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METHODOLOGY OF THREAT AUTONOMOUS ASSESSMENT AND FORECASTING THE LIFETIME OF THE MARINE STRUCTURE

Lech Murawski

Gdynia Maritime University
Faculty of Marine Engineering
Morska Street 81/87, 81-225 Gdynia, Poland
tel.: +48 58 6901481
e-mail: lemur@wm.am.gdynia.pl

Abstract

Structural Health Monitoring (SHM) is a natural extension and supplement of Non-Distractive Tests (NDT). Structure assessment during periodical NDT tests is performed by highly trained human team. However, during long sea voyage, ship crew has no knowledge and possibility for detailed assessment and, what is more, has no knowledge lifetime predicting of ship structure. SHM systems should have good designed sensors types, distribution, and automatic recording unit. However, most important (and most difficult for designing) is autonomous and self-contained procedures for marine structures hazard assessment. In the paper, basic assumptions for numerical algorithms of signal processing, damage identification and localization, threat assessment and forecasting of structure lifetime are presented. SHM systems can be based on several different measurements techniques like: comparative vacuum monitoring, electromagnetic layer, Lamb waves, vibration based methods, acoustic emission, and fibre optics. Last three methods are most promising in the marine environment, according to the author experience. Global ship hull deformation should be monitored as quasi-continuous measurements. Optical Time-Domain Reflectometer method (OTDR) is planned by author for hull global deformation monitoring. Some local strain-stress concentration of hull structure and propulsion system bearings' reactions will be monitored by Fibre Bragg Grating (FBG) sensors. Both techniques (OTDR and FBG) have been shortly described in the paper.

Keywords: *monitoring systems, non-destructive tests, ship structures lifetime prediction, damage identification and localization, lifetime forecasting*

1. Introduction

Structural Health Monitoring (SHM) is natural continuation of non-destructive tests of machines and equipments. SHM systems with damage detection techniques became more and more important from economical, human safety and environment protection point of view. SHM systems are widely adapted in the wide range of civil engineering [3], offshore structures, aviation as well as automotives, ships, wind turbines etc. Safety of ships is very important but practical implementation of experimental techniques meets several difficulties in marine conditions. Marine structures like: marine vessels, submarines and offshore structures surrounded by a harsh marine environment are exposed to long-term cyclic loadings comes from continuously acting sea waves and short-term extreme loads such as severe storms, seaquakes or even collisions. The marine environment (sea water) results in fast corrosion, erosion and scour processes. Those phenomena increase the size of an existing damage and also initiate its growth. The example of catastrophic damage of big container ship is presented in Fig. 1. The idea of the marine SHM is to build a system that is able to evaluate a condition of a monitoring structure in different environmental and exploitation conditions.

Structural Health Monitoring (SHM) is a multidisciplinary research topic intended for development and implementation of methods and systems that realize inspection and damage detection by integration of sensing systems with structures [1]. It also includes a variety of techniques related to diagnostics and prognostics. SHM system can be based on several different techniques [2], like:

Fig. 1. Broken container ship

electromagnetic layers, comparative vacuum monitoring, Lamb waves, acoustic emission, vibration-based methods, fibre optics. Last three methods are the most promising in marine structures [4]. SHM systems also potentially allow the reduction of maintenance costs directly connected to the effectiveness of the non-destructive techniques, which are used for the monitoring of important structures, and can be used to conduct non-destructive inspections for areas, which have been traditionally difficult to access. A typical structural health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment. One of the most important information is strain/stress distribution in the structure. One of the most promising sensors for that purpose is those based on fibre optics technology [6]. Two general techniques are analysed. First, one is based on Optical Time-Domain Reflectometer method (OTDR), and the second one is based on Fibre Bragg Grating (FBG) sensors.

2. Fibre optic sensors

The systems based on fibre optic technique with Fibber Bragg Grating (FBG) strain sensors are one of the most interesting and promising. In comparison to classical strain measuring method based on electric strain gauges, the new technique based on fibre optic technology and FBG sensors is much more stable and the measuring error is much smaller. Other important advantage of FBG sensor is multiplexing ability – even over hundred sensors can be multiplexed to provide measurements across the structure [5]. The main FBG sensors have advantages are as follows: high sensitivity, low sensor's size and mass, sensors can be built into the monitored structure, immunity to electromagnetic fields, applicability to chemical aggressive surroundings, multiplexing ability, sensors can support thousands kilometres unrepeated step out distances, self–calibrating and free from signal drift.

Bragg gratings are written into single-mode fibres. These fibres consist of a very small inner core (diameter 4-9 μm) and an outer part (cladding) of pure glass of 125 μm diameter. The core has a higher refraction index caused by high Germanium doping. The difference of refraction index between inner core and cladding causes the light to propagate only inside the small core. The glass fibre is coated with acrylate, polyimide or organic modulated ceramic, to protect it especially against water and hydrogen, which causes crack growing and can reduce the mechanical stability. Each single fringe reflects a very small part of all incoming wave. The reflection factor per single fringe is in the range of 0.001% up to 0.1%, depending on how much energy was used to write the Bragg grating and on the percentage of Germanium doping of the fibre core. Each single fringe reflects light with different phase shifts. Therefore, interference is a reason that the most of the light is erased. However, the reflections with equal phase shift accumulate to a strong reflection peak. The reflection of whole grating is the sum of all these thousands of very small single reflections. Reflected light travels forth and back in the fibre, therefore reflected light beams of the single grids are in phase if an integer of light wavelength fits into two times the grid distance. The scheme of FBG sensor construction and operation principle is presented in Fig. 2.

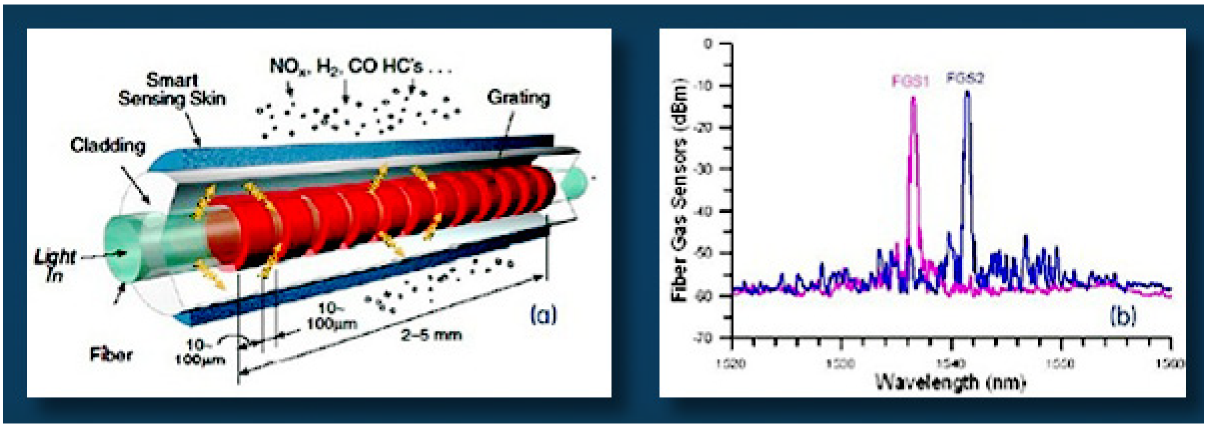

Fig. 2. FBG sensor construction and operation principle

Because temperature has a very strong impact on the FBG sensors, precise strain measurements can only be achieved with proper temperature compensation. When the FBG sensor is fixed to the specimen on a surface without mechanical strain, it works as temperature compensation sensor. If FBG sensor is strained the wavelength of the reflection peaks is shifted. It is necessary to measure these shifts very precisely. Resolution and short-term stability of ±1 pm is required. For laboratory investigations, interferometers are often used. In the commercial equipment, usually other principles are applied. Nowadays the top-class instruments are using tunable lasers. The interrogator use broad-band light source and therefore only a very small part of the light energy are related to the small bandwidth of a BFG. Therefore, the reflected peak energy is very low. A tunable laser concentrates all its energy in an extremely small bandwidth and by sweeping over the whole bandwidth range it scans the spectrum with high power and can provide an excellent signal-to-noise ratio.

An optical time-domain reflectometer (OTDR) is an optoelectronic measurement techniques used to characterize an optical fibre. An OTDR injects a series of optical pulses into the fibre under test. Light is reflected back from points along the fibre. The strength of the return pulses is measured and integrated as a function of time, and is plotted as a function of fibre length. An example of OTDR instrument is presented in Fig. 3. Optical Backscatter Reflectometer (OBR) instruments are used for strain and temperature measuring along pure fibre optic. OBR measuring device can measured with high spatial-resolution, distributed strain and temperature in standard telecom-grade fibres. The OBR uses swept wavelength interferometry to measure the Rayleigh backscatter as a function of length in optical fibre. The system allows practical measuring of distributed temperature and strain in standard fibre with millimetre-scale spatial resolution over tens to hundreds of meters of fibre with strain and temperature resolution as fine as 1 $\mu\varepsilon$ and 0.1°K.

Fig. 3. OTDR measurement instrument

Measurement techniques are based on Rayleigh backscatter in optical fibre, which is caused by random fluctuations in the index profile along the length of the fibre. The scatter amplitude as a function of distance is a random but static property of that fibre can be modelled as a continuous, with a random period. The spectral frequency associated with the Rayleigh backscatter is written in the same form as the reflection frequency of a Bragg grating. Shifts in the fibre index of refraction or in the average perturbation period caused by an external stimulus (like strain or temperature) in turn cause shifts in the local spectral frequency of the Rayleigh backscatter. Accumulated changes along the optical path also manifest as a time shift of the Rayleigh backscatter return loss amplitude pattern. Performing a cross correlation on the backscatter amplitude time domain or frequency domain data accurately measures these spectral and temporal shifts, which are easily scaled to form distributed temperature or strain measurements.

OBR measuring techniques can be used to measure the distributed spectral shift and temporal shift in the Rayleigh backscatter along an optical fibre. This capability enables distributed temperature and/or strain sensing along any standard single-mode fibre. This technique enables robust temperature and strain measurements with high spatial resolution and good accuracy. This measurement capability also provides a practical alternative to fibre Bragg gratings sensors and extrinsic Fabry-Perot interferometric sensor in situations where a large number of closely spaced measurements are desired.

3. Methodology of lifetime forecasting

The shelf life of the structures is depended on the initial properties and the global exploitation process. The marine structures are exposed to several wear and tear processes. The main ones are frictions, corrosions, erosions, plastic deformations and fatigue. In the Lorenz curve, three main periods of the wear process are highlighted: machines reaching out, exploitation and emergency wear and tear. Velocity of wear and tear process can be approximated by several theoretical distributions like normal, exponential or Rayleigh distribution. The monitoring system (lifetime forecasting algorithm) should be calibrated experimentally for chosen marine structure type.

One of the main hazards of marine structure is fatigue – cyclic, variable loads coming from exploitation process and from environment. The monitoring system should register at least three parameters: loading frequency, amplitude, and number of strain-stress cycles. Palmgren-Miner principle and rainflow counting methodology is a good method for lifetime forecasting [7]. The following equation describes Palmgren-Miner linear damage rule.

$$\sum n_i / N_{fi} = 1 , \tag{1}$$

where:

n_i – number of cycles with given amplitude,

N_{fi} – number of repetitions of this same cycle that equals the median life to failure for given amplitude.

Failure is predicted when the sum of all ratios becomes 1.0 (100%). Equation 1 is also used with other fatigue curves such as load-life or ε-N curves. Marine structures are exposed on excitations with variable amplitudes and frequencies. SHM system must compare stresses changes with analytical curves with simple constant amplitude load cycles. The application of the linear damage rule (equation 1) requires that we know the condition (mean value and amplitude of strain-stress level) to which the damaging event should be compared. Different counting methods are known in the literature [7]. Range-Pair method, Racetrack Counting, Level-Crossing method, Peak Counting method and Rainflow method are the most popular and useful. The best method, in the author opinion, of cycle counting for marine structures with environmental loads, is Rainflow method. In that method time, history of stress (or load or strain) level is drowned. The time axis is vertically downward. Changes of analysed stress value may be treated as a rain going down. Detailed procedures are described in the literature [7].

The presence of a crack can significantly reduce the lifetime of a structure. Most of SHM systems [3, 4] can find out the cracks. In the first level, the systems can detect the existence of the crack; in the next step, the systems describe its size and location. Combination of acoustic emission with vibration (measured by fibre optic sensors) based method is planned by the author for marine SHM systems. In order to prediction of fatigue crack growth (lifetime estimation), several data are needed. For example, the stress intensity factor, the fracture toughness, the initial crack size and critical crack size. All of that information can be determined on the base of measurements but necessarily compared and supported by numerical calculations (Finite Element Method is the most universal in the author opinion). All analysis should be based on information given from S-N curve (Wohler curve). High-cycle fatigue theory should be used in the marine lifetime prediction systems. S-N curve can be described by the following equation:

$$\log_{10} N = \log_{10} K - m \log_{10} S, \tag{2}$$

where:
N – number cycles to failure,
K – coefficient of the exact specimen,
m – the slope of the S-N curve.

Values of K and m coefficients can be taken from guidelines of Health and Safety Executive [8].

Crack growing process can be divided into three regions. First region is near threshold region, below which there is no observable crack growth. Rates of crack growth in that region are less than 1.0×10^{-10} m/cycle. In the third region, the crack growth rates are very high and going very fast to catastrophic (high level alarm in the SHM system) situation. The most interesting is second region, which can be described by Paris law:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\,(\Delta K)^n, \tag{3}$$

where:
$\mathrm{d}a/\mathrm{d}N$ – velocity of crack growth [m/cycle],
C – coefficient found by extending the straight line to $\Delta K = 1$,
ΔK – stress intensity factor,
n – the slope of the line of crack growth.

For metals n is in the range of 3-5. From author experiences, for cast steel $n = 2.8$ and for cast iron $n = 3.6$. Typical velocity of crack growth is in the range of 1.0×10^{-5}-1.0×10^{-4} m/cycle.

4. Conclusions

Structural Health Monitoring should have several subsystems: sensors network, periodically working recording system, signal processing, statistical data analysis with structure technical condition assessment and the most important structure lifetime forecasting. The following identification levels should be implemented in the system: damage and or structure dynamic characteristics detection, crack localisation, damage valuation (size and type determination) and assessment of the structure condition (safety of further exploitation and lifetime prediction). Each SHM system must be dedicated to specific marine structure. The structure must be previously analysed numerically and some of its elements must be tested by measurements in the fatigue laboratory. System "learning" on the real ship will be the last step of the SHM building.

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