An automated damage identification technique based on vibration and wave propagation data

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This paper is concerned with the detection and characterization of hidden defects in advanced structures before they grow to a critical size. A novel method is developed using a combination of vibration and wave propagation data to determine the location and degree of damage in structural components requiring minimal operator intervention. The structural component is to be instrumented with an array of actuators and sensors to excite and record its dynamic response. A damage index, calculated from the measured dynamic response of the structure in a reference state (baseline) and the current state, is introduced as a determinant of structural damage. The index is a relative measure comparing the two states of the structure under the same ambient conditions. The indices are used to identify damages in the forms of delaminations and holes in composite plates for different arrangements of the source and the receivers. The potential applications of the approach in developing health monitoring systems in defects-critical structures are discussed.

Keywords: structural composites; hidden defects; damage index; frequency response; ultrasonic waves

1. Introduction

Advanced composites are being used increasingly in aircraft, aerospace, marine, automotive and other structures, due to their high strength to weight ratio, formability and other favourable properties over conventional engineering materials. However, composite materials are highly sensitive to the presence of manufacturing and service-related defects that can reach a critical size during service and compromise the safety of the structure. This is in contrast to metals where such damage is usually visible or detectable at an early stage of their formation. The explosion of the Delta II Launch Vehicle in January 1997 serves as a good example of the hazards associated with impact damage in composite structures. The explosion was caused by a hidden delamination in the composite casing of one of the strapped-on graphite epoxy motors (Gunn 2000). The recent crash of Airbus AA-587 due to the loss of its composite vertical stabilizer also appears to have been caused by the presence of hidden defects (Alfonso-Zaldivar 2001) in its composite parts.

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One contribution of 15 to a Theme Issue ‘Structural health monitoring’.
The current practice of periodic inspections based on conventional non-destructive techniques, such as ultrasonic, thermal, radiographic, etc., is expensive, time-consuming and often unnecessary. According to some estimates, over 25% of the life cycle cost of an aircraft (both commercial and military) that includes pre-production, production and post-production costs can be attributed to operation and support, involving inspection and maintenance of the airframe. Further difficulty arises due to the fact that the normal operation must be interrupted and accessibility for personnel and equipment must be provided with sufficient inspection time (Abrate 1998). New military fighter aircraft, such as F-22, the joint strike fighter, etc., use health usage monitoring systems (HUMS), which record peak stress-strain, acceleration, etc., occurring in key components of the vehicle. However, these measurements do not provide detailed information about damage in real time, and they require extensive human intervention. Ultrasonic non-destructive evaluation (NDE) methods and vibrational techniques, using measurements from surface mounted or embedded sensors, provide an attractive alternative to develop viable real-time damage monitoring systems in advanced structures.

It is well known that the presence of damage modifies the dynamic behaviour of a structure and that careful model-based analysis of this behaviour can, in principle, be used to determine the location and nature of the damage before the safety and integrity of the structure are compromised by the growth of damage to a critical state (Doebbling et al. 1996). Studies have been conducted to relate the changes in the modal parameters to detect and characterize damage (Zou et al. 2000; Kessler et al. 2002; Kim & Stubbs 2002; Ndambi et al. 2002) in idealized structures. However, the effects of a small flaw on the global vibrational properties (e.g. modal frequencies and mode shapes) of a structure are usually quite small, and the associated inversion problem is highly nonlinear and non-unique. Thus, the inversion of the normal mode data to detect the presence of localized damage in a structure has proven to be extremely difficult.

Since elastic waves are extremely sensitive to the presence of defects in their propagation path, ultrasonic NDE methods have been very effective in detecting and characterizing small local defects in a variety of structural components (Bar-Cohen 1986; Rose 1999). A significant amount of research has been conducted using broadband transducers (notably, piezo-impedance transducers; PZT) to transmit and receive guided waves (Lamb waves) and to detect hidden defects in structural plates (Saravanos & Heylinger 1995; Monkhouse et al. 1997; Chang & Mal 1998; Badcock & Birt 2000). Model-based analysis of the acoustic emission waveforms has also been carried out in an effort to locate and characterize the initiation of microcracks in composite structural components (Guo et al. 1996; Haugse et al. 1999; Mal et al. 2003). A major difficulty with these methods is that in real structures, the ultrasonic signals are often contaminated with environmental and service-related noise, and their analysis usually requires the intervention of trained experts.

In this paper, a unified computer assisted automatic damage identification technique based on a damage index, associated with changes in the vibrational and wave propagation characteristics in damaged structures, is developed. The technique stipulates the use of a sparsely distributed network of low-frequency sensors to measure the global response and clusters of high-frequency ultrasonic sensor arrays located in critical areas to measure the local response of a structure.
Using the initial measurements or calculations performed on an undamaged structure as baseline, the damage indices are evaluated from the comparison of the frequency response of the monitored structure with an unknown damage under the same ambient conditions. Thus, unless the environment undergoes significant changes between the two sets of measurements (which can occur within a very short time frame), noise, in general, will have no effect on the results. The technique is applied to approximately locate and characterize various types of damage in composite plates. The relative effectiveness of the method is examined for various sensor locations relative to the defects. More accurate localization and characterization will require detailed local non-destructive evaluation of the identified areas with possible presence of defects.

2. Vibration effects

The dynamic behaviour of a linear structural system can be described by the following well-known system of differential equations:

\[ [M] \{\ddot{x}(t)\} + [C] \{\dot{x}(t)\} + [K] \{x(t)\} = \{f(t)\}, \]

where \( M, C \) and \( K \) are the mass, damping and stiffness matrices, respectively; \( x \) is the displacement vector; and \( f \) is the external applied load vector. The response of the system can be represented in the frequency domain by the following system of algebraic equations:

\[ [−ω^2M + iωC + K] \{X(ω)\} = \{F(ω)\}; \]

where \( X(ω) \) and \( F(ω) \) are the Fourier transforms of \( x(t) \) and \( f(t) \), respectively. Thus,

\[ \{X(ω)\} = [H(ω)] \{F(ω)\}, \]

where \( H(ω) \) is the complex ratio between the output and the input of the system in the frequency domain

\[ [H(ω)] = [−ω^2M + iωC + K]^{-1}. \]

The function \( H(ω) \) is the frequency response function (FRF) of the structure. The FRF depends on the mass, damping and stiffness properties of the structure, and any changes in these properties produce changes in \( H \). Thus, it is, in principle, possible to determine the induced modification by evaluating changes in the FRF. The presence and extent of the damage can be determined by measuring or calculating the FRF of the dynamic response of the structure at multiple points before and after the damage appears. For each damage size and location, it is possible to define a dimensionless quantity using the undamaged and damaged FRFs. The quantity is referred here as the damage index, \( D \), defined below and is representative of the damage level and its location.

The dynamics of a fixed ended unidirectional graphite/epoxy composite plate of dimension 200×200×1 mm is considered in the presence and absence of damage as an illustrative example. The material properties of the defect-free plate are listed in Table 1. Modal analysis is conducted first for two types of (through thickness) damage: (i) over a small area of 12.5×12.5 mm and (ii) over a large area of 37.5×37.5 mm, which are representative of damage due to foreign object impact. The damage was simulated by reducing the Young modulus \( (E_x \text{ and } E_y) \) locally by 10% in case (i) and 25% in case (ii). The simulated damage is
an approximate representation of thickness loss due to corrosion or service-related structural degradation. The size and location of the two types of damage along with the locations of the source and the receivers (referred as control points) within the plate are shown in figure 1. The finite element analysis software, ANSYS, is used to calculate the modal frequencies and mode shapes of the plate. A total of 512 eight-noded quadrilateral shell elements are used for the undamaged plate. The damage is modelled by refining the mesh with different material properties (i.e. reduced Young’s modulus). The first three modal frequencies of the damaged and undamaged plate are listed in table 2. It is obvious that the presence of damage reduces the modal frequencies and that the reduction is larger at higher modes. However, the reductions in the modal frequencies are extremely low even if the damage is quite large (e.g. case (ii)). Although the differences are more pronounced for the higher modes, the proximity of the modes makes it extremely difficult if not impossible to use them for unambiguous identification of defects (Kessler et al. 2002).

A damage identification method based on the frequency response of the structure is proposed here as an alternative to modal analysis. The basic concept behind the method is illustrated in the following sections considering vibrational and wave propagation effects in damaged and undamaged plates. The plates are excited by a unit force of $\delta(t)$ time dependence, so that the calculated response represents the FRF. For each damage level and location, a frequency response analysis is conducted and the displacements and velocities are recovered as functions of frequency at a number of control points.

In figure 2, the frequency response of the plate is plotted for control points 2 and 5. It can be clearly seen that the shift in the modal frequencies is negligible, as indicated earlier. Thus, it would be difficult if not impossible to use the modal properties directly to identify damage in the plate.

The damage index, $D_{i,DL}$ at the $i^{th}$ control point is defined by the equation

$$D_{i,DL} = \frac{\{ R_i \}^T_{DL} \{ R_i \}_{DL}}{\{ R_i \}_{DL=0}^T \{ R_i \}_{DL=0}},$$

where $DL$ is the damage level ($DL=0$ for no damage) and $\{ R_i \}_{DL}$ is the structural response at the control point $i$ for a damage level $DL$. The structural response $R$ is a vector, whose elements are the structural response parameters calculated in the frequency range of interest. The indices can be defined for a generic structural parameter (displacement, velocity, acceleration, strain, etc.). The choice of the structural parameter will generally be limited by the nature of the measured response and to provide higher sensitivity of the index to the types of damage studied. For an undamaged structure (i.e. $DL=0$), both indices are zero. The damage index defined by equation (2.4) is an extremely simple expression that can be calculated from any simulated or real set of data. Clearly,
it is a relative measure whose value, by definition, is always close to zero if the dynamic properties of the structure do not change and it is positive if there is damage in the structure. The frequency domain representation of the damage index has also been used by Kim (2003), where a reconstructed FRF was used for the damaged structure. While the main ideas are similar, our definition is more straightforward and it appears to work well at least in laboratory specimens as will be seen next.

Table 2. Modal frequencies of vibration in presence and absence of damage.

<table>
<thead>
<tr>
<th></th>
<th>mode 1</th>
<th>mode 2</th>
<th>mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>undamaged</td>
<td>272.627</td>
<td>339.150</td>
<td>477.342</td>
</tr>
<tr>
<td>small damage: case (i)</td>
<td>272.608</td>
<td>339.094</td>
<td>477.255</td>
</tr>
<tr>
<td>large damage: case (ii)</td>
<td>272.186</td>
<td>337.807</td>
<td>475.779</td>
</tr>
</tbody>
</table>

Figure 1. Excitation point, control points and damage location for the fixed ended unidirectional graphite/epoxy composite plate of dimensions 200×200×1 mm. (a) Damage over a small area of 12.5×12.5 mm and (b) damage over a large area of 37.5×37.5 mm.

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The change in the damage index for the two types of simulated damage (figure 1) is shown in figure 3. In this case, the square of the particle velocity, $V^2$, is used as the structural response parameter in the frequency range of 1–1000 Hz. It is evident that the damage index increases with the level of damage, and more importantly, the increase is more pronounced at control points closer to the damage location.

3. Wave propagation effects

The damage index defined for a structural system using dynamic response can also be applied to wave propagation data. A cross-ply graphite epoxy composite laminate with stacking sequence $[90/0]_{ss}$ and thickness 4.4 mm with two types of
defects is considered an illustrative example: (i) internal delaminations caused by impact load and (ii) through the thickness holes of different sizes drilled at two locations. Several different source/receiver arrangements are used.

Wave propagation tests are first performed on the intact plate. The elastic waves are generated by a 1 μs sinusoidal pulse on the surface of the plate using a waveform generator and are recorded at nine control points (figure 4). The plate used in the study was large enough so that the reflections from its edges could be

(a) Delaminated plate

Wave propagation tests are first performed on the intact plate. The elastic waves are generated by a 1 μs sinusoidal pulse on the surface of the plate using a waveform generator and are recorded at nine control points (figure 4). The plate used in the study was large enough so that the reflections from its edges could be
gated out. Both the sender and the receivers are broadband PZT transducers (Digital Wave B1025). An impact test is then performed using an instrumented drop weight frame (Instron Dynatup 8250). It is a drop weight system equipped with a pneumatic rebound break mechanism and compressed air to increase the impactor velocity if necessary. The impact velocity ranges from 2 to 44 ft s\(^{-1}\) (0.61–13.4 m s\(^{-1}\)). With the available weights, the machine is capable of delivering impact energies from 0.7 to 450 J. The details of the experimental setup can be found in Mal et al. (2003) and will not be repeated here. After the impact test, the plate exterior had a minor dent that is approximately 1 mm in depth and 4 mm in diameter. A 60\texttimes{}60 mm\(^2\) C-scan is performed around the vicinity of the impact location after impact tests. Significant delamination is evident in the ultrasonic C-scan shown in figure 4. The wave propagation tests are then repeated in presence of defects as that in the intact configuration. The locations of the source and the receivers with respect to the damaged area are shown in figure 4.

In both pre- and post-impact cases, the signals are recorded in the time domain and then transformed into the frequency domain by FFT. The damage index \( D \) is defined as follows:

\[
(D)_i = 1 - \frac{\{F_i\}_{\text{post-impact}}^T \{F_i\}_{\text{post-impact}}}{\{F_i\}_{\text{pre-impact}}^T \{F_i\}_{\text{pre-impact}}},
\]

where \( F \) is the frequency domain response vector of the signal, whose elements are calculated in the frequency range of interest.

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The delamination generated by the impact modifies the elastic waves propagating between the source and the receivers due to reflection, scattering and diffraction of the waves by the damaged region. Thus, the pre- and post-impact signals at all control points differ in their properties. They are shown in figure 5 for two typical control points, 5 and 6. The primary differences in the signals can be traced based on the attenuation and the velocity of propagation of the waves, but would require a time consumable inspection. As an example, for control point 6, which is located behind the damaged area, an amplitude decay and scattering effect can be identified in the post-impact signal due to the large damage induced in this case. For control point 5, which is located in front of the damaged area, reflected and scattered waves from the damaged zone can be seen in the post-impact signal, a few cycles after the arrival of the first motion. A clear difference between the frequency spectra of the pre- and post-impact signals can also be seen in figure 6. A careful model-based analysis of the signals can in principle be used to determine the nature, location and severity of the damage. However, the damage caused by impact is extremely complex and the solution of even the direct problem of wave interaction with the damaged region is extremely difficult (e.g. Guo et al. 1996; Chang & Mal 1998). Unfortunately, it is difficult if not impossible to automate the identification process using this approach, due partly to the complexity of the interaction process and partly to the need for the sensors to be very close to the defect. The damage index approach offers a more pragmatic approach for approximately locating and characterizing the damage. The index is calculated using the square of the measured voltage as the response parameter in equation (3.1) at nine control points in the frequency range of 0.1–2.5 MHz and is plotted in figure 7. It can be seen that the influence is pronounced at control points 3 and 6 due to the direct transmission of the waves through the damaged area. The indices are relatively high at these points due to the large damage induced by the impact load.

Figure 5. Pre- and post-impact signals at: (a) control point 6 and (b) control point 5.
The same composite plate with two holes of different sizes is considered next. More realistic transducer (sources and receivers) arrangements are used in this case. A schematic of the plate with holes and transducer locations is shown in figure 8. The same set-up as that for the delaminated plate case is used. A 2 μs sinusoidal pulse is used as the source for this test. The wave propagation tests are performed on the defect-free reference plate. The two holes are drilled and the tests are repeated. In this experiment, one of the transducers is used as a source and the others as receivers, resulting in a larger number of signals. As an example, if the transducer at location 1 is used as the transmitter (source), then the transducers at locations 2, 3 and 4 will be used as receivers. As a result, four sets of damage indices can be obtained. Each set is denoted by $S_i$, where $i$ is the source location number. They are shown in figure 9.

(b) Plate with holes

The same composite plate with two holes of different sizes is considered next. More realistic transducer (sources and receivers) arrangements are used in this case. A schematic of the plate with holes and transducer locations is shown in figure 8. The same set-up as that for the delaminated plate case is used. A 2 μs sinusoidal pulse is used as the source for this test. The wave propagation tests are performed on the defect-free reference plate. The two holes are drilled and the tests are repeated. In this experiment, one of the transducers is used as a source and the others as receivers, resulting in a larger number of signals. As an example, if the transducer at location 1 is used as the transmitter (source), then the transducers at locations 2, 3 and 4 will be used as receivers. As a result, four sets of damage indices can be obtained. Each set is denoted by $S_i$, where $i$ is the source location number. They are shown in figure 9.

Figure 6. Frequency spectra of the pre- and post-impact signals at: (a) control point 6 and (b) control point 5.

Figure 7. Damage index calculated using equation (3.1) for the cross-ply graphite/epoxy composite plate of figure 4.
Figure 8. Locations of the transducers and the holes used for the test. Any one of the transducers can be used as a source.

Figure 9. Damage indices calculated using equation (3.1) for the plate with holes: (a) index set $S_1$, (b) index set $S_2$, (c) index set $S_3$ and (d) index set $S_4$. 

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The sets $S_1$, $S_3$ and $S_4$ show the highest index at the control point 2, which is closer to the 7 mm diameter hole. For set $S_2$, the damage index is highest at control point 4, since the hole falls almost in the direct transmission path of the wave propagating between the source at location 2 and the receiver at location 4. Even though the transducers are farther apart than that in the delaminated plate case, the presence of a moderate defect can easily be identified. The existence of the second hole (3 mm in diameter) cannot be detected easily from this study. This may be due to the fact that the scattered wavefield from the larger hole combines with that from the smaller hole for all combinations of source and receiver positions. Some insight into the presence of the smaller hole, however, can be obtained when indices at locations 3 and 4 are considered from sets $S_3$ and $S_4$. Although it is not clear that the sensors located far apart in this fashion can localize the existence of two or more smaller defects, it can be concluded that the onset of damage within a region can be predicted with some confidence. Once the damage zone is predicted, a close inspection (using conventional NDE methods) over the smaller region can be made.

4. Concluding remarks

The damage index approach presented here can be used for detection and, under certain conditions, characterization of degradation in aircraft, aerospace and civil structures. While the vibration-based analysis is expected to identify widespread damage within the structure, the analysis of the waveform signals would provide detailed information on the location and nature of smaller defects. The unified computer assisted automatic data analysis procedure should improve the reliability of the defects detection capability and aid in the development of onboard health monitoring systems for defects-critical structures. The results presented here clearly illustrate the potential effectiveness of the ‘damage-index’ to predict the approximate location and severity of the damage from a large dataset collected by a network of distributed sensors and actuators in a large structure with almost no manual intervention. More precise characterization will require local NDE of the identified areas with possible presence of defects. However, practical implementation of the technique in a real structure will require additional research involving laboratory tests and theoretical modelling, decisions on areas to be instrumented, installation of sensor arrays and codification of the algorithm to identify general areas of damage. Pattern recognition techniques may be used if the number of dataset becomes very large. It would also be necessary to address technologies, e.g. development of a wireless network of distributed miniaturized sensors, which can collect data from remote location.

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