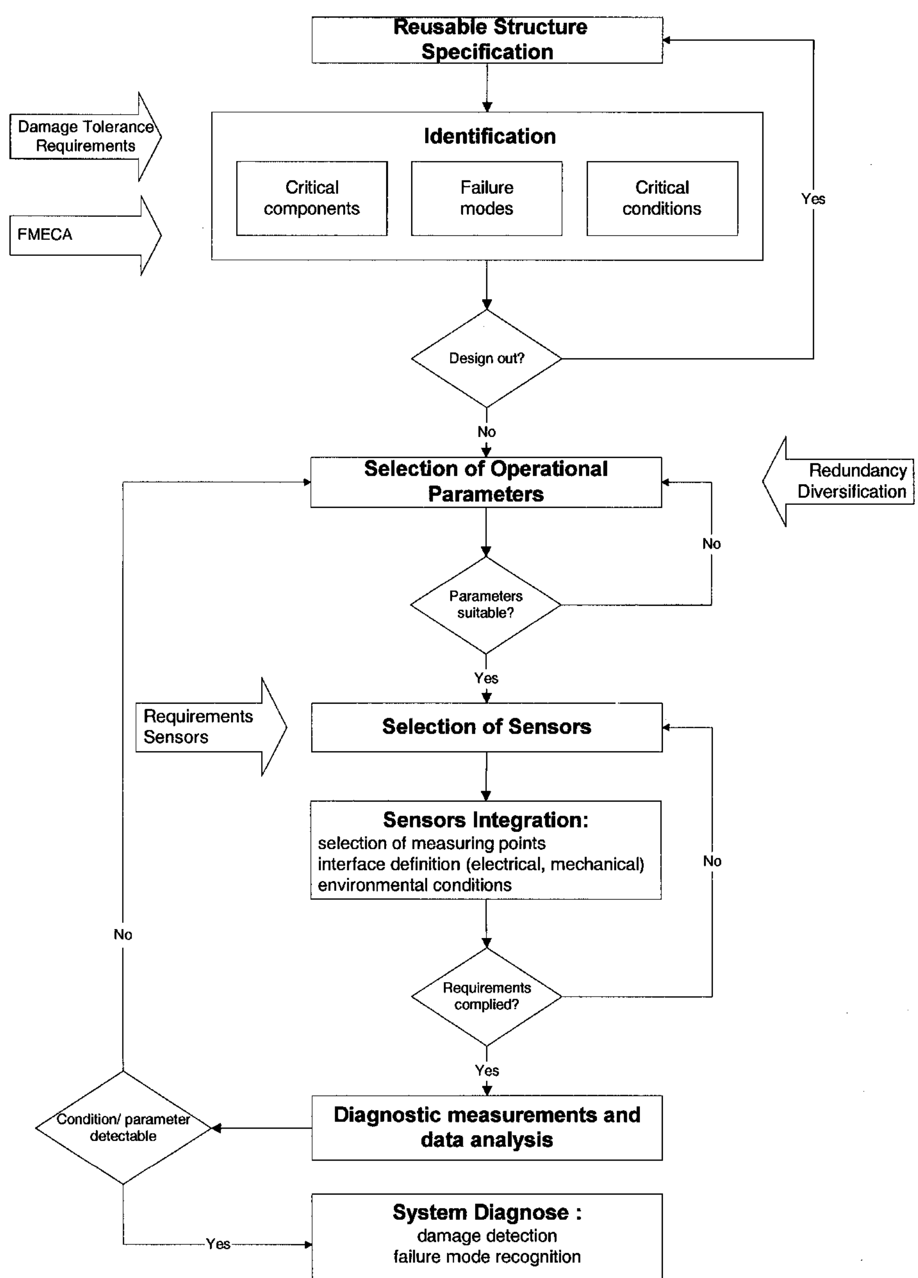

Fig. 1 Integrated health monitoring logic flowchart for reusable structures.

diversification and analytical redundancy.[2] Diversification means that several physical complementary parameters for each failure mode should be monitored with the help of a suitable independent sensor. The application of different physical characteristics will give a more precise assessment combining various measurement features, for example, range and resolution. As to redundancy, it depends on the severity of component damages and their impact on the assembled tank structure. All damages should be determined, localized, and monitored in accordance with damage tolerance design principles.

A very important task in the development of the integrated HMS is a careful study of sensor aspects: assessment and establishment of preferred sensor technologies, definition of the best sensor location in the structure, sensor instrumentation, and accommodation aspects such as integration and interface. The practical integration of sensor elements into the tank structure is followed by the wide and complex field of sensor data processing and evaluation, computation, system diagnostics, and failure mode recognition. This part of IHM evaluates the structural condition level from the various sensors signals. Sensor evaluation and integration aspects will be highlighted in the next sections.

IHM Sensors Evaluation

Advanced HMS are to be based on advanced in-flight sensors embedded or attached to the tank structure to monitor rapidly and efficiently different physical parameters and failure modes (such as strain, temperature, stress loads, vibrations, hydrogen leakage, etc.). For postflight inspection, HMS will be supported by suitable ground-based NDI methods. The most critical areas in the field of IHM/NDI applicability for reusable cryogenic tank structures are the following: restricted access to hidden items (e.g., cryogenic insulation, TPS standoffs, composite tank wall structure, etc.), large inspection area of the tank, cost and time constraints (between flights inspection), limited capabilities of conventional HMS/NDI methods for assessment of various structural defects (e.g. cracks, delaminations, disbonds, inclusions, etc.) and failure modes in critical locations of cryogenic tank structures.

The choice of sensor technology is one of the key points for adequate structural health monitoring. Selection criteria for IHM/NDI techniques embrace the following aspects: detection and operation capabilities, automation and remote sensing, survivability with respect to the intended extreme temperatures and load environments, robustness, and technical maturity. One of the main technology challenges lies in developing of in-flight and on-ground sensors/NDI methods for areas with limited access that will be appropriate for reusable cryogenic tank structures.

Based on an extensive database survey and considering today's experimental experience, the sensor candidates presented in Fig. 2 are of primary interest for cryogenic tank structural health monitoring. The highest priority requirement is the need to increase significantly the reliability of onboard sensors, instruments, test equipment, and associated wiring and connectors. There is a large number of sensors, as well as actuators and control algorithms, that are already space qualified and available for aerospace applications.

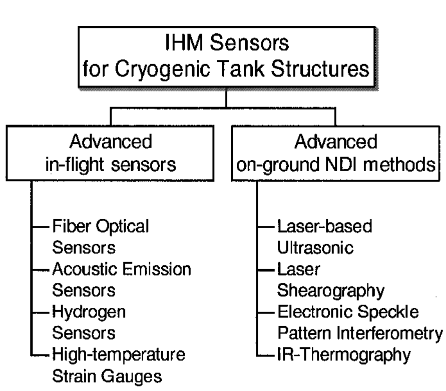

Fig. 2 IHM sensors for reusable cryogenic tank health monitoring.

These common sensors include thermocouples, strain gauges, and accelerometers for sensing temperature, strain, speed, acceleration, as well as humidity, liquid hydrogen volume flow, or electromagnetic signals. In particular, in-flight monitoring with the help of strain gauges can be provided by bonding them to selected critical areas of the tank structure and measuring strain sequences.

However, along with conventional sensors that can be used as a part of HMS, new types of sensors, effectors, and instruments are needed to achieve more complete coverage of potential failure modes and to enable more comprehensive system analysis and response. If possible, sensors should be designed to be noncontact, nonintrusive, and easily serviced. In addition, their size, mass, and support requirements (power, communications, data processing) should be minimized. A brief description of such sensors is given in the following.

Sensors Validation for In-Flight IHM

The main criterion for selection of new sensing techniques is their in-flight applicability considering the possibility of being integrated into cryogenic tank structures. Advanced in-flight IHM technologies proposed to be considered for future HMS include acoustic emission and fiber optical sensors.

Acoustic Emission

This method has been used successfully for monitoring fracture behavior, deformation, fatigue failure, discontinuities detection in pressure vessels, storage tanks, rotating machinery, and aircraft structures. Acoustic emission (AE) is detected by installation of ultrasonic transducers on the surface of the structure at preliminary defined strategic points to record the acoustic signals caused by structural damages. Key to structural monitoring with AE sensors are stress concentrations that cause defects that sound while the rest of the structure is silent. The noises may arise from friction (including bearing wear), crack growth or propagation of delaminations, turbulence (including leakage), and material changes such as corrosion. Thus, AE sensors can function as ears and highlight regions that threaten the integrity of the structure. They can provide unique information in real time by means of noninvasive in situ measurements with the highest standard of intrinsic safety and low installation cost.

The basic principle of the AE method is shown schematically in Fig. 3. Piezoelectric sensors attached to the structure register acoustic signals in the frequency range between 10 kHz and 1 MHz. The signal is then preamplified and analyzed with measurement electronics with regard to amplitude, duration, and other specific features.

A major advantage of AE technology is that it does not require access to the whole examination area. This means that removal of TPS or internal process fluids is not necessary. For AE inspection to function reliably as a whole-structure test, the structure must be loaded in such a way as to stimulate emission from all structurally significant defects. AE sensors can be used to gather data during the manufacturing and test programs to establish baselines for the detection of different defects generated during flight; thus, continuous monitoring in service is possible. The data can be gathered and reviewed by computer to monitor the structural integrity of the cryogenic tank.

An example of AE application is a composite liquid hydrogen tank to be used as a flight tank on the DC-XA vehicle in the RLV program.[3,4] The purpose was to verify techniques for using AE on cryogenic fuel tanks and to monitor the tank for acoustic indications of structural damages. AE transducers, preamplifiers, and corresponding adhesives were chosen based on their ability to withstand both ambient and cryogenic environments. During the structural test, the basic techniques for performing AE on a cryogenic tank structure were verified. However, the space applicability of the dedicated AE transducers with industrial quality level has to be further evaluated. In particular, some items will require future investigations, namely, selection of frequency range to monitor, appropriate choice of adhesives, and characterization of signals from a cryogenic environment.

Table 1 NDI/sensor applicability matrix for reusable cryogenic tanks[a]

	Evaluation								
NDI/sensor technology	Crack	Delamination	Disbond	Strain	Surface damage	Coverage	In-flight application	Maturity	Complexity
			Conventional						
Resistive strain gauges	—	—	—	++	—	Local	Yes	High	Simple
Contact ultrasonic inspection	++	++	++	—	++	Wide area	No	High	Simple
Eddy current	++	—	—	—	++	Scan area	No	High	Simple
X and gamma radiography	++	+	++	—	++	Scan area	No	High	Complex
Visual and dye penetrant	++ Surface only	+ Surface only	—	—	++	Wide area	No	High	Simple
			Advanced						
Acoustic emission	++	++	+	—	++	Wide area	Yes	Middle	Simple
Laser-based ultrasonics	++	++	++	—	++	Scan area	No	Low	Complex
Holography	+	+	+	—	+	Scan area	No	Middle	Complex
Laser shearography	+	++	++	+	+	Wide area	No	Low	Average
IR thermography	+	+	++	—	++	Scan area	No	High	Simple
Fiber optic sensors	+	+	+	+	—	Local	Yes	Middle	Average

[a]Detectable ++, possible +.

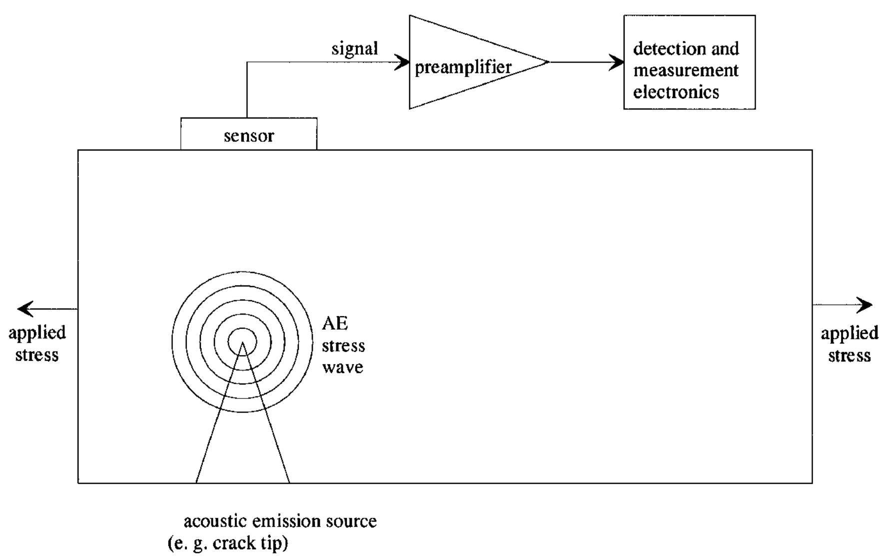

Fig. 3 Basic principle of the AE method.

Fiber Optic Sensors

Fiber optic sensors (FOS) also have very good potential for structural health monitoring due to their small size, light weight, chemical inertness, immunity to electromagnetic interference, high sensitivity and bandwidth, and potential low cost and availability.

The main operating principle of FOS is based on the output light modulation with respect to changes in the physical, chemical, or other properties to be measured. FOS can be characterized by the primary modulation techniques, such as intensity, phase, polarization, wavelength, time/frequency shift, backscatter intensity, and optical path length. Common types of FOS are spectrometers, polarimeters, interferometers, and Bragg gratings.

There are currently a number of FOS that are commercially available and manufactured for use within aerospace structures. They can be mainly used for measurement of strain and temperature as well as for damage assessment. FOS have recently been considered to offer several benefits in reusable cryogenic tank applications.[5,6] Implementation of FOS can be especially effective for reusable composite tanks because they can be easily embedded into composite tank wall during the manufacturing process without degrading mechanical performance and can be an integral part of composite tank structure. Furthermore, the sensors can operate in a wide temperature range, from cryogenic temperatures up to 500–600°C and survive the harsh space environment, while providing an accurate measurements of strain, temperature, and other factors affecting the tanks. Another application of FOS for cryogenic tanks that hold liquid hydrogen fuel can be hydrogen leakage detection. This is because coated optical fibers in an optical interferometer configuration can be used to measure in situ and in real time the strains induced by chemical changes in the coatings. An interesting solution for hydrogen sensing appears to be application of optical fibers with palladium coatings because the latter enhance hydrogen solubility and, therefore, may be used to detect hydrogen. The fiber interferometer concept is based on optical fiber coated with palladium. However, this technique is only in the development stage and needs to be verified and confirmed.

Some problems may arise when applying FOS for cryogenic tank structures. They include greater complexity of the signal processing compared to electrically based sensors, stricter joining requirements (particularly for large arrays), and the difficulty in replacing or repair if the sensor fails.

Both AE and FOS require further development and testing to be accepted in the cryogenic tank operational environment. The progress in fiber optics technology and piezoelectric ceramics used for AE sensors will certainly help to diminish the disadvantages mentioned earlier. Note however, that no sensor alone is capable to cover all of the required measurements and inspections. Thus, a combination of in-flight sensors supported with ground-based NDI methods will be needed to detect and monitor various types of failures, damages, and physical characteristics considering the different requirements for each specific cryogenic tank subsystem.

Advanced NDI Methods for Cryogenic Tank Structures

Another important aspect of IHM is application of relevant NDI procedures for on-ground maintenance and turnaround. Through a comprehensive database survey, the capabilities of various both conventional and advanced techniques have been analyzed and compared to identify the best NDI concept for reusable cryogenic tank structures. Table 1 summarizes an overview of NDI

Table 2 Potential NDI/sensor technologies for failure/damage detection in different subsystem of assembled reusable cryogenic tank

Failure/damage	Subsystem	Potential NDI/sensor technologies
Surface and impact damages, cracks and other defects in TPS	TPS panels, hot insulation, oxidation protection coatings	Visual inspection, IR thermography, ultrasonic, AE
Cracks through the thickness	Tank wall (metallic)	Ultrasonic inspection, optical interferometry, AE
Delaminations, fiber and/or matrix cracking	Tank wall (composite)	FOS (strain, temperature), AE, laser shearography, electronic speckle interferometry
Disbonds	Cryoinsulation/tank wall insulation core splices carbon fiber reinforced plastic skin/insulation core	Laser shearography, ultrasonic S-scan, IR thermography, holographic interferometry, telerobotic systems
Hot joints failure	TPS/tank wall	Laser-based ultrasonic, AE
Hydrogen leakage	Cryoinsulation/tank wall	Hydrogen sensors, FOS (hydrogen detection)

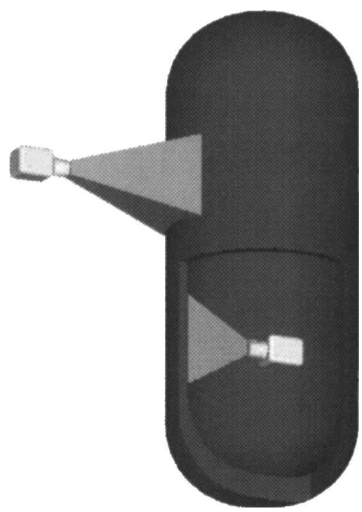

Fig. 4 NDI of cryogenic tank by laser shearography from inside and outside.

methods with selection criteria, which takes into account evaluation of specific defects and damages, coverage, applicability for in-flight monitoring, level of maturity, and operation complexity. Potential NDI/sensor technologies for failure detection in different subsystems of the tank are presented in Table 2.

From the large number of candidate NDI methods considered in Tables 1 and 2, laser shearography and infrared (IR) thermography seem to be the most appropriate techniques for on-ground monitoring of cryogenic tanks.

Laser Shearography

Laser shearography is one of the most advanced optical interferometric imaging techniques and rapidly gained acceptance by the industry in the early 1990s. It is suitable for noncontact, full field NDI of various materials. Combined with materials stressing methods, it allows measurement of differential displacement of the test object and, therefore, provides detection of subsurface defects and information of strain/stress distribution on the surface of the component. This method is well suited for NDI vibration and strain analysis because strains are functions of displacement derivatives.

Possible applications of laser shearography for the cryogenic tank are delamination detection and identification of inhomogeneous material compositions, inspection of adhesive joints, and detection of disbonds between various parts of the tank, as well as strain and vibration analysis. Laser shearographic devices can be used to inspect the cryogenic tank from outside and from inside (Fig. 4).

For large objects, such as reusable cryogenic tanks, the inspection tool incorporating in a single apparatus both the shearographic camera and the stressing device, for example, thermal, acoustic, vacuum stressing, vibration, excitation, etc., to be applied directly to a local area of the tank can be proposed. A possible configuration of a prototype system is shown in Fig. 5. The inspected tank area is illuminated and imaged by the shearographic camera through the transparent inspection window. Rubber seals can be used to facilitate the sealing between the stressing device and the tank. Such hardware, portable for use on launch site, can be designed to be practically implemented for the field inspection of the large cryogenic tank structures.

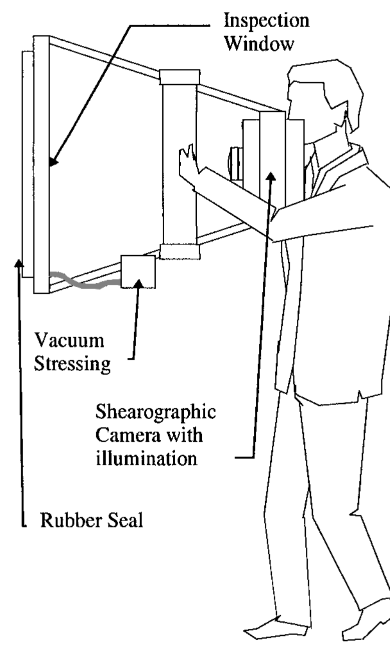

Fig. 5 Model of application of laser shearographic camera for the assembled cryogenic tank.

IR Thermography

This method is also well suited for cryogenic tank applications for several reasons. It requires no physical contact either for thermal excitation or detection by the IR camera, and, thus, one-sided inspection is possible. Because it is a fast and economical technique, IR thermography can be applied for rapid inspection of large areas of the tank to detect and sort parts with anomalies in infrared thermal images. After that, the damaged parts will be more closely inspected with another selected NDI method. Specifically, thermography can be used for postflight inspection of TPS directly after landing. Hotter areas detected by thermographic cameras will indicate defects on the TPS panels or insulation. The defected areas will be then checked more precisely to define whether the panel may be repaired or it should be replaced.

NDI and Telerobotic Methods

Sophisticated structures such as large reusable cryogenic tanks assembled with cryogenic insulation and integrated TPS have areas with restricted access by humans performing NDI measurements. Typical restrictions are limited access to certain areas due to structural constraints and limited access to areas with environmental conditions hazardous for humans providing inspection. If inspection tasks have to be performed in such areas, the application of telerobotic methods becomes necessary. The use of advanced NDI combined with robotic methods for inspecting the tank surfaces offers significant advantages for future reusable launchers with respect to safety and economy.

In particular, because automated robots are computer-operated machines, their inspection work does not suffer from human errors, which improves the quality of the inspection and increases the system safety of the tank. In addition, automated robotic systems

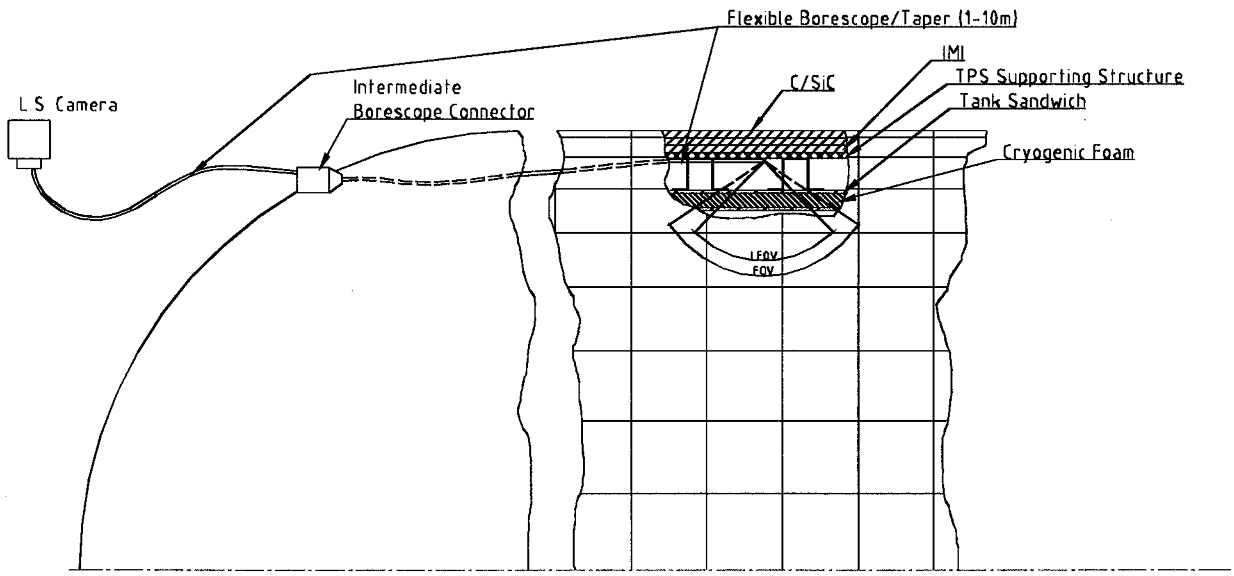

Fig. 6 NDI of hidden items by laser shearograph.

reduce the amount of expensive human resources for the inspection of a large assembled cryogenic tank structure and provide a very time-effective nondestructive evaluation that will be advantageous for mission schedules.

Today the application of robotic inspection for space explorations is progressing rapidly. Specifically, in recent years NASA has sponsored some projects that developed and systematically investigated methods for telerobotic inspection of Space Station Freedom. A tendency toward robotic technology to perform maintenance and routine tasks will be seen in efforts to move robotic systems from laboratory level into actual space programs. Future reusable tanks will also undeniably benefit from typical advantages offered by robotic systems.

It is clear that the conceptual tank design should be optimized not only in terms of maximum performance and minimum weight, but also in terms of easy inspectability. For this purpose, an effective reusable tank structure should include design features that support telerobotic inspections in restricted tank areas. Typical features desirable to support telerobotic inspections should be in following fields:

1) Support of the robot for moving and orientating in/at the structure should be provided. Rails, mechanical links, and orientation marks at various parts of the structure, for example, which enable the system to determine precisely at any time the robot position and orientation in and at the structure should be part of this type of telerobotic support.

2) Robot support requirements need to be provided, such as cables, power supplies, communication links, etc.

The semiautonomous, selfintelligent robotic systems that can enter the tank, inspect it remotely, and send information to computers for evaluation are critical needs for safe, cost-effective, and reliable cryogenic tank operation. Potential areas for robotic inspection are tank inspection from the inside, TPS integrity verification, surface impact detection, verification of the piping and fitting, and leaks detection. Integrated health monitoring telerobotic systems equipped with suitable inspection sensors (cameras, camera positioners, manipulators, corresponding NDI sensor heads, etc.) that perform tank examination and servicing in different critical areas with limited access will play an increasing role in future missions for the next generation of spacecraft.

A further application of laser shearography for inspection of hidden critical items that cannot be scanned from outside or inside is shown in Fig. 6. Flexible borescope or optical fiber taper technology with ground support equipment umbilical very lightweight shearographic detector heads can be permanently embedded into the tank sandwich structure. During on-ground maintenance, fish eye optics with a very large field of view enables direct access to even hidden items to monitor the structural integrity lifetime status.

Conclusions

IHM will become an integral part of future reusable cryogenic tanks allowing verification of their structural and functional integrity and health aspects without disassembling and dismounting. The key point in the IHM concept is design and development of innovative intelligent HMS that will identify and detect the most important failure modes and their characteristics well before the failure can actually happen. Requirements and benefits for instrumentation of advanced sensoric and NDI technologies will be the guidelines for the cryogenic tank structural design in future activities directed to the development of reusable launchers.

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