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Image fusion of ultrasonic and thermographic inspection of carbon/epoxy patches bonded to an aluminum plate

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ABSTRACT

Inspecting damaged structures repaired with composite patches is one of the most challenging issues of different industries, especially in aeronautical vehicles. Various inspection methods such as ultrasonic (UT) and thermographic methods are commonly applied to the patches and bondings. Although, both ultrasonic and thermographic inspections have their own capabilities, they are also associated with some limitations especially in the inspection of complicated structures such as multilayers. Different data fusion techniques can be used to overcome these limitations, by exploiting the advantages of each inspection technique to achieve the goal to have a more precise and reliable defects assessment. In this paper, different image fusion algorithms are used to fuse the UT C-scan and thermal images obtained from thermographic inspection of carbon/epoxy patches bonded to an aluminum plate. The inspected specimen contained several delaminations of various sizes and locations along with some disbond defects which were artificially embedded in five samples of composite patches. The resulting images of 28 fusion algorithms and the input images have been quantitatively compared using Average Differences (AD) to clarify the efficiency of the fusion algorithm. Comparing results revealed that contrast pyramid was selected as the best image fusion algorithms which can be used for NDE fusion of carbon/epoxy patches bonded to an aluminum plate.

1. Introduction

In recent years, reliable repairing of damaged structures of different industries is considered to be a crucial requirement. Damaged metal structures are usually repaired using composite patches. To have a reliable repairing, the patch integrity and the bonding between the patch and the damaged structure should be carefully assessed. The presence of some defects such as delaminations and disbonds would introduce severe challenges, since they prevent the shear stress to be transferred between layers and could result in catastrophic failure [1]. The geometry of such defects specifications including their dimension and position should be identified through a proper defect assessment procedure. Currently, different thermographic [2] and ultrasonic [3] techniques are widely employed to characterize defects in the repaired structures.

Active thermography is an infrared imaging technique of an object using an external heat, which is widely used for assessment of various materials such as composites [4–6]. So far, some limitations were observed in the application of thermography to characterize some types of defects [7–9]. For instance, non-uniform surface heating which is mostly unavoidable in active thermographic methods may cause some complexities, especially for defect quantification. Lateral heat diffusion is also an inevitable problem in the thermographic inspection. The amount of lateral heat diffusion is basically related to the thermal properties of the material [10,11]. Additionally, the spatial resolution of the infrared camera and the frequency of image acquisition may cause some difficulties in defect characterization [12]. In case of smaller and deeper defects inspection, the above-mentioned limitations become more serious. For the repaired structures, it is observed that the accuracy of detection is significantly decreased when the defects are distant from the surface [13] such as disbond [14,15]. To overcome these limitations, several post processing techniques such as pulse phase thermography (PPT), principle component analysis (PCA) and thermal signal reconstruction (TSR) have been developed [16]. The capabilities and deficiencies of these thermographic post processing methodologies have been investigated in some recent researches [17–20]. For instance, it is observed that PPT can considerably reduce the effects of non-uniform heating [21], while TSR is effective in decreasing the amount of blurring due to lateral diffusion [22]. However, it seems that, sometimes these processing approaches cannot fulfil all the expectations when they are considered as the sole technique [23,24]. Especially, in case of limitations associated with the experimental

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equipment, post processing techniques may not be the best tool. In these cases, other type of inspection such as ultrasonic test is found to be beneficial.

Ultrasonic pulse echo technique uses normal incidence waves for the inspection and hence is an appropriate choice for characterizing defects parallel to the surface such as delaminations and disbonds [25]. Several applications of the UT C-scan technique for the inspection of composites and repaired structures have been reported so far [26–30]. In most researches, various difficulties were mentioned in the defect characterization, especially in multi layered materials [31]. One of the major limitations in ultrasonic inspection of multilayered structures is due to the high level of background noise. These ultrasonic noise signals would lead to severe challenges especially in detection of small defects [32]. This problem may become more challenging when the surface of the specimen is rough. As an alternative, signal processing techniques can be used to amplify the detected echoes [33]. There exists a variety of such techniques that are applicable in analyzing ultrasound signals including, signal averaging, auto and cross correlation, matched filtration, frequency spectrum analysis, spectral correlation and autoregressive analysis. Most signal filtrations methods are based on the fact that the signals reflected from defects usually have different frequencies from the noise signal [34]. Advantages and limitations of the mentioned techniques have been comprehensively investigated [35,36]. However, same as thermographic processing techniques, UT signal processing cannot solely overcome all problems and in some cases, other type of inspection techniques is needed. For instance, ultrasonic measurements are inefficient in detection of very thin defects [37]. Although, the limitations listed for the UT inspections may be also valid for other types of inspection, however the severity of the mentioned limitations may defer for each type and different inspection methods show different performance when facing these limitations.

Different data fusion techniques can be used to improve the efficiency of inspection techniques by exploiting their advantages. So far, some researches were performed on investigating the application of image fusion in NDT [38]. For instance, the application of some statistical and probabilistic algorithms was studied for fusion of thermographic and eddy current images at the pixel level [39–42]. In the other research, some basic function algorithms and multi-resolution algorithms were used to combine the images of eddy current, magnetic flux leakage and thermographic testing at the pixel level [43]. Except for the pixel level data fusion, feature and symbol levels can also be used to combine NDI images. So far, all three levels of fusion were evaluated for the classification of ultrasonic and eddy current images [37]. Although, feature and symbol level approaches are proved to be efficient, however their actual data fusion performance is thoroughly dependent on the type of preprocessing and the data extraction technique [44]. Hence, the feature and symbol levels are not the first choice to be opted. Based on the current knowledge, NDT image fusion at pixel level is appropriate to obtain details of the defect location and size. However, more research is necessary to determine the adequate fusion method, since the performance of the fusion algorithm is highly case sensitive [39].

According to the literature, NDT image fusion at pixel level can improve defect characterization. Regarding the wide number of fusion algorithms which can be applied to combine thermographic and UT C-scan images, it seems necessary to clarify the ability of these algorithms to improve inspection results of repaired structures. Therefore, in this research, the ability of some basic algorithms, pyramid algorithms and wavelet algorithms, which are commonly used for NDI image fusion, have been quantitatively investigated. For this purpose, five patches containing delaminations and disbonds with different sizes and locations were inspected via step heating thermography and UT C-scan. Then, the obtained thermal images and UT C-scan images were fused at pixel level with the mentioned image fusion algorithms. According to the comparison of image quality metric (average difference) of the fused images, the most appropriate algorithms for the fusion of the resulting images were determined. The fundamental theory of the used image fusion algorithms is briefly described in the next section.

2. Image fusion algorithms

Image fusion [45] is a process of combining images of a same scene, obtained by different sensors to improve the contents of images in order to make detection of targets easier. In this research, besides the basic fusion algorithms, some multi-resolution image fusion techniques such as pyramid and wavelet transform have been used to combine the NDI images at the pixel level. Pixel level image fusion is performed on a pixel-by-pixel basis. Despite the simplicity of basic image fusion algorithms like averaging, the features contrast presented in either of the images is greatly reduced. Multi-resolution fusion can successfully resolve this problem using a feature-based selection rule for performing the fusion operation. The fusion should be performed in the transform domain, firstly to access the information of the sharp construct changes and secondly to be capable of providing spatial and frequency-domain localization [40]. As a result, a comprehensive image description would be obtained by studying an image structure over a range of scales. The substructures become accessible and quite clear only by taking a closer look into the image. However, the clarity of the outlines is lost. On the other hand, the details of the picture are faded at low magnifications. The method used to extract (obtaining coefficients) and later combine (selecting coefficients) the image features are of a great importance in multi-resolution approaches. Each transform (various pyramid or wavelet methods) is efficient in extracting a specific feature of the image [38]. Since, the larger is the absolute transform value the sharper would be the brightness changes, the fusion rule can be defined as choosing the larger absolute value of the two coefficients at the same point to bold the image features such as edges, lines, and region boundaries.

Comparing pyramid and wavelet based fusion approaches, pyramid transform has a better performance in representing and manipulating low-level visual information [46], while wavelet transform is more powerful in producing more naturally fused images when the input images are very different [47].

Prior to implementation of fusion algorithm, the input images should be pre-processed [48]. The pre-processing consists in three steps of image registration, image resampling and histogram matching. Image registration is the process that transforms several images into the same coordinate system. After image registration, the images should be resampled. Resampling changes the size of the image. Finally, the pixel values of the input images should be changed by a nonlinear transform such that their histograms match together.

2.1. Basic fusion algorithm

The presently used basic image fusion techniques are: Average, maximum, minimum and principal component analysis (PCA) algorithm. The resulting image of the average method is obtained by averaging the corresponding pixel values of the input images. Similarly, the result of maximum/minimum method is the image with maximum/minimum pixel values between input images. In the PCA algorithm, a matrix was generated by importing every input image pixel values as a column vector. The normalized Eigen vector values of the matrix covariance act as the weight values of the input images. The fused image matrix was obtained by summation of the two scaled matrices.

2.2. Pyramidal fusion algorithm

The basic idea in the pyramid based fusion algorithms [49] is to build the pyramid transform of the fused image from the pyramid transforms of the source images. The fused image is obtained by applying the inverse pyramid transform. Typically, every pyramid

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