STRUCTURAL HEALTH MONITORING TECNIQUES FOR DAMAGE DETECTION IN HYDROGEN PRESSURE VESSELS

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ABSTRACT

Damages due to mechanical impacts on the structural integrity of pressure vessels in composite material to store compressed hydrogen can lead to disastrous failures if they are not detected and fixed on time. A wide variety of damage modes in composites, such as delamination and fiber breakage introduced by impact, is difficult to be detected by conventional methods.

Structural Health Monitoring (SHM) provides a system with the ability to detect and interpret adverse changes in a structure like a pressure vessel. Different types of methods will be proposed for damage detection based on comparing signals to baseline recorded from the undamaged structure. Guided wave based diagnosis method is one of the most effective used techniques due to its sensitivity to small defects.

The paper pretend to identify the more adequate inspection methods to classify by smart rules based in artificial intelligence, the effect of an impact on the structural integrity of the pressure vessel, thus improving the level of safety.

1. INTRODUCTION

The use of hydrogen as an energy carrier has given rise to the necessity of detecting damage that may occur in pressure tanks, some of which are constructed with composite materials, due to the high pressures as well as the possibility of damage.

In our case, damage is understood as any change introduced to a structure that could affect the current or future structural characteristics of hydrogen tanks with the possibility of leakage affecting safety.

The application of SHM[1] techniques for tanks helps to understand the existence and types of damage, its location, scope and severity for highly integrated structures, applying signal processing techniques and statistical or Artificial Intelligence methods such as classification of damage signatures.

The primary challenge in designing an SHM system is to understand the defects to look for and how to identify them. The characteristics of the damage that may be present on any particular structure play a significant role when defining SHM system architecture. "Changes" or "damage-sensitive features" caused by defects that may arise will be of great use in order to determine the type of sensors and analysis methods required since different sensors and the technologies they use offer different capacities to detect defects and to determine structural behavior.

2. SHM ON COMPOSITE STRUCTURES

As previously mentioned, the hydrogen storage tank industry uses composite materials (CFRP) due to their excellent properties in terms of strength, specific rigidity and thermal insulation. Nevertheless, using SHM, the detection of damage for composite materials is more difficult than for metal structures due to the anisotropy of the material, fiber conductivity, etc. On the other hand, these materials offer full system integration during manufacturing processes, which may give rise to a multifunctional element equipped with a sensor network, as if it were a nervous system.

Composite materials are susceptible to damage caused by impact. Particularly, one type of damage known as: Barely Visible Impact Damage (BVID), may go unnoticed. Detection is critical since the originally damaged area may spread as a result of material fatigue caused by high pressure, and the rear surface of the composite material may have even greater damage depending on its thickness.

In order to monitor these structures, a research work has been carried out on sensors and actuators, the objective being to design robust, light, reliable sensors, which respond to real-time structural maintenance that may be superficially applied or embedded during the manufacturing process at a reasonable cost.

In the case of structures manufactured using composite materials, typical defects that habitually require the use of a monitoring system are: delamination, development of micro-cracks in matrix and breakage of fibers, debonding, delamination and loss of secondary adhesion between the different elements of the structure, water absorption, ageing of materials and start and progression of cracks due to thermal-mechanical fatigue.

The effects listed above may be caused by a singular reason or by a combination of several simultaneously acting locally or globally; primarily, tensile loads that cause greater stress than recent stresses on the structure. They may also be caused by high or low force impact that may damage the structure.

3. STRUCTURAL MONITORING TECHNOLOGIES

While there are numerous applicable technologies, the four considered most suitable shall be discussed.

In a first group, acoustic technologies based on the propagation characteristics of sound waves are considered; they may be of two types:

- **AE, Acoustic Emission**[2], based on the measurement of the commonly named "crunch" of the material upon propagation and spread of the defect. Detection systems react against non-inherent material sounds that are generated by cracks, delamination, impact, etc. upon breakage of the material. This is a passive dynamic method for local measurement.
- **Acoustic-Ultrasonic (AU)**, also known as **Lamb waves**. A transducer/actuator emits ultrasonic frequency waves that propagate on the medium. Upon detecting discontinuity or defect, the signal deforms and is captured by a sensor. The system compares the

signals and may be able to determine the location and magnitude of the structural damage.

In a second one, **Electromechanical Methods** based on the measurement of electrical parameters of actuators affected by the defects are studied. The measurement of electromechanical impedance, which is affected by the defect, is in fact an acoustic measurement, but is included here as it usually measures electrical impedance at the actuator input. It is a local measurement and is used by coupling a thin piezo ceramic transducer (PZT) to the structure. The electrical impedance of the PZT and the mechanical impedance of the structure are coupled. By measuring the electrical impedance at the PZT input, the mechanical impedance of the structure may be obtained and subsequently its status.

Finally, this paper will consider an emerging technology consisting of **Remote Interrogation** of structures at **microwave frequencies** on electromagnetically activated surfaces so that any parameter affecting the reflected wave is a function of its structural condition.

4. ACOUSTIC EMISSION

Monitoring techniques based on acoustic emission operate in the same way as those based on Lamb waves, except for the fact that the signals detected by the sensors are generated by the damage itself and only generated while the damage spreads.

Acoustic emission is formally defined as "the phenomenon which releases elastic energy into the material, which then propagates as an elastic wave". Sources of mechanical stress waves are associated with breaks in the molecular structure, i.e. in the bonds of the polymer backbone chain or in weaker secondary bonds.

These waves have a high frequency (100 KHz - 2 MHz), which makes this technique insensitive to mechanical vibrations generated under normal operating conditions.

The objective of acoustic emission systems is to convert mechanical waves generated, for example by the spread of a break, into an electrical signal. When breakage or impact occurs on a monitored structure, energy in the form of mechanical waves is released at the molecular structure level.

AE is a very sensitive technique. Thus, it is sensitive to microcracks even prior to detection by other techniques and, of course, prior to any possible danger.

5. ELECTROMECHANICAL IMPEDANCE

Consist of the excitation of vibrations using a specialized transducer that simultaneously measures the applied normal force and the induced velocity. It measures the electrical impedance imposed by the actuator and that which is influenced by the local mechanical impedance of the structure. Evidently, this is an active technology based on energy transferred between the actuator and the mechanical system. This methodology uses both impedance modulus and phase (i.e., real part and imaginary part) in order to detect damage. It is high frequency with local measurement near the transducer.

The basic idea of this method is to apply high frequency structural excitation to a structure in a local area close to the actuator in order to monitor and detect changes in impedance which show mechanical damage, especially at higher frequency bands (> 30 kHz).

A fundamental aspect of impedance-based SHM is the use of piezo ceramic materials (PZT) as sensors and actuators.

The effect of active piezoelectric sensors applied to the structure is the induction of local deformation parallel to the surface, which creates stationary elastic waves in the structure.

It is well known that in order to detect damage, the wavelength of the signal used must be less than the characteristic length of the damage. In order to meet this requirement and to be able to detect incipient damage, the frequency range used is between 30-400 KHz. Additionally, the frequency used must be less than 500 KHz; anything higher, the sensitive area is very small and responds to the piezo ceramic patch as well as the conditions of attachment to the structure, more than the structure itself.

One significant aspect worth mentioning in terms of this method of analysis is that it requires very little power in comparison with other active technology-based methods, such as Lamb wave propagation.

6. LAMB WAVES

Lamb Waves[3] are guided elastic waves propagated on the interior of solid plates. They are a combination of shear and longitudinal waves occurring only on relatively thin plates (for several wavelengths), such as in the case under study. Behavior depends on material density, elastic properties, geometry and frequency.

They are generated by means of a piezoelectric actuator at ultrasonic frequencies. Propagation rate and number of nodes present depend on the working frequency. Any structural defects modify wave propagation characteristics (dispersion and attenuation) on the structure and may be detected.

7. SENSORS

In theory, the most suitable sensors are those, due to size and reliability, which may be embedded in the structure during the manufacturing process without affecting any functional characteristics. Furthermore, superficially applied sensors capable of withstanding normal operating conditions and ageing may also be considered.

While there is a wide variety of sensors and actuators available, sensor technologies being applied are:

- FBGs - Fiber Bragg Grating Optic Sensors[4] These have the advantage of being able to multiplex several sensors in a single fiber optic. Its diameter is $127\mu m$.
- Piezo ceramic sensors: Monolithic PZT or PWAS
- Glass-coated amorphous ferromagnetic sensors. Its diameter may be less than $10\mu m$, making it a much less intrusive system.

8. EMBEDDING OF FIBER BRAGG GRATING SENSORS

The processes of embedding fiber optics into composite materials is carried out very delicately by hand.[5] One research line of great interest would be to try to automate this process with respect to the type of tank. One particular difficulty is a singular fiber optic input/output to the outside in order to connect measurement equipment that is robust and reliable.

In this study some solutions have been proposed. The conditions that input/outputs must meet are the following ones:

- The fiber optic input/output must not be a weak point in terms of structural strength and in terms of the strength of the system itself.
- The connection system must be sealed against any possible entry of resin during the curing process.

Figure 1. Embedding of fiber optic input/output in composite material.

The figure displays an input/output that allows for embedded fiber optics to connect to external measuring equipment, and which complies with the requirements above.

9. CREATION OF SENSOR SURFACES AT MICROWAVE FREQUENCIES

Dielectric properties at microwave frequencies for composite materials with glass-coated soft ferromagnetic microwires[6], both those embedded in the material as well as those applied superficially, have been researched.

Experience has shown that in both cases damage is detected in the composite material since the spectrum of permissiveness varies in certain frequency ranges[7,8]. This demonstrates the potential of microwires as sensor elements for detecting damage in composite structures, with the advantage of having a damage-sensitive structure that can be interrogated remotely.

10. CONCLUSIONS

As we have seen, there are many SHM techniques applicable to monitor composite manufactured hydrogen tanks. One difficulty is the tank´s shape and the embedding of sensors. Creating a damage-sensitive structure that can be interrogated remotely may lead to a simple and easy solution; this is being studied for composite material manufactured pressure vessel for hydrogen storage, thus contributing to the safety of hydrogen applications.

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