Structural Damage Detection Using Laser Vibrometers

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Abstract. Laser vibrometers offer reliable, fast and non-contact measurements attractive for damage detection in aerospace structures. The paper demonstrates a few possible approaches with non-contact measurements. This includes methods based on modal analysis, Lamb waves and nonlinear vibro-acoustic modulations. Laser velocity measurements are also used for strain estimation.

1. Introduction

Aircraft designers, manufacturers and operators face many challenges in the near future. New large capacity civil airframes that make greater use of composite materials are being developed and will be more widely used. At the same time, new military structures exhibit improved performance associated with greater structural complexity. All these developments are a major challenge to inspection and maintenance methods of aircraft structures. Existing ageing aircraft structures already require a significant maintenance effort. The application of new materials and wider use of damage-tolerant concepts in new aircraft will also require reliable damage monitoring for quality control, with regular periodic inspections to maintain the safe life.

Over recent years, a number of new technologies have evolved with the potential for damage detection in aerospace structures. Methods based on non-contact optical/laser measuring techniques are particularly attractive for aerospace applications. Low-frequency scanning, multi-point laser vibrometers have been used for many years to perform vibration and modal analysis. More recent applications include high-frequency ultrasound measurements such as Lamb waves sensing [1-2]. Three-dimensional (3-D) scanning laser vibrometers provide combined out-of-plane and in-plane measurements. A number of 3-D configurations have been reported, implemented commercially and used for elastic wave propagation measurements. Scanning laser vibrometry for damage detection include applications based on vibration/modal analysis [1-2], Lamb waves [3-9] and strain measurements [11-12].

The paper demonstrates a number of possible applications of laser vibrometry for structural damage detection. Multipoint non-contact vibrometers are not only attractive to measure directly vibration or ultrasound but also to estimate strain, to monitor for possible structural damage or to perform optimal sensor location investigations, as illustrated in the
paper. The classical application of vibration measurement for modal analysis is illustrated. Velocity measurements are used to estimate strain level associated with vibration and ultrasonic excitations. Ultrasound measurements are illustrated using two damage detection examples, i.e. Lamb wave inspection and nonlinear acoustics. The final application illustrates how to use scanning laser vibrometry for optimal sensor location.

2. Laser Vibrometers

Laser vibrometers measure surface motion utilising the Doppler shift phenomenon in order to obtain the velocity of surface vibration. Two different laser vibrometers were used in the current investigations. The first one was the 1-D Polytec PSV-300 scanning system with the maximum measurable frequency bandwidth of 1 MHz whereas the second one was the 3-D PSV-I-400 LR (OFV-505) scanning system offering 2 MHz bandwidth capability. The major difference between the two systems is that the 1-D laser is equipped with one optical scanning head and measures only out-of-plane motion. In contrast, the 3-D system is equipped with three independent optical scanning heads allowing for in-plane and out-of-plane motion measurements. Figure 1 gives an example of the 3-D laser vibrometer setup.

![3-D laser vibrometer experimental set-up.](image)

3. Low-Frequency Vibration Measurements

3.1 Modal Analysis

Experimental modal analysis was performed for the rectangular 150×400×2 mm uncracked and cracked aluminium plate. The plate was freely suspended and excited using a PI Ceramics PL-055.31 stack actuator. The excitation signal was a chirp starting at 1 Hz and crossing 2000 Hz in 2 s. This signal was generated using a two-channel TTI-TGA 1242, 40 MHz arbitrary waveform generator and amplified to the maximum 100 V peak-to-peak level with a PI E-505 LVPZT piezo-amplifier. The entire plate was then scanned using the 3-D laser vibrometer. Modal analysis was performed to obtain the Frequency Response Function (FRF) and vibration modes, as illustrated in Figure 3.
Various vibration-based characteristics can be used to detect structural damage. The test performed focused on the natural frequency shift. Only the first vibration mode resulted in the 8% natural frequency shift when the plate with the 69 mm crack was tested. The frequency shift for other vibration modes and smaller crack lengths was less than 3%, as expected. Global damage detection based on modal parameters, obtained using 3-D laser vibrometry, is easy and fast to perform but works only well for large damage severities, as expected.

3.2 Crack Divergence Analysis

The cracked aluminium plate was excited harmonically using a Noliac piezoceramic ring stack actuator. Different amplitude levels and the frequencies of the 1\textsuperscript{st}, 3\textsuperscript{rd} and 6\textsuperscript{th} vibration modes were used. These three excitations led to three different crack modes, i.e. opening (crack mode-I), tearing (crack mode-III) and sliding (crack mode-II), respectively. The 3-D laser vibrometer was used to measure relevant velocity in the vicinity of the crack at two points, i.e. above and below the crack line. This allowed for the indirect crack divergence analysis.

![Figure 2. FRF amplitude and example of one vibration mode extracted.](image)

![Figure 3. Crack edge divergence analysis: (a) x direction (b) z direction.](image)
3.3 Strain Estimation

It is well known that laser vibrometers can be used for static and dynamic strain analysis when deflection measurements are performed and additional calculations (e.g. Polytec StrainProcessor software) used. Application examples in this area include strain analysis for damage detection [11-12]. Another approach for estimating strain levels uses the relation of dynamic bending strain with measured velocity [13]

\[ \varepsilon(x, y, f) = \frac{K_{\text{shape}}}{c_L} v(x, y, f) \]  

(1)

where \(v(x,y,f)\) is transverse velocity at position \((x,y)\) for vibration frequency \(f\), \(K_{\text{shape}} = \sqrt{3}\) is a non-dimensional shape factor, \(c_L = \sqrt{E/\rho(1 - \mu^2)}\) is a longitudinal wave velocity, \(\rho\) is density and \(\mu\) Poisson’s ratio. Equation (1) can be used to obtain the upper-bound estimation of strain level in the far-field, i.e. the area sufficiently away from main vibration energy source where pressure fluctuations and particle velocities are in phase. The method is particularly useful when small strain levels involved are difficult to measure with electric or piezoelectric strain gauges. This approach was used to estimate strain levels for the piezo-excitation used in Section 3.1. The results - for different vibration mode excitations and out-of-plane measurements using a 3-D laser vibrometer - are given in Figure 4. The analysis shows that the 1st vibration mode excitation produces the largest strain level for the excitation used. The 3rd and 6th vibration modes result in strain levels that are well below \(10^{-6}\).

Figure 4. Strain level estimation based on velocity measurements.
4. High-Frequency Ultrasound Measurements

4.1 Nonlinear Vibro-Acoustic Modulation Technique

Non-contact measurements are useful when non-linear acoustics is applied for structural damage detection. The method relies on various nonlinear phenomena associated with ultrasonic wave propagation and wave interaction with contact-type damages. Vibro-acoustic modulation technique [14-17] was used to demonstrate this approach. The rectangular aluminium cracked plate was modally excited using a Robotron electromagnetic shaker. Single-point harmonic excitation with the frequency of the 1st vibration mode was used. Once the plate was excited modally, ultrasonic 60 kHz sine wave was introduced to the plate using one of the low-profile, surface-bonded PI Ceramic PIC 155 piezoceramic transducer. Acoustical responses were measured using the 1-D laser vibrometer. Figure 5 gives an example of the results. A series of modulation sidebands – corresponding to the frequency of the 1st vibration mode excitation – around the fundamental 60 kHz ultrasonic component can be clearly observed in the response power spectrum. The amplitude of the acoustical response (A0) and the first two modulations sidebands (A1 and A2) can be used to calculate the modulation index \( R = (A1 + A2) / A0 \). This index can be used to detect a fatigue crack in the plate.

![Figure 5. Power spectrum displaying vibro-acoustic modulations in a cracked aluminium plate.](image)

4.2 Lamb Wave Based Inspection

Lamb waves are widely used for structural damage detection in plate-like structures [18]. Although, the method is very attractive for health monitoring, it is always associated with major problems in any practical applications due to the complexity of wave propagation and signal processing used for damage detection. This damage detection approach often requires a significant number of transducers for monitoring of large structures. The need for “baseline” measurements representing “undamaged condition” of any monitored structures is another important limitation. Recent years have demonstrated that laser vibrometers can be used effectively for Lamb wave sensing and damage detection [3-9]. A simple example demonstrating this approach is demonstrated in this section. A rectangular 530×225×7 mm composite plate, fabricated from the T300/914 carbon/epoxy unidirectional prepreg, was monitored for hidden impact damage. A low-profile PI Ceramic PIC 155 piezoceramic transducer was surface bonded to the plate. This transducer was used to introduce a 100
kHz ultrasonic signal. A series of burst signals comprising five cycles of sine wave, with the Hanning window envelope, was introduced to the plate to propagate Lamb waves. Lamb wave responses were captured using a 3-D laser vibrometer. The plate was scanned to reveal clear delamination in Figure 6. Lamb wave amplitude analysis across two measurement lines can be used to estimate the area of hidden damage. Classical X-ray analysis performed for the plate has confirmed the location and size of the estimated damage.

Figure 6. Lamb wave scan for the out-of-plane z direction propagation – contour plot and amplitude profiles.

5. Optimal Sensor Location

Laser vibrometry can offer relatively fast and non-contact low- and high-frequency measurements for large number of structural locations. This is particularly useful when optimal sensor location is analysed in applications related to modal analysis, nonlinear acoustics or guided ultrasonic waves. This section demonstrates the nonlinear acoustic application. Other high-frequency applications related to Lamb waves can be found in [7]. Section 4.1 has demonstrated that modulation sidebands in vibro-acoustic laser responses can be used for fatigue crack detection. The problem is to find the best measurement position to obtain the largest value of the modulation index R indicating damage. The non-linear vibro-acoustic modulation test, described in Section 4.1, was used. Figure 7a gives positions of low-frequency vibration and high-frequency ultrasonic excitation together with positions were responses were measured using the 3-D laser vibrometer. Modulation indices R were then calculated for all analysed response locations (Figure 7b). Interestingly, the largest values of modulation intensity (R parameter) were obtained when the response measurements were taken in the lower part of the plate, where the excitation transducers
were located. The study illustrates how to optimise sensor location to achieve the best damage detection results.

5. Conclusions

The paper has demonstrated a number of possible applications of laser vibrometry for non-destructive testing and structural health monitoring. Low-frequency (vibration) and high-frequency ultrasound measurements with laser vibrometers were performed for in-plane and out-of-plane oscillations. The work presented illustrates applications related to modal analysis, crack divergence analysis, strain estimation, damage detection and optimal sensor investigations.

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References


