The use of strain gauges in vibration-based damage detection

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Abstract. Strain gauges and strain measurements have been widely used in structural health monitoring (SHM) systems as a means of detecting and localizing damage, due to their higher sensitivity to local damage. These damage identification techniques normally use strain related measurements such as the mode curvature, strain frequency response function or strain energy as the main parameter to detect damage. However, damage detection techniques based on acceleration measurements have also been investigated in the past, using modal parameter comparison and other methodologies. In this paper, the use of vibration-based strain measurements for use in SHM systems will be evaluated, with the purpose of characterizing their higher sensitivity in damage detection, when compared to other vibration measurements, such as acceleration-based measurements. Since the choice and use of the most damage sensitive parameter can lead to a more sensitive and robust system, the assessment of the more suitable sensor and processing of information is very important. For this purpose, numerical and experimental examples will be discussed to evaluate the higher performance of the strain gauges.

1. Introduction

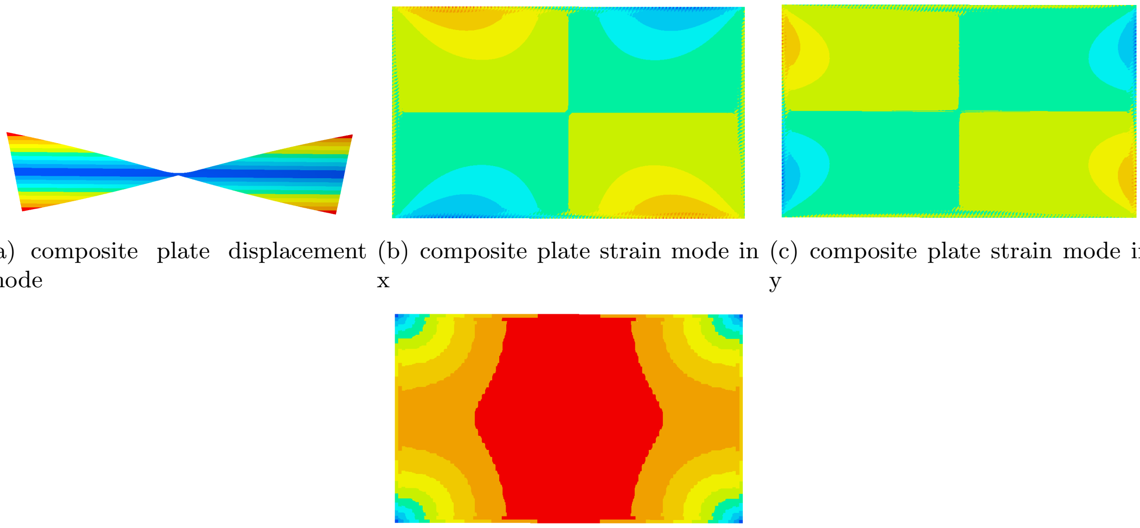
One of the objectives of structural health monitoring (SHM) systems is to continuously monitor a structure during its complete lifetime, being able to detect, locate and even diagnose damage present in multiple locations. In this way, many challenges lie in designing a robust and efficient monitoring system of this kind - how to detect changes, how to identify them and which types of damage or problems are to be detected - all of these play an important role in determining the sensor network and system architecture to be used, as well as the damage detection methodology.

Vibration-based and modal based methods [1, 2] use the vibration response of a structure to determine their characteristics and to be able to pinpoint some types of damage in the system. However, methods that directly use acceleration measurements are not so sensitive to damage [3]. On the other hand, there are many studies that use strain gauges and strain modes to detect damage [4, 5], or that calculate the strain modes from the displacement modes [6, 7], which can make strain modal analysis an attractive option for vibration-based damage detection methods.

2. Modal Analysis and Strain

Experimental modal analysis methodologies can have as sensors the more commonly used accelerometers, but can also be carried out using strain gauges. The use of accelerometers will lead to the identification of the displacement mode shapes, while with the strain gauges, the strain mode shapes are identified [8]. There are some small differences on the modal formulation for the use of strain gauges[9, 10], but the same modal identification techniques can be used to identify the strain mode shapes [11].

The visual interpretation of the strain modes, however, is something less commonly carried out and not as straight forward. While the displacement modes can be easily visualized and interpreted, the strain modes are harder to be interpreted and understood. As an example, Figure 1 shows the first displacement mode and strain modes (planar x and y and shear) from the finite element model of a rectangular carbon fiber composite plate. While it is easy to interpret the displacement mode, it is harder to arrive to the same conclusions when looking at the strain modes.



(a) composite plate displacement mode (b) composite plate strain mode in x (c) composite plate strain mode in y

(d) composite plate strain mode in shear

Figure 1. Carbon fiber composite plate (free-free) first vibration mode (0,0): (a) displacement mode; (b) strain mode in x direction; (c) strain mode in y direction; (d) shear strain mode

Strain and displacement modes are nonetheless directly related to the resonances of the structure, and therefore they also have some degree of relation with respect to each other. These relations can come from the mode curvature (for planar strain) and twist (for shear strain) of a structure [12]. The mode curvature relations are a very well known method used for estimating the strain mode shapes from the displacement mode shapes [13], something commonly done in SHM techniques that use the modal strain energy formulation [14, 15].

For the bending modes of a beam, this relation between displacement and strain can be easily formulated - equation (1) shows the relation between the displacement mode ϕ and the mode curvature κ of a beam (approximated for small displacements), while (2) shows the relation between the strain mode ψ and the mode curvature (where h is the distance between the neutral line and the surface of the beam).

$$\kappa \approx \phi'' \tag{1}$$

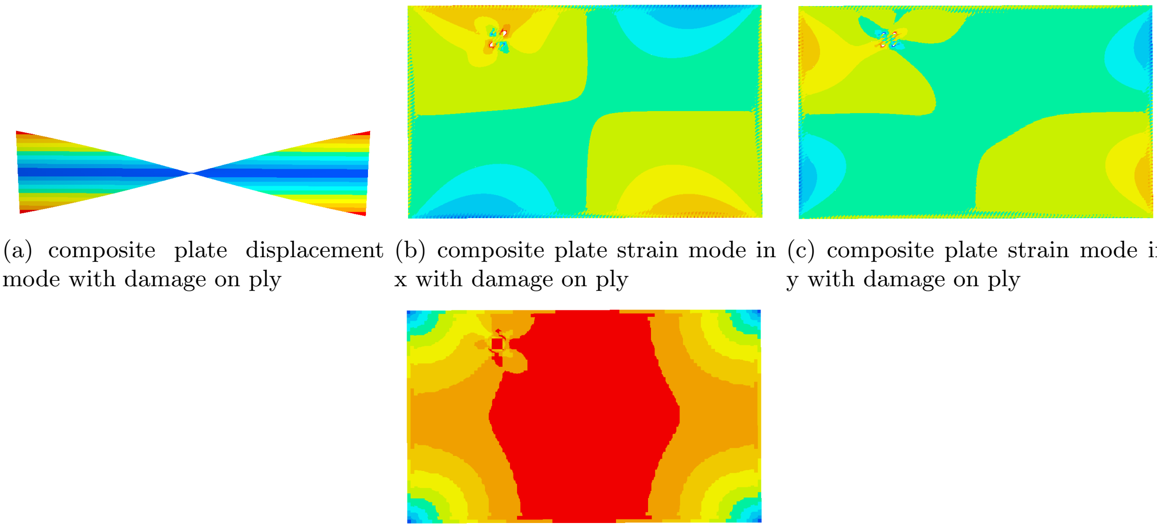
$$\psi = h \cdot \kappa \tag{2}$$

By using (1) into (2), we obtain the relation between strain and displacement modes:

$$\psi = h \cdot \phi''_{beam} \tag{3}$$

The above equation is valid for the condition of small strains and displacements, which can be satisfied in modal analysis. There are similar relations for plates or plate-like structures, but then the relation is extended to strains in both normal directions.

This characteristic makes strain more sensitive to changes in the system. As an example, damage was simulated on the plate model shown in the previous figure. Stiffness was decreased by 15% in a small region in one of the plies, on the top left part of the plate. Figure 2 shows the first modes of the damaged system. As it can be seen, the damage is easily visible on the strain modes, but not noticeable at all on the displacement mode.



(a) composite plate displacement mode with damage on ply (b) composite plate strain mode in x with damage on ply (c) composite plate strain mode in y with damage on ply

(d) composite plate strain mode in xy with damage on ply

Figure 2. Carbon fiber composite plate (free-free) with damage - first vibration mode (0,0) : (a) displacement mode; (b) strain mode in x direction; (c) strain mode in y direction; (d) shear strain mode

The example shows that if a very fine grid of strain sensors would be present on the structure (in this case, as fine as the finite element mesh), damage would be easier to detect. However, this is not the case in real life structures - there are usually few sensors and locations available on the structure, and therefore the measurement results are much more limited.

To evaluate how sensitive (and effective) strain gauges and strain modes can be when only a coarse sensor grid is available, some experimental cases will be evaluated in the next section.

3. Experimental Cases

In this section, some experimental strain modal analysis cases will be shown, with the objectives of understanding how to properly measure strain with a limited number of sensors. The first experimental case shown will be a composite carbon fiber plate, instrumented with strain gauge rosettes, where the objective was to try to characterize the full (modal) state of strain of the plate, compare it with a finite element model and come up with some conclusions with respect to how to properly interpret and use the measured data. Then, a second experimental case will be shown - the ground vibration testing of an F-16 aircraft. In this case, one of the wings of the aircraft was instrumented with piezo strain sensors to obtain the strain modes of the structure, while the full aircraft was instrumented with the commonly used accelerometers.

3.1. Carbon Fiber Composite Plate

A composite carbon fiber plate was manufactured to be used in the experiments. The composite plate is composed of 7 plies, with a stacking sequence of [0,90,0,90,0,90,0]. Each ply is made of unidirectional carbon fiber prepreg (Hexply M10R 38% UD300 CHS) and the plate was cured using an out-of-autoclave process. The dimensions of the plate are 500mm x 300mm with a thickness of 2mm.

To investigate the full state of strain of the vibration modes, the plate was instrumented with 15 strain gauge rosettes (Micro-Measurements CEA-06-250UR-350), forming a 5x3 grid of sensors. Figure 3 shows the strain gauge rosette locations on the plate.

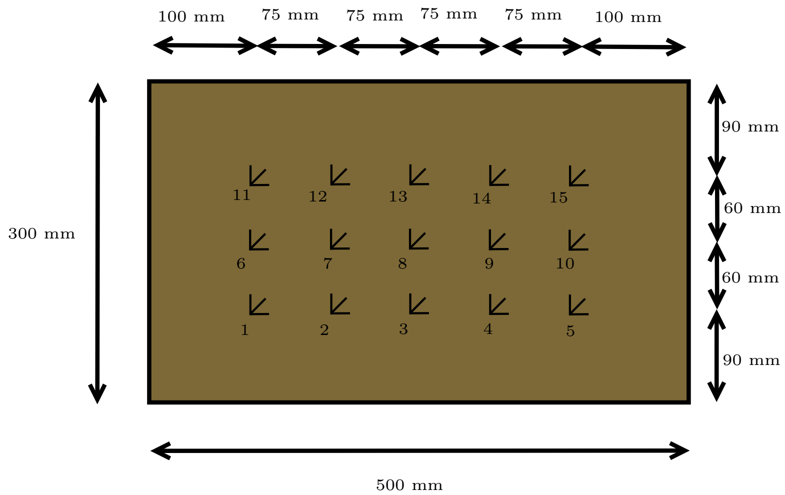
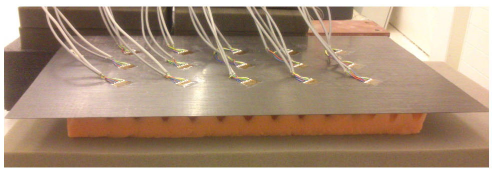


Figure 3. Composite plate: strain gauge rosette locations

Each individual strain gauge from the rosette was connected using a quarter-bridge configuration (resulting in 45 total measurement sensors). For the strain modal analysis, the plate was supported on polyurethane foam, to achieve a free-free boundary condition. Figure 4 shows the strain rosette sensor grid bonded on the plate, as well as the test set-up with the boundary conditions.

(a) Composite plate with sensors



(b) Composite plate boundary conditions

Figure 4. Composite plate used for tests: strain gauge rosettes and boundary conditions

The modal analysis was carried out using impact tests. For this purpose, a modal impact hammer (PCB 086C03) was used to excite the structure. To acquire the data, two LMS SCADAS mobile acquisition units were used. Then, impact test data can be processed in LMS Test.Lab software, using the PolyMAX least squares technique [16].

Before the identification of the strain modes, a transformation has to be carried out to be able to calculate the shear strain modes from the measurements. The middle strain gauge (45 degrees) from the rosette does not directly measure shear strain, but its measurements (plus the measurements in the other 2 directions) can be used in the constitutive equations to calculate the shear strain [17]. This procedure is carried out to generate a new set of SFRFs that are representative of the shear strain, and then the strain modes in x, y and shear(xy) can be identified.

To compare and better understand the identified strain modes, a comparison and correlation with a finite element model was carried out. The model was created in LMS Samcef Composites, using the ply material properties provided by the prepreg manufacturer. As expected, the plate has bending and torsional modes, as well as modes that are a combination of bending in the x and y directions. Table 1 shows the mode pairing between simulation and test, for the first 9 modes.

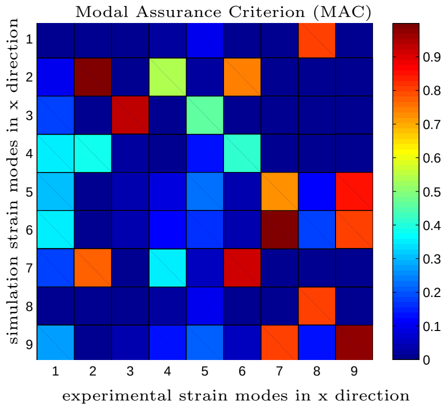
Table 1. Strain modes comparison - natural frequencies (ω_n) from simulation and test

Mode number	ω_n [Hz] simulation	ω_n [Hz] test	Difference %	Mode number	ω_n [Hz] simulation	ω_n [Hz] test	Difference %
1	29.05	33.41	13	6	171.07	168.92	1.2
2	62.07	61.63	0.7	7	174.46	164.82	5.8
3	85.41	82.60	3.4	8	191.63	185.17	3.5
4	112.52	116.03	3.0	9	270.08	254.12	6.3
5	126.46	125.31	0.9				

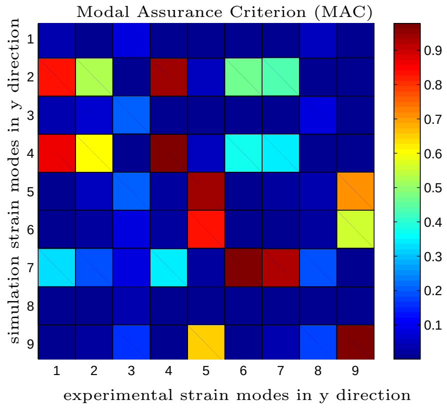
Moreover, a good way to compare the modes is to carry out the modal assurance criterion (MAC). In this case, there are many possibilities of comparison - each direction (x,y and shear xy) can be compared individually, or all the directions can be put together in a vector for the MAC calculation. Figure 5 shows these comparisons.

It can be seen from the Figure that whenever only one direction is taken into account, the MAC is degraded significantly - the comparison between the shear shows better quality, representing the shear strain from torsion, that is always present, except in the pure bending cases. Once all the directions are taken into account, the MAC is drastically improved (modes 6 and 7, which are very close in frequency, are switched). This shows how to be able to fully represent the plate strain modes, strain measurements are required in all directions. However, the MAC improvement in quality might also be related to the increased number of points used - when the directions are compared separately, 15 measurement points are used, while when they are put together, 45 measurement points are used. To understand whether the improvement comes from the increased number of points or not, a MAC with a reduced number of measurement rosettes was calculated - rosettes 1,5,8,11 and 15 were use for the calculation, with a total of 15 measurement points (3 per rosette). Figure 6 shows the comparison between the MAC using all 15 sensors (45 measurements), and the MAC with a reduced sensor grid of 5 sensors (15 measurements).

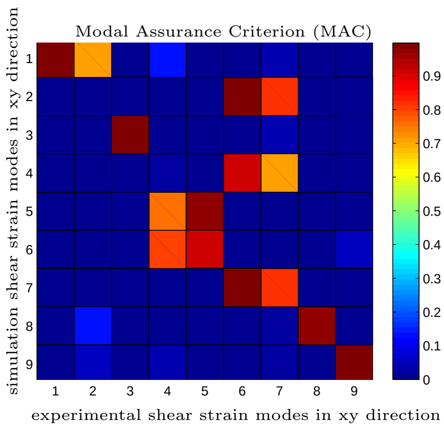
Comparing the results in Figure 6, it can be seen that even though the quality of the correlation decreases slightly for some modes, the overall quality is very good and superior to the correlation using the individual directions. This proves that using a coarser grid of strain gauges in all directions yields better results than using a finer sensor grid, but measuring in only one direction.



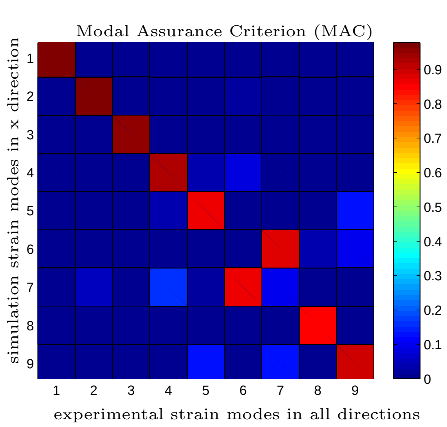
(a) Test and simulation correlation: strain measured in x direction



(b) Test and simulation correlation: strain measured in y direction



(c) Test and simulation correlation: strain measured in xy (shear) direction



(d) Test and simulation correlation: all directions

Figure 5. Carbon fiber composite plate test correlation with strain modes: (a) strain modes only in x direction; (b) strain modes only in y direction; (c) strain modes only in xy (shear); (d) strain modes in all directions;

3.2. Strain Modal Analysis Applied on the Ground Vibration Testing of an F-16

On this second experimental example, the use of dynamic piezo strain sensors on the ground vibration testing (GVT) of an F-16 aircraft will be shown. This test campaign was part of the LMS GVT Master Class [18]. In total, 149 sensors were used to instrument the whole aircraft - of these, 20 were strain sensors instrumented on the left wing. An LMS SCADAS Lab and a SCADAS mobile were used for the data acquisition, and 2 shakers were used to excite the structure, near the tip of each wing. Figure 7 shows part of the test set-up and the left wing with collocated strain sensor and accelerometer. The objective was to visualize the similarities and differences between the displacement and strain modes on the wing.

The shakers excited the structure with a burst random signal and the modes were estimated using the PolyMAX method. The first two modes of the aircraft are shown in Figure 8. The modes show that the strain pattern from the wing cannot always be directly inferred or understood from the displacement modes. In the first case (Figure 8(a)), for the wing bending, there is a high concentration of strain in the middle of the wing, possibly because of the complex internal structure of the wing. In the second case (Figure 8(b)), the strain measurements clearly

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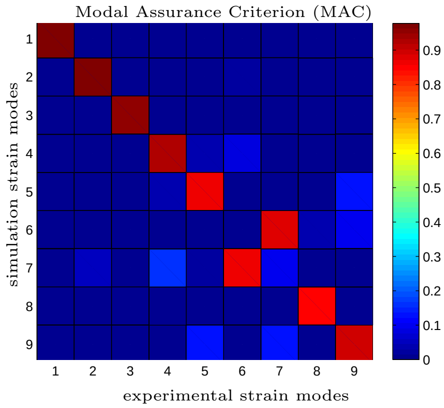
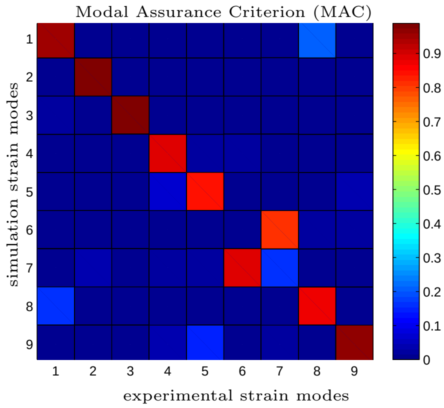


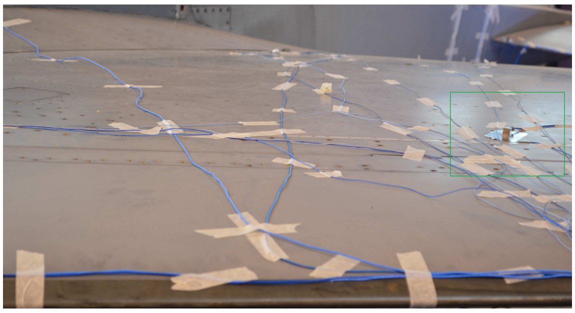
(a) Test and simulation correlation: MAC using all 15 strain gauge rosettes



(b) Test and simulation correlation: MAC using 5 strain gauge rosettes

Figure 6. Carbon fiber composite plate MAC with strain modes: (a) MAC using all 15 strain gauge rosettes; (b) MAC using 5 strain gauge rosettes

(a) F-16 Test set-up



(b) F-16 left wing - collocated strain sensor and accelerometer

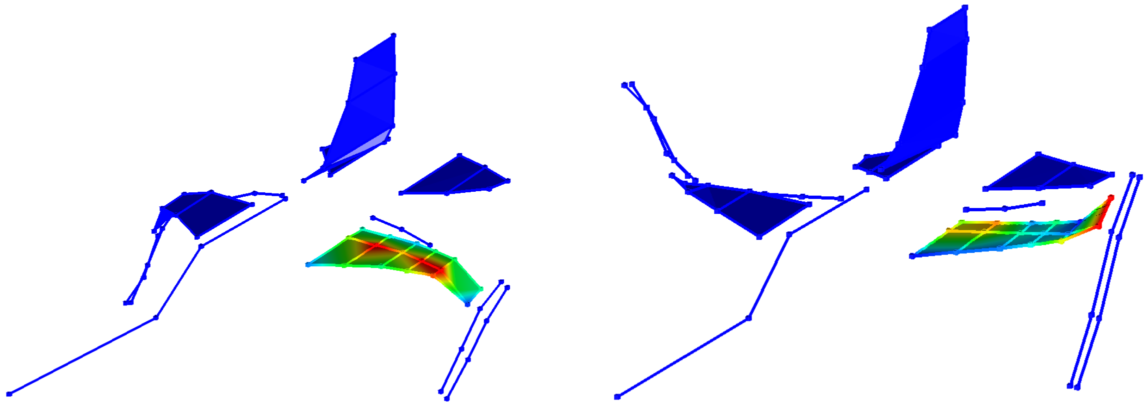
Figure 7. F-16 Test set-up and close-up on left wing with strain sensor and accelerometer

help visualizing the high amount of stress incurred on the tip of the wing, where the attachment to the bomb is.

4. Conclusions

In this paper, some advantages and difficulties of using strain gauges for modal analysis were presented. It was shown how the visual interpretation of the strain modes is harder to be carried out, when in comparison with the displacement modes. Additionally, the extra sensitivity to damage that the strain modes have when compared with displacement modes was also discussed.

Then, some experimental cases were shown - first, a modal analysis of a composite carbon fiber plate was carried out, using strain gauge rosettes to measure the full state of strain. It was shown how it is important to measure the strain in all directions, even if it means having less sensor locations. Moreover, some experimental results of the ground vibration testing of an F-16 aircraft were shown. In this case, the extra sensitivity of the strain modes was put into evidence, as they were able to properly show regions with high strain concentration, something that is not clear with the displacement modes.



(a) F-16 first wing symmetric bending mode at 5.19 Hz (b) F-16 first wing torsion mode at 6.63 Hz

Figure 8. F-16 displacement and strain modes on left wing

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