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THE FUNDAMENTALS OF STRUCTURAL HEALTH MONITORING BY THE ACOUSTIC EMISSION METHOD

Dr. Boris Muravin, Prof. Gregory Muravin, Dr. Ludmila Lezvinsky

Margan Physical Diagnostics Ltd. P.O.B. 8155, Ha-Omanut 12, 42160, Netanya, Israel
Tel: +972-9-8655510, Fax: +972-9-8655514, email: bm@margan.com

ABSTRACT

Structural Health Monitoring (SHM) is an emerging field of modern engineering that deals with diagnosis and monitoring of structures during their operation. Increasing requirements for safety, development of tools and criteria for condition based maintenance (CBM), cost reduction are all driving development of SHM methods in different industries. The primary goal of SHM is detection, identification, assessment and monitoring of flaws or faults/conditions that affect or may affect in a future safety or performance of structures. SHM combines elements of non-destructive testing and evaluation, condition/process monitoring, statistical pattern recognition and physical modeling. Acoustic emission method uniquely fits to the concept of SHM due to its capabilities to examine, monitor structures and assess structural integrity during their normal operation.

In this work, the fundamental definitions and principles of application of Acoustic Emission as a method of SHM are elaborated. This includes:

- Recommended terminology and definitions of SHM by the AE method.
- Outline of recommended process of AE SHM.
- Fundamental assumptions and principals regarding development of new SHM procedures, selection of equipment and methods of data acquisition and analysis, diagnosis, monitoring and prediction by AE SHM.

The developed principals provide an outline for systematic and standard development of new SHM applications based on Acoustic Emission method.

KEY WORDS

Acoustic emission, structural health monitoring, flaw and fault detection, identification, location, assessment and monitoring.

INTRODUCTION

Structural health monitoring is an emerging field of engineering that deals with development and application of approaches for on-line assessment and monitoring of structures [1, 2, 3]. Safety and commercial needs are primary motivations behind SHM development.

Safety motivation

Analysis of failures in different industries over the world showed that proper design, selection of materials and construction do not necessary guaranty safety of structures in a long term. This is because structures can be subjected to extreme loads and harsh environmental conditions during their operational life. Material properties may degrade significantly over the time. Also, statistics of failures show that periodic non-destructive examinations of structures are not enough to prevent possible failures due to:

- Their statistical local application on a small portion of a structure.
- Too large re-inspection intervals.
- Limited monitoring capabilities.
- Inability to distinguish developing and non-developing flaws.

Therefore, in order to reduce a risk of unexpected failure, it is necessary to develop methods capable of performing on-line, outage independent, global assessment and monitoring of structures.

Commercial motivation

Another driving force behind SHM is a commercial need to develop methods that can provide measurable, quantitative criteria for condition-based maintenance. CBM is a relatively new approach being adopted in different industries that defines maintenance schedule based on the condition of structure. In other words, maintenance is performed whenever and wherever is necessary, allowing cost effective operation, minimizing need in outages and reducing risk of failure.

Structural health monitoring vs. non-destructive testing

Structural health monitoring is applied non-destructively and in many cases incorporates different non-destructive evaluation (NDE) methods. However, there are several conceptual differences between both approaches. Usually, the primary objectives of NDE in industrial applications are limited to detection and evaluation of flaws' geometry and orientation. Flaw assessment and remaining lifetime evaluation usually are not considered goals of NDE and performed separately, if at all. In addition, traditional NDE methods normally cannot be applied during operation and inappropriate for continues monitoring.

Acoustic emission and structural health monitoring

Acoustic emission method fits uniquely to the concept of structural health monitoring due to multiple phenomenological advantages. Particularly, it can be used for:

- Diagnostics of overall structural integrity including detection, location, identification and assessment of flaws/faults during normal operation of a structure [4].
- Continuous or periodic monitoring.
- Identification of operation conditions that cause flaw/faults origination and development.

Below, we elaborate fundamentals of structural health monitoring by the Acoustic Emission method, which include terminology and definitions, fundamental assumptions and standard process of SHM.

TERMINOLOGY AND DEFINITIONS

Structural health monitoring is relatively new engineering field and this probably explains the lack of standard and commonly excepted terminology. Sometimes terminology proposed for used in SHM conflicting with terminology from other related engineering fields like NDE. For example, terms *defect* and *fault* defined in [2] contradict with the standard terms defined in [5] and [6] respectively. In order to ensure correct understanding of SHM terminology, the following list of terms and definitions was elaborated, where the terms flaw and fault were adopted form existing standards:

- *Structural health monitoring* is a process of diagnosis and monitoring condition of structures normally performed during their operation.
- *Diagnosis* is a process of detection, identification and assessment of flaws, properties or conditions that affect or may affect in future safety/performance of a structure.
- *Diagnostic AE* is an acoustic emission methodology capable to achieve goals of diagnosis.
- *Flaw* – an imperfection or discontinuity that may be detectable by nondestructive testing and is not necessarily rejectable [3].
- *Fault* - an abnormal condition or defect at the component, equipment, or sub-system level which may lead to a failure [4].
- *Monitoring* - a process of follow-up over changes in the condition of a structure.
- *Prediction* – a process of estimation of possible future flaw/fault deterioration based on results of diagnostics, monitoring and/or numerical modeling.

THE PROCESS OF STRUCTURAL HEALTH MONITORING

The process of structural health monitoring can be divided on the following typical stages:

- SHM procedure development.
- Sensing.
- Diagnosis.
- Monitoring.
- Prediction.

SHM Procedure development

The first stage of procedure development is dedicated to collection of all necessary information regarding the structure, its design and materials, operational conditions, statistics of failures and etc. In addition, laboratory and/or full scale tests are conducted on structures with known flaws/faults at known stage of development in order to develop ability to detect, identify and assess specific flaws/faults in goal applications. Based on the collected information, an optimal instrumentation, methods of data acquisition and data analysis, and loading policies, and etc. are elaborated.

Sensing

Sensing is a process of data measurement. It involves measurement of AE as well as parametric data like pressure, temperature, strain and other according to the developed SHM procedure. There are several important aspects to address during the sensing stage. First, it is important check that data collected during data acquisition process is valid and can be satisfactory used for the purposes defined in the developed SHM procedure. If this is not a case, additional measurements with different setup or loading, operational and/or environmental conditions may be required. Second, during the sensing process, an express evaluation of a structure is normally performed to identify or rule out possible major conditions that may threaten the structure immediately or in a short term.

Diagnosis

Diagnosis is one of the primary goals of SHM. It effectively distinguishes a typical AE NDE from AE SHM. The objectives of diagnosis process are not only to detect and locate flaws/faults as in typical NDE but also to identify and assess them. To achieve these objectives special development efforts are required including material research, numerical modeling, and small or full scale samples tests. Diagnosis performed based on collected data using methods of statistical pattern recognition. Numerical modeling, analysis of stress conditions, history of the inspected structure, local application of different NDE methods, material investigations and other may be required to crystallize the most correct diagnostic picture of the condition of an examined structure.

Monitoring

Monitoring performed to follow over condition of a structure over time. It is performed periodically or continuously depending on the particular application. For success of monitoring it is necessary to identify quantitative and/or qualitative AE characteristics that are changing with flaw/fault development. It is important to performed monitoring under normal operational and environmental conditions of a structure. If a change in stress/operational/environmental conditions occurs from any reason or a structure has been subjected to extreme influence and trauma, it may require change in a monitoring policy. Another important goal of monitoring is to identify conditions causing flaw/fault origination and development in the inspected structure. Examples of such conditions are fatigue, mechanical and thermal overstresses, and etc.

Prediction

The goals of prediction are to:

- Identify the useful a remaining lifetime of structure.
- Define an appropriate re-inspection/monitoring policy based on diagnostic and monitoring results.
- Provide information necessary for CBM decisions.

Prediction normally done based on diagnostic results, several monitoring and in conjunction with all information about the structure, its history and all know measurable or non-measurable risk factors.

FUNDAMENTAL ASSUMPTIONS OF AE STRUCTURAL HEALTH MONITORING

Structural health monitoring by the AE method as any other scientific concept is based on a set of fundamental assumptions that are normally self-evident and not necessary have to be scientifically proven. The role of assumptions is to define a systematic basis of a concept or theory. Based on the author experience in the fields of AE, fracture mechanics, material science, physics of solids, a set of fundamental assumptions of SHM by the AE method was elaborated. It cannot be claimed at this moment that this set of assumptions is complete and thus further modifications and corrections could be required. Fundamental assumptions were divided to four groups: *AE SHM procedure development*, *structure diagnosis and monitoring*, *data analysis*, *prediction and recommendations*.

Assumption group 1 – AE SHM procedure development

1. An optimal SHM procedure is one that ensures a maximum probability of flaw/fault detection while minimizing false negative findings.

2. Development of new AE SHM applications is essentially based on a learning process. This includes collection and analysis of information about:
   - Structural design, history of operation, repairs and results of previous inspections.
   - Material properties.
   - Applied loads, operational and environmental conditions.
   - Typical flaws/faults that can develop in the inspected structure.
   - AE characteristics of flaws/faults to be detected, assessed and monitored.
   - Wave propagation characteristics in the material and geometry of the inspected structure including propagation modes, attenuation, dispersion, scattering and other characteristics.
   - AE instrumentation appropriate for the particular application.
3. An optimal loading and/or environmental conditions for performing SHM are considered those under which flaws/faults naturally originate and develop in the inspected structure.

Assumption group 2 – Structure diagnosis and monitoring

4. A specific AE methodology can be considered diagnostic if essentially it allows:
   - Detection.
   - Location.
   - Identification.
   - Assessment (qualitatively or quantitatively) of flaws/faults in the inspected structure.
5. Acoustic emission is flaw/fault-stage-material specific, i.e. different flaws and faults at different stages of their development in different materials have different AE characteristics.
6. Flaw/fault identification (typification) and assessment in AE SHM is possible when unique AE characteristics or AE fingerprints characterizing different flaws/faults at different stages of their development in the specific material can be identified, effectively distinguished and compared with similar characteristics obtained in similar applications or in laboratory tests with known flaws/faults at known stage.
7. During flaw/fault assessment, a conservative approach should be taken in case of uncertain results. Flaws/faults that can be equally classified into two different groups by their severity level should be attributed to the group corresponding to more severe flaws/faults.
8. Comparison of loading, operational and/or environmental conditions with AE activity or AE characteristics reflecting kinetic characteristics of flaws/faults development can be used to identify conditions causing flaw/fault origination, development, acceleration or arrest.
9. Flaw/fault monitoring is possible when quantitative and/or qualitative AE characteristics changing with flaw/fault development are identified.
10. Reliable monitoring and prediction is possible when there are no changes in the stress and/or environmental conditions through the monitoring period.

Assumption group 3 – Data analysis

11. The process of data analysis in AE SHM necessary includes the following steps:
    - Analog and/or digital signal filtering.
    - Initial feature extraction.

- Feature selection and dimension reduction.
- Clustering (unsupervised classification) and/or discrimination (supervised classification).
- Interpretation.

12. Detection of AE activity suspected to flaw/fault development is a problem of statistical outlier detection.
13. Signal's features selected for data analysis should be a minimum set of statistically significant features necessary for the specific SHM application; filtered and normalized whenever is required so influence of background noise is minimized and data measured at different times and different locations is comparable.
14. Features used in data analysis should have established relationship with physical phenomena being measured during AE SHM in order insure correct diagnosis of the inspected structure.
15. AE activity distinguishable from AE background noise should be considered as flaw/fault related activity unless different is proven.
16. All detected AE activity distinguishable from AE background noise should be analyzed regardless if it is locatable or not.
17. Flaw/fault detection and location typically can be done using unsupervised methods while identification and assessment by supervised methods of statistical patter recognition.

Assumption group 4 – Prediction and recommendations

18. A non-developing flaw/fault cannot cause a failure unless there is a change in loading, operational and/or environmental conditions.
19. Optimal re-inspection interval is such that a risk of unexpected failure is reduced to the minimum acceptable probability, defined for the specific application.
20. Remaining life-time of the inspected structure can be evaluated when a law of flaw/fault development is established using monitoring data and/or numerical modeling.

CONCLUSIONS

In this work, the fundamental principles of the structural health monitoring by the Acoustic Emission method were elaborated and discussed. This includes terminology, standard process of AE SHM and fundamental assumptions. The proposed fundamentals can be used for systematic development of new AE SHM procedures and applications.

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