Module 5: Experimental Modal Analysis for SHM
Lecture 35: Experimental modal analysis for damage detection in composite plates using laser doppler vibrometer

The Lecture Contains:

- Introduction to Laser Doppler Vibrometer (LDV)
- Review of literature related to Experimental Modal analysis (EMA)
Introduction to Laser Doppler Vibrometer

The composites are gaining importance as structural material in many critical and advanced applications. Their extensive use is still lagging due to the lack of efficient and reliable damage detection methods which could ensure sustained reliability and well being of the structure over its planned service life. There is a growing need for continuous monitoring of structures made of advanced composites to avert catastrophic failures and to provide confidence for the rapid introduction of these high performance and heterogeneous materials into service. The dynamic responses of structure offer unique information on defects inside the structure. Changes in the physical properties of the structures due to damage alter the dynamic responses such as natural frequencies, modal damping and mode shapes. These changes in physical parameters can be extracted to estimate damages in the structure by experimental modal analysis. In this module, dynamic responses of glass-epoxy composite laminates with different ply orientations are studied. Laser Doppler Vibrometer has been used to capture the vibration characteristics of dynamically excited healthy and delaminated composite laminates. Delaminations have been introduced in the laminates at different locations to simulate damage situations. The effect of delamination on modal characteristics (natural frequencies, modal damping and mode shapes) of the composite laminates has been analyzed for the purpose of damage detection, its location and severity. The first four natural frequencies recorded during experimental modal analysis for healthy laminates are compared with a standard FE software ABAQUS. Perceptible changes in natural frequencies, damping and mode shapes are observed in all delaminated specimen during experimental modal analysis. Laminates with longitudinal and transverse direction fiber arrangements are more prone to these changes while cross ply laminates are only marginally affected. A change in modal damping in a locality is a good indicator of potential delaminating site.
Damage detection using LDV

Composite structures are prone to unpredicted failures due to greater complexity of design, high operational loads and longer service life. Fiber-reinforced composites mainly exhibit four types of damages namely- fiber breakage, matrix cracking, delamination and debonding. Generally, failure occurs due to combination of two or more of these damage types. In this chapter, detection of delamination in composite plates using dynamic analysis is studied. Delamination is a debonding or separation between individual plies in composite laminates. High strength of fibrous composites in the direction of reinforcement is accompanied by a low resistance against interlaminar shear and transverse tension. This may cause delamination leading to initiation and propagation of cracks. Delamination may arise at the fabrication stage itself (e.g., incomplete wetting, air entrapment), during transportation (mishandling, low intensity impacts) and/or during its use (e.g., low velocity impact, bird strikes on aircraft panels). Delaminations present nearer to the surface are greatly affected by local buckling. When situated deep inside the bulk of the material, they act similar to a crack in the medium. The presence of delamination significantly reduces the stiffness and strength of the structure and affects critical design parameters. If modified dynamic response of the structure due to damages is closer to the operating frequency range during the use, it may cause serious damage to the structure due to uncontrolled vibration response.
### NDT versus LDV

Non destructive testing procedures such as X-ray imaging, ultrasonic scans, infrared thermograph and eddy current methods are commonly used for damage detection. These techniques have their own limitations. They are time consuming and difficult to implement in field conditions. Most of the above techniques require the vicinity of damage known a priori and readily accessible. In many complex structures even if the detection of defect is accurate, its location and characterization may be difficult and require expert opinion.

The use of advanced and precise optical measurement systems such as Laser Doppler Vibrometer is gaining in extracting vibration signatures for the purpose of damage detection as mass loading of the specimen due to sensors and actuators in embedded systems may be avoided and repeatability and reproducibility of measurements may be ensured. A Polytec Scanning Vibrometer (PSV-3D) [Polytech GmbH, Germany] has been used in this study for experimental modal analysis.
Review of literature related to experimental modal analysis (EMA)

Damages in a structure may alter its modal parameters (i.e. modal frequencies, mode shapes and modal damping) and structural parameters (i.e. mass and stiffness). These dynamic characteristics are used to study the condition of the structure as they reflect the state of the whole structure.

Some of the researches related to damage detection using dynamics based approach are summarized as follows:

- Cawley and Adams [1979] have noted that ratio of frequency changes in two modes is a function of damage location. Location of damage zone is identified where the theoretically determined ratios of frequencies and experimental values are equal.
- Vandiver and Mitome [1979] have used the same principle of changes in natural frequencies to detect damage in offshore platforms.
- Swamidas et al [2003] have explained experimental procedure for crack detection in beams using changes in frequencies and corresponding amplitudes in frequency response functions.
- Pandey et al [1991] have proposed the use of curvature mode shapes for damage detection in concrete beam sections. Curvature mode shapes are related to the flexural stiffness of the beam cross sections. Curvature of the mode shape increases due to reduction of stiffness at the damage region. Absolute change in the curvature for damaged and undamaged beam can be used for measuring the degree of damage. Curvature changes increase with the increase in the damage size.
- Valdes and Scoutis [1999] have applied resonant ultrasound spectroscopy for obtaining modal frequencies of delaminated specimen. Resonant ultrasound spectroscopy is based on the study of spectra obtained by forced mechanical resonance of test objects using swept sine excitation. It is used to determine the elastic constants of a test specimen from its resonance spectrum. In this method, the test object is placed on actuator-sensor couple. The actuator is excited with a sine wave producing mechanical vibrations within the specimen at the same frequency as the actuator and the sensor detects the amplitude of the induced vibration. The complete response spectrum of the object is obtained by this method. It has been reported that the effect of delamination is pronounced in the high frequency region. For low frequency region, the positioning of actuating and sensing devices is critical for excitation of specific modes.
- According to Tracy and Pardoen [1989], delamination has no more than twenty percent effect on the first four natural frequencies of the delaminated beams compared to the undamaged composite beams.
- Hanagud and Luo [1993] have proposed a method of delamination coefficients to study the existence of delamination in composite plates without visualizing the mode shapes. Higher values of these coefficients are used as quantitative measure of delamination in the composite plates.
- Yam et al [2004] have proposed a mode dependent energy dissipation method for locating the delamination in cantilever composite plates. For a given mode shape, there is an associated strain field related to the displacements at different sections of the object. The modal strain energy stored in different sections gives unique information regarding
energy distribution for a given mode shape. Presence of a defect induces more damping leading to more energy
dissipation in that region. Intact and delaminated composite plate specimens are analyzed using modal stain energy
distribution for locating the delamination.

- Kessler *et al* [2002] in their pioneer work have used Laser Doppler Vibrometer for observing changes in natural
frequencies and mode shapes for various types of damages such as impact, cut-out and delamination in graphite-epoxy
composite beams. Frequency response based methods are found to be more reliable than mode dependent damage
detection methods as coalescence of higher frequency modes makes it difficult to analyze the true nature of the
damages.

- In-depth information regarding mechanics of delamination and its effects and vibration based detection methods are
found in the reviews of Bolotin [1996] and Zou *et al* [2000].