Acoustic Emission Signal Analysis of 15CDV6 Pressure Vessel Using Pattern Recognition Method

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Abstract

Acoustic Emission NDT is widely used for the structural integrity assessment of aerospace hardware viz. pressure vessels, tanks and structures. Due to many desirable aerospace properties, the 15CDV6 steel is used for the fabrication of tanks for storing the rocket fuels. To avoid the chemical reactions with the fuels the inner surface of the pressure vessels are coated with an insulating material like epoxy. The AE signals captured from the pressure vessel during the pressure test will be a combination of noise signals and genuine AE signals. In addition to the extraneous noises, the signals generated by the internal resin coating are also a major hindrance for the AE data analysis. Pattern recognition analysis of acoustic emission signals is a widely accepted practice for classifying the various source mechanisms involved by which we can effectively segregate the genuine signal from the noise. This paper gives the details on the analysis carried out on AE data obtained during the pressure testing of 15CDV6 steel alloy pressure vessels with internal resin coating using the pattern recognition feature of the AE analysis software Noesis developed by M/s Enviroacoustics. The characteristics of the noise signals generated from the internal resin coating are evaluated through the comparative studies carried out on coated and uncoated hardware through cluster analysis.

Key words: Acoustic emission (AE), 15CDV6 steel alloy, Pressure vessel, Structural integrity assessment, Signature analysis, Pattern recognition

Introduction

AE is a transient elastic wave generated by the rapid release of energy from a localized source within a material [1]. The classic sources of acoustic emission are deformation processes such as crack growth and plastic deformation. Other mechanisms that produce AE in metals include the movement and multiplication of dislocations, micro crack formation and growth, sudden crack advances and frictional processes during crack closure and opening. The amount of AE energy released depends primarily on the size and speed of the local deformation process. The formation and movement of a single dislocation does produce an AE stress wave, but it is not large enough to be detected as an isolated event. However, when millions of dislocations are combined and move at the same time, the individual stress waves overlap and superimpose to give a detectable AE [2]. Without stress, there is no emission. Therefore, AE monitoring is usually carried out during
controlled loading of a structure. A typical AE test setup is illustrated in Fig.1. AE sensors mounted on the structure detect the displacement of the surface and convert this tiny movement to an electrical signal by using a piezoelectric crystal as shown in Fig.2. After sensing and pre-amplification, the signal is transmitted to the main instrument, where it is amplified and filtered. Detection of the signal is accomplished with a comparator circuit, which generates a digital output pulse whenever the AE signals exceeds a fixed threshold voltage. The threshold level is usually set by the operator and is the key variable that determines the test sensitivity. AE equipment is highly sensitive to any kind of surface displacement within its operating frequency range, typically 20 to 1200 kHz. The equipment can detect not only crack growth and material deformation but also such processes as solidification, flow and phase transformation.

Currently AE is widely used as a passive NDT inspection technique which unlike ultrasonic testing need not interrogate the material by sending a signal through the structure, but detects stress waves from the damage itself when it propagates. A few sensors can monitor a relatively large volume and can detect different types of growing damages usually long before the sizes and severity attains the detectable range of other NDT techniques. Also AE testing can be performed when the structure is in service. This makes AE monitoring an ideal tool for structural integrity assessment. Though the AE signal parameters straight away gives an indication about the actual damage type, exact source location which is also possible can additionally aid in the assessment of structural integrity. The most widely used signal measurement parameters in AE signal analysis is given in Fig.3. They are counts, amplitude, duration, rise time, and energy [2]. Amplitude is the highest peak voltage attained by an AE waveform. This is very important parameter because it directly determines the detectability of the AE event. AE amplitudes are directly related to the magnitude of the source event, and they vary over a wide range from microvolts to volts. The amplitudes of AE are customarily expressed on a decibel scale, in which 1 µV at the transducer is defined as 0 dB, 10 µV as 20dB, 100 µV as 40dB and so on.

The analysis of the recorded AE of a pressure vessel with internal coating is more complex than a normal pressure vessel. The 15CDV6 pressure vessels are normally coated with the resin to avoid corrosion. The micro-cracking of the internal coating can produce AE activity which must be distinguished from the genuine AE signals from the material. Thus, advanced data treatment techniques are needed. Most of the times, empirical techniques are used for noise identification and filtering, while evaluation of genuine emissions from filtered data is performed by means of predefined criteria. There are no fixed
procedures for filtering process and in most cases the quality of AE data and noise filtering strongly depends on operator experience. Pattern recognition (PR) techniques are presented as an alternative and or complementary AE data processing technique, to the well-established knowledge based systems, aiming to help operators in noise identification and/or filtering as well as assisting the overall AE based evaluation. Pattern recognition was applied on the data of a pressure test using the commercially available “NOESIS” pattern recognition and neural networks software for AE applications [3]. NOESIS is a WINDOWS based software package, specially designed and optimized for the analysis of Acoustic Emission data. With this software Acoustic Emission users can do the data analysis and evaluation of common AE parameters using extended analysis capabilities through clustering and classification of multidimensional data. Pattern recognition of tensile specimen data through the cluster analysis is used to obtain the characteristics of AE signals and the same is implemented for the hardware.

Theory

The Pattern recognition (PR) technique is carried out through the clustering method. Clustering is the process of grouping the data into classes or clusters, so that objects within a cluster have high similarity in comparison to one another but are very dissimilar to objects in other clusters. Dissimilarities are assessed based on the attribute values describing the objects. Often, distance measures are used. Clustering has its roots in many areas, including data mining, statistics, biology, and machine learning. A cluster of data objects can be treated collectively as one group and so may be considered as a form of data compression. Although classification is an effective means for distinguishing groups or classes of objects, it requires the often costly collection and labeling of a large set of training patterns, which the classifier uses to model each group. Mainly there are two types of pattern recognition method based on the knowledge of dataset. They are unsupervised and supervised pattern recognition methods [4].

Unsupervised pattern recognition is the process by which objects are classified in general groups according to their similarity. This process does not require any previous knowledge or database. Objects are classified into groups by comparing their features based upon their similarity. In such cases, the number of classes/categories must be estimated as well as a meaningful grouping of the data for further use as a training set during the classifier design. Unsupervised measures of cluster validity is often divided into two classes: measures of cluster cohesion (compactness, tightness) which determines how closely related objects in cluster are, and measures of cluster separation (isolation) which determine how distinct or well separated a cluster is from other clusters. There are several clustering methods that can be used to find clusters of similar records. Available methods are Max-Min Distance, K-Means, Forgy, Cluster-Seeking, Isodata, and L.V.Q. Each clustering method introduces its own parameters [5]. All these methods are available in the Noesis software.

In this analysis K-means algorithm is used. This algorithm takes the input parameter, ‘k’ and partitions a set of ‘n’ objects into ‘k’ clusters so that the resulting intra cluster similarity is high but the inter cluster similarity is low. Cluster similarity is measured in regard to the mean value of the objects in a cluster, which can be viewed as the cluster’s centroid or center of gravity. The k-means algorithm proceeds as follows. First, it randomly selects k of the objects, each of which initially represents a cluster mean or center. For each of the remaining objects, an object is assigned to the cluster to which it is the most similar, based on the distance between the object and the cluster mean. It then computes the new mean for each cluster. This process iterates until the criterion function converges. Typically, the square-error criterion is used, defined as

$$E = \sum_{i=1}^{\text{n}} \sum_{p \in c_i} |p - mi|^2$$

(1)
Where \( E \) is the sum of the square error for all objects in the data set; \( p \) is the point in space representing a given object; and \( m_i \) is the mean of cluster \( C_i \) (both \( p \) and \( m_i \) are multidimensional). In other words, for each object in each cluster, the distance from the object to its cluster center is squared, and the distances are summed.

To extract the best suited class number for discriminating among the different AE mechanisms sources, different criteria is used. The evaluation of clustering results is based on the \( R \) criterion defined by Davies and Bouldin (1979) [10]. The criterion relies on the calculation of

\[
R_{ij} = D_i + \frac{D_j}{D_{ij}} \quad (i, j = 1...C)
\]

(2)

Where \( D_i \) and \( D_j \) denote the average within-class distance of clusters \( i \) and \( j \) respectively. \( D_{ij} \) denotes the distance between the two clusters \( i \) and \( j \) and \( C \) is the number of clusters.

Denoting by \( r_j \)

\[
r_j = \max \{ R_{ij} \}
\]

(3)

The criterion is defined as [10]

\[
R = \frac{1}{c} \sum_{i=1}^{c} r_i
\]

(4)

Lower the value of \( R \) provides better the clustering. The index \( R \) is then calculated from the maximum values of \( R_{ij} \) divided by the number of clusters [10].

**Test Article**

All pressure vessels are made of 15CDV6 heat treated steel and is used for storing the gas injectant as shown in Fig. 4. These tanks are coated internally with pure aluminium and sealed with epoxy 1061 resin for resistance against corrosive action of the propellant as shown in Fig. 4a. The tank is approximately 4m long and about half a meter diameter. It is made of three cylindrical segments with long seam TIG weld, joined together by means of circular seam TIG weld with torispherical end domes capped on both sides. The photograph of hardware and internal epoxy resin coating is shown in Figs. 4 and 4a respectively. These tanks are being fabricated at Brahmos Aerospace, Trivandrum. Tanks are proof pressure tested for acceptance before regular use. For the purpose of testing for acceptance both the end flanges of tanks are closed with closing flanges and proof pressure tested using hydraulic medium.
Instrumentation

Thirty two resonant frequency sensors (PAC R15, 150 kHz) were mounted on a hardware. Highly viscous ultrasonic couplant was used to acoustically couple the sensor to the specimen. The sensors were connected to PAC 2/4/6 preamplifiers supplied by PAC, USA using 1 metre long cable. 32 channel Mistras SAMOS board was used for real-time data acquisition and NOESIS pattern recognition software for the analysis and pattern recognition studies. Simulated AE signals produced by mechanical pencil-lead breaks (0.3 mm, 2H) near to every sensor was used for sensor calibration. It has been ensured that Hsu - Nielson pencil break given anywhere on the hardware could be picked up by at least three more AE sensors with very less attenuation, which indicate the adequacy of the coverage and any active defect occurring anywhere on the hardware would be indicated on-line.

Test Results

The performance of the vessel during the hydraulic proof pressure test is shown in Fig.5. During the first pressure cycle, the tank registered a large number of emissions from the beginning itself. The emissions were continuous and having Amplitude below 80dB. “Roll over” phenomena was not observed during the pressure holds. During maximum expected operating pressure (MEOP) and Proof pressure hold phases also the tank registered AE with amplitude below 80dB. During repeat proof pressure cycle, the vessel was silent upto MEOP and beyond that low amplitude emissions with low duration continuous signals were observed. The emissions were observed during the repeat pressure holds also.

Analysis through Pattern Recognition

AE emissions obtained during hydraulic proof pressure test as shown above is a combination of genuine AE signals from defects or some dislocation and noise signals. Due to presence of these unwanted signals the AE evaluation the hardware is very difficult. The unsupervisory pattern recognition through clustering method with NOESIS software is used for analysis. The first step of the UPR is to select a representative set of AE features based on which the data
would be segregated into classes, exhibiting similar characteristics. The degree of correlation of features in the dataset viewed in the form of a dendrogram is shown in Fig. 6, where the correlated features are joined together at the top. A correlation value less than 0.7 indicates presence of various sources [6]. Based on the above procedure, AE features selected for the discrimination of different failure mechanisms and the remaining noise sources are Channel, Rise time, Counts to Peak, Energy, Amplitude, ASL, Average Frequency, Reverberation Frequency, Partial Power 1, Partial Power 2, Frequency Centroid and Peak Frequency. As features are not measured in the same range or same units, the dataset is normalized before any unsupervised or supervised algorithm is applied.

To extract the best suited number of clusters among the AE data sets, a different criteria is used. The selection of number of clusters is based on the R criterion defined by Davies and Bouldin and τ criterion defined by Bow. According to above criterion the cluster members separate more distinctly for low values of R and high values of τ or the ratio R/τ should be minimum[7]. The number of clusters vs R/τ, R, τ formed from the data of a coated and uncoated vessel is shown in Fig.7. It is found that for the uncoated tank there are two clusters and for internally resin coated pressure vessel, there are three clusters or acoustic emission sources.

![Vessel without coating](image1)

![Vessel with coating](image2)

Fig.7. Number of Clusters V/S R/τ, R, τ of Coated and uncoated pressure vessel

The pattern analyses of the vessels with and without coating are analyzed using the k-means algorithm. The number of clusters formed by the coated and uncoated vessels is shown in Figs.8 & 9 respectively. The uncoated tank showed two clusters while the coated tank showed three clusters. The class-0 signals of the uncoated tank is having low amplitude, low duration and low energy and class-1 signals have high amplitude, high duration and high energy as shown in Figs.10 & 11. These are from two sources from hardware itself, the high energy with high amplitude class of signals are genuine AE signals showing micro level defect growth and low energy-low amplitude class of signals denote global dilation.

![Fig. 8. Amplitude data of Uncoated tank](image3)

![Fig. 9. Amplitude data of coated tank](image4)
The AE data of the coated hardware forms three distinct classes of acoustic emission. The class-0 & class-1 signals from the coated vessel are showing similar characteristics of signals observed from the uncoated tank. The duration, counts and energy of the class-0 & 1 signals of these two hardware are in similar range. The AE features of genuine AE band and global dilation class of two hardwares are compared are illustrated in Fig. 12 & 13 respectively. Therefore these two classes of AE signals are originating from similar sources from the hardware itself.

Therefore the other class of signals of coated hardware is from the coating. This class of signals is due to the activities in internally coated epoxy resin due to loading of the structure. From the above discussion three acoustic sources of from the coated 15CDV6 tanks are validated. Of these three classes of signals genuine AE signals can be exported and analyzed to assess the structural integrity of pressure tanks. If genuine AE signals satisfy the AE criteria for pressure tanks then integrity of tanks are good. In order to obtain a range for the AE features of different sources, few more case studies were carried out and values compared. By comparing the AE features, a fixed band is obtained for the AE features like Amplitude, energy, duration & counts. By analyzing all case studies it is found that there is one class which has most of AE hits. This class has almost 90% of total AE hits and it is from resin coating. This class is found to have similar band for AE features like Counts, Energy and Duration.

<table>
<thead>
<tr>
<th>Features</th>
<th>Mean Value</th>
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</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>60</td>
</tr>
<tr>
<td>Energy</td>
<td>11-18</td>
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<tr>
<td>Duration</td>
<td>400-600</td>
</tr>
<tr>
<td>Counts</td>
<td>5-6</td>
</tr>
</tbody>
</table>

Table.1. Mean value of AE features from resin coating
Conclusion

Pattern recognition based on clustering methods was applied on the AE data and was found to be beneficial in noise filtering of internally resin coated pressure tanks. AE features of five cases have been studied a range for AE features from epoxy resin coating compiled. Supervised method can effectively separate signals of different sources and can be effectively used to filter the noise signals due to the micro cracking of internally coated epoxy resin to aid in real time structural integrity assessment.

Acknowledgement

Authors acknowledge Director, VSSC, Deputy Director, Structural Engineering Entity and Group Director, SDEG, VSSC for permission to publish this paper. We also acknowledge the efforts of engineers and technical assistants of Acoustic Emission Testing Lab, VSSC for completing testing and analysis.

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