STRUCTURAL DAMAGE LOCALIZATION IN A STIFFENED-PLATE USING LASER HOLOGRAPHY, IMAGE PROCESSING TECHNIQUES AND A HIGH-ORDER CURVE FITTING METHOD

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I DEDICATE THIS THESIS TO

MY MOTHER

RAJYALAKSHMI

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ABSTRACT

An aluminum stiffened-plate panel resembling aircraft-fuselage was built and modal-tested in the laboratory using holographic methods. The purpose of the test was to extract out-of-plane modal data before and after infliction of damage, which were used later to evaluate a global Non Destructive Evaluation (NDE) damage localization technique. The NDE damage localization technique is based on modal strain energy differences between the undamaged and damaged states. Digital image processing techniques were used to filter the data collected. To compute the modal strain energies and to enhance the resolution of damage detection, the modal bending and twisting curvatures were obtained through the adoption of an iterative curve-fit procedure using estimated curvatures obtained from finite differences and curve fit of the experimental mode shapes. Strain energy differences between matching modes of the undamaged and damaged structure help locate the inflicted damage by indicating apparent increases in modal strain energy distributions. The damage indications provided by several modes were probabilistically combined to create damage maps that attempt to predict the correct location of the inflicted damage. The test article was excited by a electromagnetic shaker exerting uncorrelated continuous random forces from 0 to 3500 Hz. Forty mode shapes were found within this range and mode shapes were extracted. This thesis presents the results, conclusions and recommendations of the global NDE technique used. Emphasizing the improved accuracy that resulted from combining probabilistic and fringe information, digital image processing techniques, and using high-order, curve-fit algorithms to estimate curvatures.

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INTRODUCTION

1.0 General

Nowadays in every engineering field, structures are getting more and more complex and are often required to remain in service longer. An example would be aircraft of commercial airlines and some future space vehicles that do not have expendable parts. Its importance is because a considerable percentage of the fleet already endured the service life for which they were originally designed. The high cost of replacing aged aircraft structures had led to extend their serviceability long beyond the design service life while improving preventive maintenance and NDE inspections. Old aircraft must be subjected to frequent routine visual inspections and periodic maintenance where the aircraft are disassembled and inspected. However, visual inspections could result in reduced reliability, since human error is easily produced in a structure of this magnitude and complexity. Robust NDE methods having less susceptibility to human and environmental factors are essential to offset the increasing inspection burden. A less obvious but not less important benefit of improved inspection methods is that the development of reliable and cost effective NDE methods can reduce possible collateral damage associated with disassembly, re-assembly and modification of airplane structures made during visual inspection.

detection of cracks, disbonds, corrosion and other forms of damage. These techniques have proven over the years to be capable of detecting and quantifying small defects. All the techniques above, however, have the major limitation that their effectiveness depend on correctly placing the corresponding sensors on or in the close vicinity of the defects. For this reason, these methods are typically applied to known areas or locations of potential damage. Because of this requirement, traditional NDE methods, such as those mentioned, are classified as "local". Another problem associated with the techniques above, with the exception of X-ray radiography, is that they have a depth limitation to detect defects. For example, Eddy currents are good for surface cracks and can not inspect deeper that the surface skin. Likewise, ultrasonics has problems of detecting defects in the inner structural members when inspecting from the outer skins. For this reason, in order to inspect inner structural members, disassembly is usually required.

One approach undertaken to circumvent the problem of the local NDE techniques has been to use scanning systems mounted on the aircraft skin. A scanning system provides local NDE methods with the capability of inspecting larger areas. Some of the systems consist of robotic crawlers that adhere to the aircraft through suction devices. As a result, the robotic crawlers have the capability of positioning local NDE instruments and sensors over certain surfaces of the aircraft.

The international engineering community has great interest in carrying out a new real-time health monitoring system, which can guarantee higher safety standards and reduce management costs. Therefore, holographic interferometry has been successfully employed to characterize the materials and behavior of diverse types of structures under

stress. Specialized variations of this technology have also been applied to define dynamic and vibration-related structural behavior. Such applications of holographic technique offer some of the most effective methods of modal and dynamic analysis available. Real-time dynamic testing of the modal and mechanical behavior of aerodynamic control structures for advanced missile systems has always required advanced instrumentation of data collection in either actual flight test or wind-tunnel simulations. Advanced optical holography techniques are alternate methods, which define actual behavioral data on the ground in a noninvasive environment. These methods offer significant insight in both the development and subsequent operational test and modeling of advanced composite control structures and their integration with total vehicle system dynamics. Structures and materials can be analyzed with very low amplitude excitation and the resultant data can be used to adjust the accuracy of mathematically-derived structural models.

Holographic interferometry offers a powerful tool to aid in the primary engineering and development of advanced graphite-epoxy fiber composite materials for use in advanced aerodynamic platforms. Aircraft, missile, and smart weapon control structure applications must consider environments where extremes in vibration and mechanical stresses can affect both operation and structural stability. These are ideal requisites for analysis using advanced holographic methods in the initial design and subsequent test of such advanced components. Holographic techniques are non-destructive, real-time and definitive in allowing the identification of vibrational modes, displacements, and motion geometries. Such effects are directly indicative of various

types of induced mechanical, thermal, and acoustic structural stress related to hidden structural anomalies and defects. Deriving such information can be crucial to the determination of mechanical configurations and designs, as well as critical operational parameters of structures composed of advanced engineering materials.

1.1 Background

The interest in the ability to monitor a structure and detect damage at the earliest possible stage is pervasive throughout the civil, mechanical, and aerospace communities. The need for global damage detection methods that can be applied to complex structures has led to the development of damage identification methods that examine changes in the vibration characteristics of the structure. Some of the earliest work was performed by Cole [1] by applying damage detection to aircraft structures. Cole investigated the possibility of detecting structural damage by exciting the structures with random excitation through a shaker and measuring the response with conventional accelerometers. Cole developed a technique called the Random Decrement Method for the extraction of the vibrational characteristics. He primarily relied on changes in the resonant frequencies to detect that some damage had occurred in the structure but did not address the issue of localizing the damage.

Adams, *et al.* [2], was the first to address the issue of locating defects. They used the ratio of the resonant frequency changes due to damage to locate crack damage in beams. Subsequently, Stubbs and Osegueda [3] introduced a method to locate and quantify damage that is based on sensitivity expressions. Such expressions related the

changes in the resonant frequencies due to changes in the structural stiffness, mass and damping. These techniques were limited by the fact that only information of the resonant frequencies was used to assess damage. The sensitivity techniques required the measurements of several resonant frequencies to be effective.

More effective vibrational methods that were based on measured changes in the mode shapes were later introduced. Stubbs, Kim and Topole [4] introduced the damage index method. The method relies on estimates of modal strain energy content of the undamaged and damaged structure obtained from measured mode shapes. A damage index is computed by taking the ratios of the modal strain energy of the damaged structure to the modal strain energy of the undamaged structure. This method is summarized in Chapter II. A similar technique was also proposed by Osegueda, *et al.* [5] that relied in the modal strain energy differences between the undamaged and damaged structure as a means to localize damage. Both the damage index method and the modal strain energy difference method provide similar detection results, as discussed in Chapter II. The strain-energy based methods have proven effective in detecting and quantifying damage in a wide variety of structure types, such as truss-like structures [6], aircraft parts [7], Beams [8] and offshore structures [4].

Despite the fact that the strain-energy-based vibrational methods have proven very effective in detecting damage, their effectiveness in detecting damage in continuous type of structures, such as beams and plates, has been limited. The limitation comes as a result that the methods require estimates of the strain energy distribution in each mode. These estimates can be determined through expressions that are functions of the curvature

of the modal deformations. In the case of beam-like structure, only one curvature is required. However, in the case of plate-like structures, the strain energy estimates require the bending curvature in two perpendicular directions and the twisting curvatures. Thus, these curvatures are obtained by estimating the second spatial derivatives of the modal shape deformations. However, since the mode shapes are only measured in a finite number of discrete points, the numerical estimation of the curvatures is required. Current algorithms for doing this typically utilize cubic- or quintic- splines and tend to yield significant errors in the estimates of the curvatures. If cubic splines are used, then the curvatures are incorrectly estimated as piece-wise linear functions. On the other hand, if quintic splines are used, the techniques do not provide the capability of specifying known displacement, slope or curvature boundary conditions. As a consequence, the results lead to significant errors at support locations. In addition, numerical methods such as Shannon's sampling theorem have also been proposed to solve this problem. However, this theorem only works well for simple-supported boundary conditions and cannot be applied when the structure has other conditions. This thesis proposes a new method for estimating modal curvature functions for beam and plate-like structures from an array of measured points that circumvent the problems above exposed.

1.2 Objectives

The objectives of this thesis are: (1) to investigate the Modal Strain Energy Difference Method (MSEDM) for detecting damage in a stiffened plate resembling aircraft construction, and (2) to improve the quality of the data by filtering the noise using

digital image processing techniques and incorporating a numerical curve-fit procedure to estimate modal curvatures. This thesis includes:

- an overview of vibrational damage detection methods;
- holographic methods;
- filtering techniques;
- description of mode-curve fit algorithm;
- experimental setup and damage scenarios;
- a description of the procedure to localize the inflicted damage;
- the damage detection results.

In addition, the work here also explores some of the limitations of locating damage using the proposed approach. The test object is a aluminum stiffened-plate. The plate is stiffened with 2 by 2 inch aluminum plate 1/16th inches in thickness. The experimental modal analysis was performed from a frequency range of 0-3500 Hz. Where a non-contact electromagnetic shaker provided the excitation forces. Data were obtained with a holography setup using a television monitor and a software (PCHOLO) program.

CHAPTER II

OVERVIEW OF VIBRATIONAL DAMAGE DETECTION METHODS

2.0 Introduction

In this chapter the strain energy differences method is explained and derived. The areas where these strain energy differences can be applied are then discussed. Finally, these concepts are extended into the formulation of the Stubbs's Damage Index [3].

2.1 Modal Strain Energy Difference Method

The basic idea of the modal strain energy difference method (MSED) is that the distribution of the relative strain energy stored in the mode of a structure will change around the location of the damage. If a structural member experiences a reduction in its stiffness (damage), then that element will have larger deformations as a result of the same amount of modal strain energy. Since the damage location is not known ahead of time, the damage is reflected by an apparent increase in the modal strain energy. Since, the stiffness reduction causes a deviation from the original strain energy distribution of the undamaged structure, then, the difference in the strain energy distributions of the undamaged and damaged structures can be used to detect and locate damage.

The Modal Strain Energy Method considers the same structure in the undamaged and damaged states. Damage in an element reflecting a stiffness reduction, causes changes in the modal shapes in the vicinity of, or at the location of the damage. In general, if the

structure is defined via finite elements, then, the total Modal Strain Energy of a k[th] mode for the undamaged and damaged structure are, respectively, discussed in Refs. [14] and given by the expressions:

$$U_k = \frac{1}{2}\sum_{i=1}^{N} \{\phi_{ik}\}^T [k_i] \{\phi_{ik}\}, \tag{1}$$

and

$$\bar{U}_k = \frac{1}{2}\sum_{i=1}^{N} \{\bar{\phi}_{ik}\}^T [\bar{k}_i] \{\bar{\phi}_{ik}\}. \tag{2}$$

Here, $[k_i]$ is the undamaged stiffness matrix of the i^{th} element, and $\{\phi_{ik}\}$ are collections matrices conformal with $[k_i]$ which contain the k^{th} undamaged mode shape components associated with the degrees of freedom of the element i. The bar notation is used to denote the appropriate parameters for the case of the damaged structure.

The change in the element contribution to the modal strain energy is given by

$$\Delta U_{ik} = \frac{1}{2}\{\bar{\phi}_{ik}\}^T [\bar{k}_i] \{\bar{\phi}_{ik}\} - \frac{1}{2}\{\phi_{ik}\}^T [k_i] \{\phi_{ik}\}, \tag{3}$$

where ΔU_{ik} is the strain energy difference of the i^{th} element in the k^{th} mode. The difference is obtained by subtracting the strain energies of the undamaged structure to that of the damaged structure. Negative differences are indication of the presence of damage. Assuming that the change in the element strain energy is zero and that

$$[\bar{k}_i] = [k_i] + \alpha_i [k_i], \tag{4}$$