Experimental Evaluation of Vibration-Based Damage Identification Methods on a Composite Aircraft Structure with Internally-Mounted Piezodiaphragm Sensors

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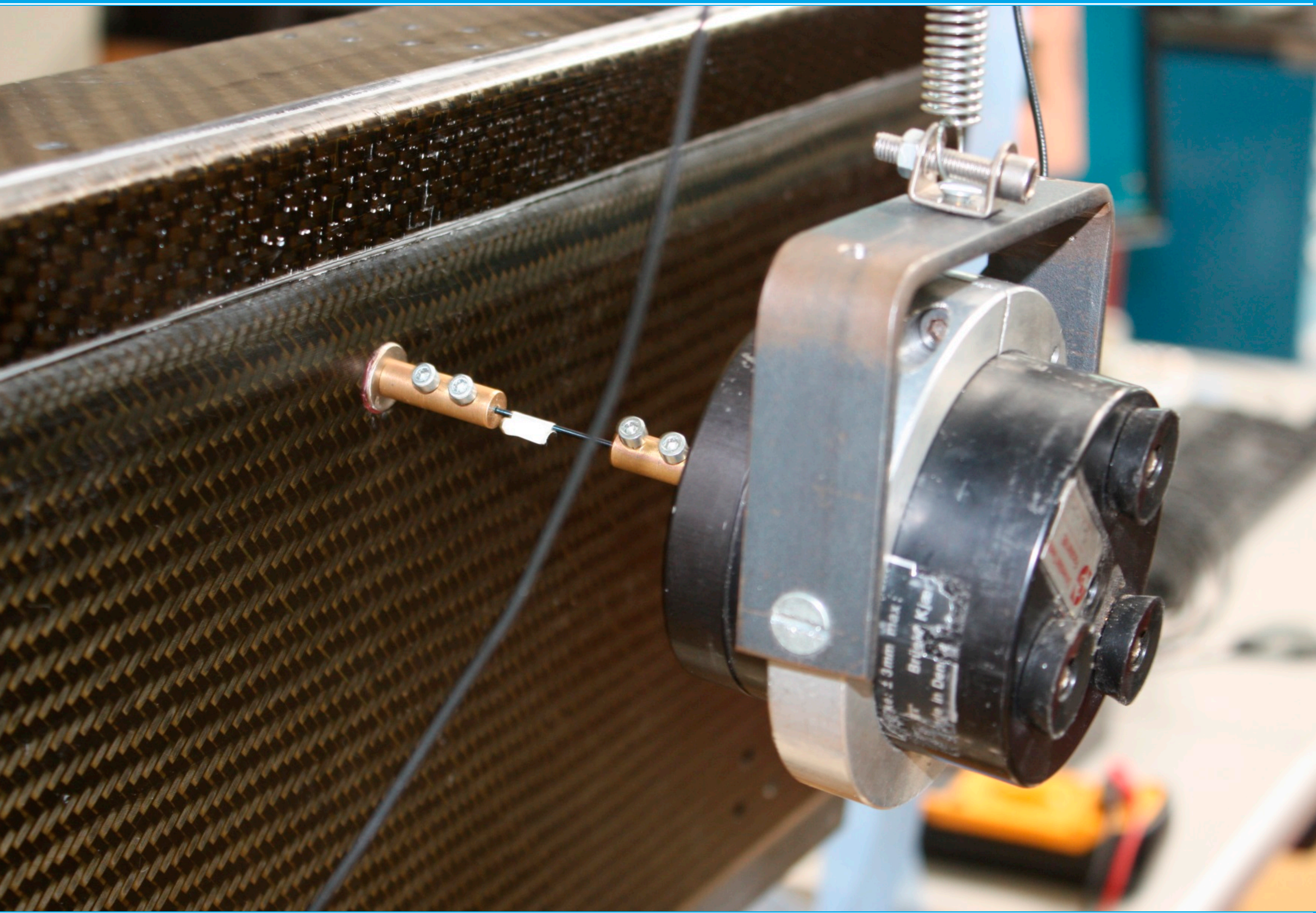

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Experimental Evaluation of Vibration-Based Damage Identification Methods on a Composite Aircraft Structure with Internally-Mounted Piezodiaphragm Sensors

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Probleemstelling

De onderhoudsbenadering in verschillende sectoren, o.a. de luchtvaartsector, verplaatst zich van gebruikstijd-gebaseerd naar een conditie-gebaseerd strategie. Structural Health Monitoring (SHM) wordt gezien als een belangrijke techniek voor deze nieuwe strategie. Terwijl er veel aandacht wordt besteed aan deze relatief nieuwe techniek, een echte doorbraak is nog niet bereikt. Een manier om dit te bereiken is het in kaart brengen van de prestaties van de verschillende SHM technieken.

Beschrijving van de werkzaamheden

Deze studie toont het belang aan van de noodzaak om het dynamisch gedrag van de constructie goed te begrijpen voordat men een SHM strategie kan kiezen. Voor dit doeleinde werden 19

This report is based on a presentation to be held at the 10th International Workshop on Structural Health Monitoring (IWSHM), Stanford University, CA, September 1-3, 2015.

piezo sensoren inwendig aangebracht aan een composiet aileron gebaseerd op de ervaringen uit verleden maar zonder voorkennis van de constructie zelf. Deze "ad-hoc" benadering wordt meestal gehanteerd door de huidige SHM systeem ontwerpers.

Resultaten en conclusies

Deze studie heeft de toepasbaarheid en de limitatie van een modaal-domein gebaseerde SHM strategie aangetoond. Aan de hand van 19 piezo sensoren werden modale eigenschappen voor en na de impact loading gemeten. Daarnaast werd Modal Strain Energy Damage Index (MSE-DI) berekend aan de hand van de mode shape. Deze MSE-DI heeft succesvol de schade gedetecteerd. Het lokaliseren van de schade was gedeeltelijk succesvol: rij B (zie Figuur 5) geeft de locatie van de schade accuraat aan, terwijl de predictie van rij A ongeveer 30mm afweek van de werkelijke schade lokatie.

Toepasbaarheid

Deze studie heeft aangetoond dat er behoefte is aan een manier om de prestaties van verschillende SHM technieken goed mee te vergelijken. De volgende stap zal worden gericht op de prestatiegevoeligheidsstudie van de SHM technieken.

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Summary

This study has shown the feasibility and limitations of a vibration-based modal-domain SHM strategy with an internally mounted sensing system. 19 piezodiaphragms each with 5mm diameter were able to measure vibrational dynamics of the structure prior and post impact loading. Moreover, the mode shapes extracted from the measurement were successfully employed to derive Modal Strain Energy Damage Index (MSE-DI) enabling to detect the presence of a damage. The localization of the damage has been partly successful: row B (see Figure 5) indicate the presence of the damage accurately while row A predicted the location of the damage approximately 30mm off.

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Content

Abbreviations

Acronym	Description
CFRP	Carbon Fiber Reinforced Plastic
DI	Damage Indicator
FFT	Fast-Fourier Transform
MAC	Modal Assurance Criterion
MSE	Modal Strain Energy
NLR	**Nationaal Lucht- en Ruimtevaartlaboratorium**
RUAG	Rüstungs Unternehmen Aktiengesellschaft
SHM	Structural Health Monitoring

1 Abstract

Maintenance strategies in various fields of industry, including aerospace applications, are shifting from time-scheduled to condition based strategies. An important requirement to allow this shift is to acquire knowledge on the failure modes and mechanisms of the system under observation. This implies for the aerospace industry that knowledge on composite failure modes, such as a typical skin-stiffener delamination, is essential. Prior research of the authors [2] revealed the use of vibration based structural health monitoring, with application on laboratory specimen. The next step is to apply the methods developed to a more complex real aerospace structure.

The objective of this study is to employ an internally-mounted piezo electric transducers based SHM strategy to a composite aerospace-related structure. Previous studies in laboratory-scale composite studies have revealed that delamination in a composite structure can be detected and localized by calculating the Modal Strain Energy (MSE) from vibration measurements of a pristine and damaged structure. In this study, a Carbon Fiber Reinforced Plastic (CFRP) aileron having a complex and representative aircraft geometry is used to evaluate the SHM approach where internally-mounted piezo diaphragms are used to calculate MSE damage indicator. The structure was excited by an electro-mechanical shaker inducing a 50 to 1000 Hz sine sweep. 19 piezo diaphragms, divided over two rows, are internally mounted on and next to a stringer where impact was applied to. The results show that the MSE damage indicator derived from the internal sensors can detect and (partly) localize the damage.

2 Introduction

Maintenance strategies in various fields of industry, including aerospace applications, are shifting from time-scheduled to condition based strategies. According to Pisupati et. al. [1], SHM is an enabler for the condition based maintenance with a capability to initiate inspections not only based on the scheduled intervals, but also on actual wear indicators exhibited by the equipment at that given point in time. Even though many research projects on this topic have been performed, a major breakthrough has not been reached yet. An important requirement for this is to acquire more confidence in the emerging SHM technologies. In order to achieve this, understanding and knowledge on the failure modes and dynamics of the system under observation is important, as well as the limitations that a certain SHM strategy has given the operational and external factors.

There are two objectives persuaded in this study: to explore the use of internally mounted piezo electric transducers and to demonstrate the importance of understanding the dynamic behavior of the system prior to choosing the SHM strategy. To show this, a case study employing an internally-mounted piezo diaphragm SHM strategy to a composite aerospace-related structure is given. Furthermore, an impact loading is applied to the structure expecting (a) delamination-like damage(s) to occur. Previous studies in laboratory-scale composite studies [2-3] have revealed that delamination in a composite structure can be detected and localized by calculating the MSE from vibration measurement of a pristine and damaged structure. Prior to the sensor placement, the authors assumed that the impact loading will cause delamination-like damage to the structure based on previous experiences.

3 Test Article

The CFRP aileron consists of 4 ribs and 2 stringers glued on the upper and lower skin surfaces. The material used overall here is a Cytec MTM44-1/HTA40(6K) prepreg except for the L-stringer, which is made of MVR444 resin instead of MTM44-1. The geometry of the aileron is 652 x 293 x 86 mm with 2mm thickness. Figure 1 depicts an overview of the aileron. After the initial dynamic measurement, an impact loading has been applied to the upper skin between rib number 2 and 3 where the stringer is glued underneath. The impact loading represents a tool dropping on the structure. More detailed test article description and the impact loading can be found in [4].

Figure 2 shows a close-up of the area where the 19 piezo diaphragms are attached distributed over two rows. The diameter and the thickness of the piezo diaphragm are 5 and 0.4mm respectively. The U-shaped rib leaves no space for the sensor placement, hence only 9 transducers are placed on this side. The sensors were attached inside the aileron prior to the assembling process. The sensors are connected to the digital signal processor with a 38-way flat cable.

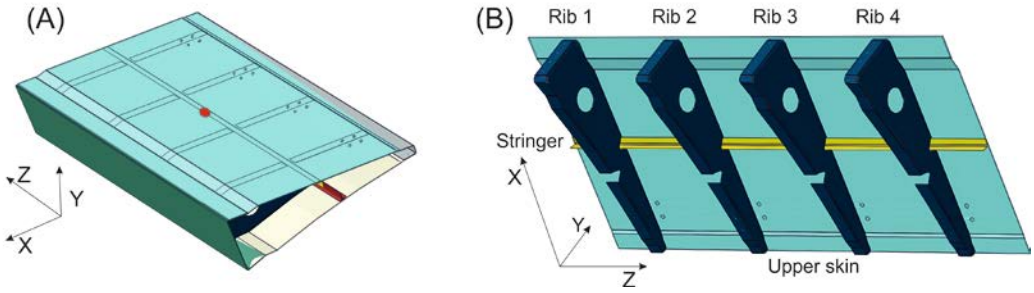

Figure 1. Overview of the aileron (A) and the open view (B). The red dot indicates the impact location.

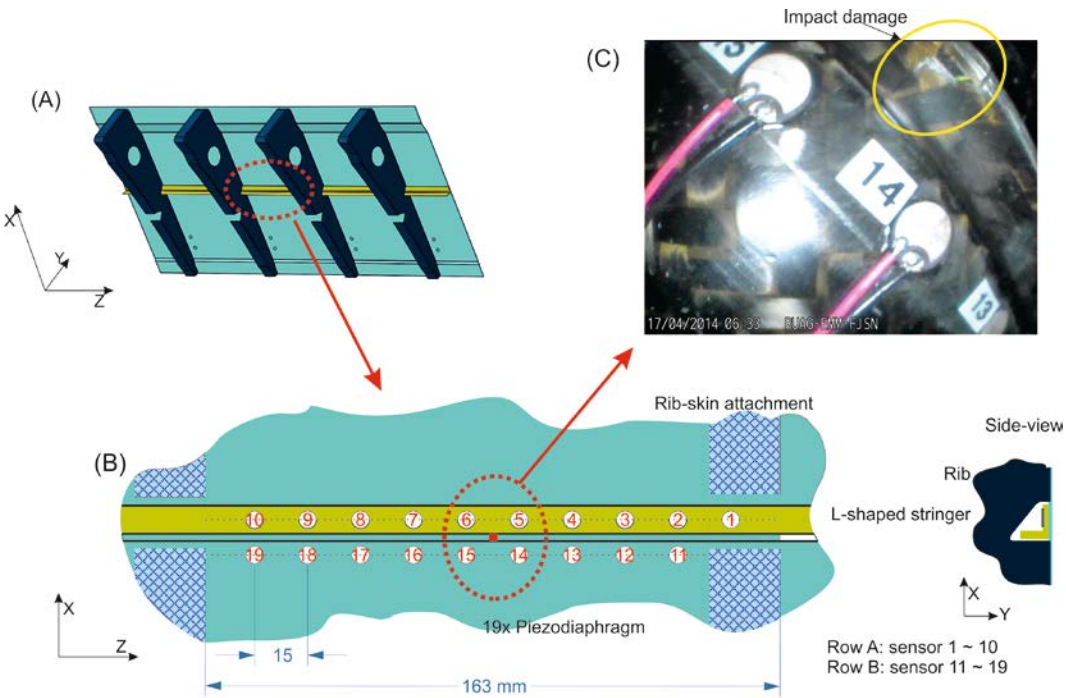

Figure 2. Subfigure (A) displays the inside-view of the aileron. The red ellipse shows the stringer-area which is monitored with two-rows of piezodiaphrams (B). The impact damage was applied from the outer-skin side. The impact has caused the breakage of the stringer somewhere between piezo sensor number 14 and 15 (C)

A visual inspection and a thermograph inspection have been performed after the impact loading. The outer skin has a barely visible impact damage. However, an internal probe camera reveals that the stringer has broken completely (Figure 2C). An ultrasonic A-scan (pen-probe sensor) was performed to detect a skin-stringer delamination with a diameter of approximately 4mm around the impact location.

4 Test Setup

The output-only vibration measurements were performed on the CFRP aileron before and after impact loading is applied. The complete dynamic set-up and data acquisition scheme used for the experiments are presented in Figure 3. The wing section has been suspended using rubber straps and thin metallic wires attaining a free-free mounting condition. The electro-mechanical shaker has been coupled to the aileron with a slender rod and a circular disc glued on the outer skin. The shaker has been aligned perpendicular to the surface avoiding the introduction of in-plane force as much as possible. Furthermore, the shaker has been suspended with a spring to preserve a free-free condition. The shaker has introduced a sine-sweep signal covering a bandwidth of 50Hz to 1kHz in 10 seconds. The output voltages from the internally-mounted piezo diaphragms are acquired using the data acquisition system with a sampling frequency of 24kHz. The test has been repeated 4 x 144 times (2 sets for pristine and damaged structure each, at 144 moments in time, since laser vibrometer measurements were done at 144 points).

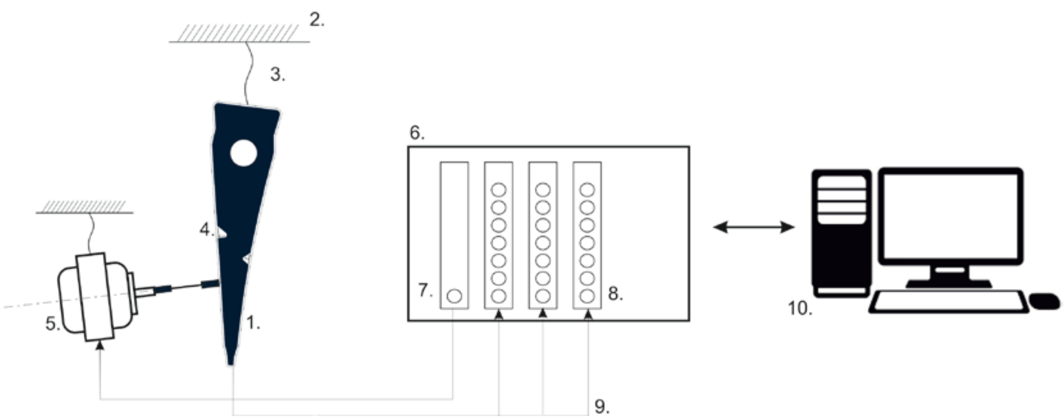

Figure 3. Test setup used in this study. See Table II for the descriptions for the numbered components.

Table I. Description of the hardwares used as shown in Figure 3

#	Description	Hardware	#	Description	Hardware
1.	CFRP Aileron		6.	Data acquisition system	NI PXI 1042Q
2.	Fixed frame		7.	Waveform generator	NI PXI 5412
3.	Elastic wires		8.	8-Channel signal acquisition module	NI PXI 4472
4.	Piezodiaphragms	STEMiNC SMD05T04R111WL	9.	Flat-cable, 19 pares of 2	3M, 3601 series
5.	Electro-mechanical shaker	Bruël & Kjær, type 4809	10.	Computer, LabVIEW	

5 Damage Indicator

In this study, only one Damage Indicator (DI) method, namely MSE-DI, has been used. MSE-DI falls under the category of vibration-based modal-domain damage feature extraction methods, employing curvatures of the mode shape. An extensive description of the MSE-DI is omitted in this paper. See [5] for more details. In general, dynamic strain is deduced from the displacement mode shapes, which is used to determine the mode shape curvature. In this study, the beam-like structure with bending is considered, leading to the strain energy U to be:

$$U_i^{(n)} = \frac{1}{2}\int_{z_{i-1}}^{z_i} EI_x \left(\frac{\partial^2 u_y^{(n)}}{\partial^2 z}\right)^2 dz \approx \frac{1}{2} EI_x \int_{z_{i-1}}^{z_i} \left(\frac{\partial^2 u_y^{(n)}}{\partial^2 z}\right)^2 dz \qquad (1)$$

where EI_x stands for bending rigidity in x-direction, $U_i^{(n)}$ and $u_y^{(n)}$ stand for the strain energy and displacement in y-direction at the element i for the mode shape n respectively (see Figure 2 for the coordination system). The DI is extracted by comparing the strain energy for each element and mode shape before and after impact loading is applied to the structure:

$$\beta_i = \sum_{n=1}^{N}\left(\frac{\tilde{\gamma}_i^{(n)}}{\tilde{\gamma}^{(n)}}\right) \Bigg/ \sum_{n=1}^{N}\left(\frac{\gamma_i^{(n)}}{\gamma^{(n)}}\right) \qquad (2)$$

where $\gamma_i^{(n)}$ stands for the left-hand side n^{th} mode shape integral of equation (1) without the flexural rigidity term EI, and the tilde indicates the same quantity from the damaged mode shape. $\gamma^{(n)}$ and $\tilde{\gamma}^{(n)}$ stand for the integral over the whole length of the beam. The damage indicator can be normalized by:

$$Z_i = \frac{\beta_i - \bar{\beta}}{\sigma} \qquad (3)$$

where $\bar{\beta}$ and σ stand for the average and standard deviation of the DIs for all mode shapes and elements respectively. In general, a minimal damage detection threshold can be set as Z_i larger than 2.

6 Results

Each measurement was converted to frequency domain by Fast Fourier Transformation (FFT) and then averaged to reduce the noise effects. Two sets of averaged frequency-domain representation of each of the pristine and damaged structure are derived. From each averaged FFT signals, the eigenvalues and mode shapes are calculated. In order to check the repeatability of the measurements, the Modal Assurance Criterion (MAC) is employed. The MAC correlates two vectors providing a measure for the similarity between two (modal) vectors. The MAC is defined as [6]:

$$\mathrm{MAC}(m,n) = \frac{\left|\left(\varphi_m^{(1)}\right)^T \left(\varphi_n^{(2)}\right)^*\right|^2}{\left(\varphi_m^{(1)}\right)^T \left(\varphi_m^{(1)}\right)^* \left(\varphi_n^{(2)}\right)^T \left(\varphi_n^{(2)}\right)^*} \quad (4)$$

where $\varphi_m^{(1)}$ stands for the modal vector of mode m at the measurement 1, $\varphi_n^{(2)}$ stands for the modal vector of mode n obtained at the measurement 2. MAC can be a value between 0 and 1: a value close to one indicates a good correspondence between the modal vectors. The measurement is considered to be well repeatable when the diagonal terms, that is $m=n$, of MAC is above 0.9. All diagonal MAC values lie within 0.98 indicating good repeatability of the mode shapes.

The dynamic measurements performed prior and after the impact loading have shown the shift of the eigenfrequencies. Table II shows the eigenfrequencies determined prior and post impact loading. Notice that the eigenfrequency shift is not significant; some eigenvalues have risen after the damage has occurred. Furthermore, the MAC value can be used here to compare the mode shapes before and after the impact loading. The corresponding MAC values show that the mode shapes have changed after impact loading. The observed change of eigenfrequencies and MAC values can be considered as a first indication of damage.

Figure 4 depicts mode shapes number 5 and 10 of the pristine and damaged structure as an example. The mode shapes from the pristine and damaged structure are used for damage identification by the MSE-DI algorithm, presented in equations (1) to (3). The required second-order derivatives of the mode shapes are obtained after elaborating the cubic spline from the measurement and evaluating interpolation points at 50 points for each row of piezodiaphragms.

Figure 5 shows the MSE-DI calculated with the measurements from piezo-diaphragm 1 to 10 (attached to the stringer, called row A) and 11 to 19 (attached to the skin, called row B). This DI shows that damage, expected to be located around z = 80mm, is detected successfully. However, peak with significantly higher Z on the row A (Figure 5B) is present which deviates from the stringer failure by approximately 30 mm. On the other hand, the DI calculated with the measurements from the row B indicates the damage location correctly. This shows that the placement of sensor array influence the performance of the SHM strategy significantly. A possible explanation for this biased results can be found in the stiffness difference in the structure. Row A and B experience different stiffness from the structure, resulting in less sensitive measurements in row A compared to B. This could have been avoided if the distance between row A and B was set larger such that the stiffness in both rows are (more or less) equal. Additionally, the global mode shapes could be captured better in less stiff area, where the vibration amplitude can be expected to be higher.

Table II. Eigenfrequencies identified (Hz)

Mode number	Pristine	Damaged	MAC	Mode number	Pristine	Damaged	MAC
1	268.5	264.5	0.83	7	758.5	702	0.67
2	331.5	323	0.86	8	781.5	766	0.69
3	339.5	338	0.89	9	816.5	798	0.77
4	354	356.5	0.76	10	875.5	876	0.85
5	661.5	629.5	0.72	11	961.5	961	0.094

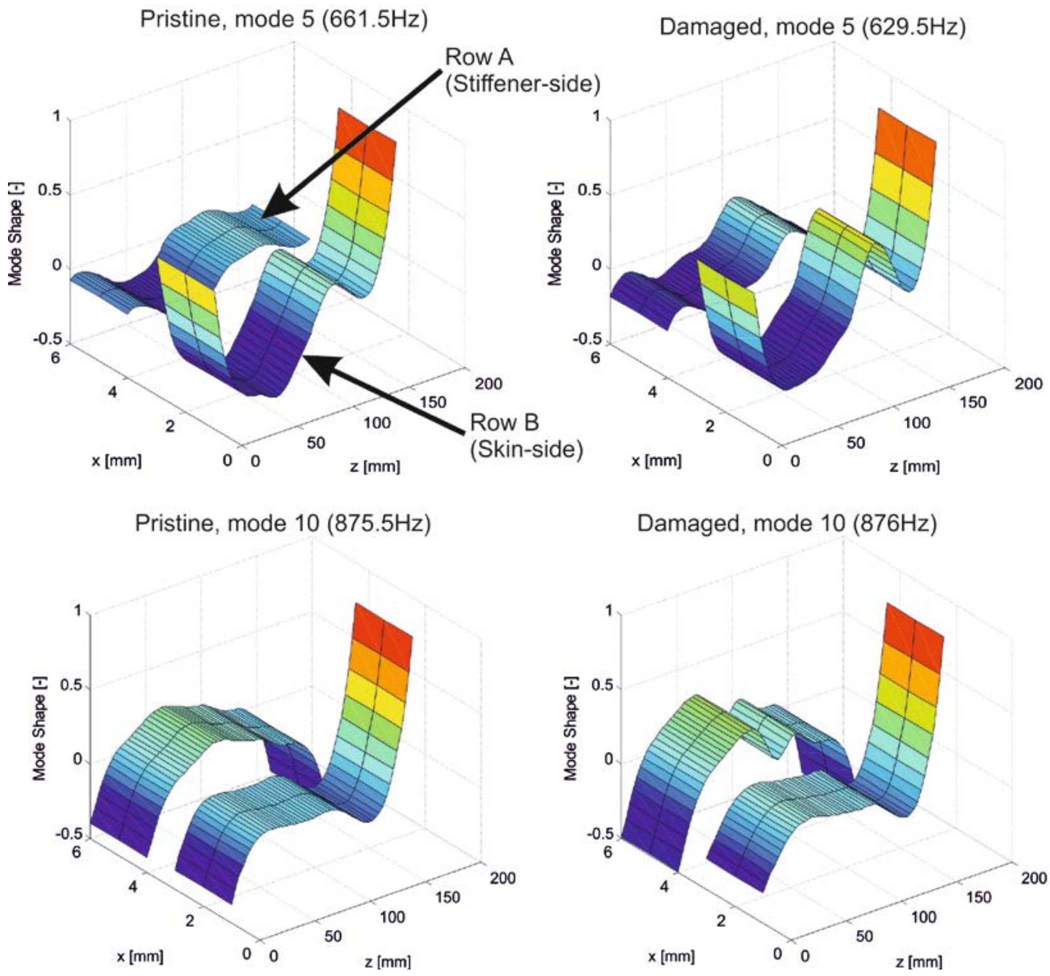

Figure 4. Experimentally obtained mode shapes number 5 and 10

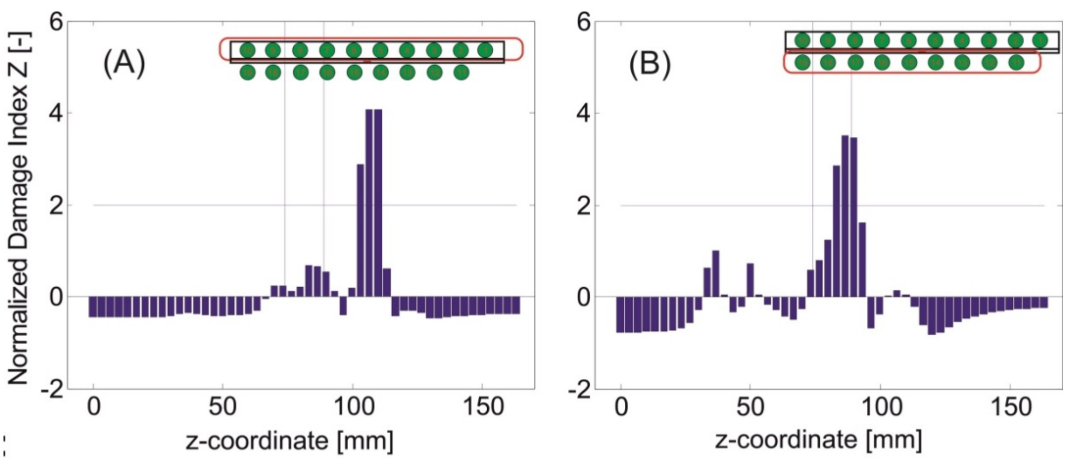

Figure 5. The normalized MSE damage indicators calculated from the dynamic measurements on row A and B. The damage has occurred between 79 and 94 mm (two vertical lines). The green dots indicate the piezodiaphragms used to calculate the normalized DI, the red curve encloses the sensors used to create the DI plot

7 Discussion

This study has raised a question: why did the analysis on the results from row B successfully localize the damage while the sensor row A fails to do so? And could this have been predicted beforehand? Earlier studies where the MSE-DI was determined from a composite T-structure experiencing delamination after impact loading (see [2-3]) have proven the effectiveness of this SHM strategy. The differences in this case study compared to these earlier studies are the complexity of the structure (non-symmetric geometry), the damage mode (stiffener breakage instead of delamination) and the sensor (the piezo diaphragms instead of the laser vibrometer). Based on this single case study, it is not clear which and how much these three differences contribute to the performance degradation. The authors have assumed "blindly" that this SHM approach will perform well based on the experience. These shortcomings stress out the importance of the prior understanding of the dynamic behavior of the system for choosing an optimal SHM strategy.

The first objective of this study, namely the exploration of internally mounted piezo sensor transducers for SHM purpose, has been shown. The second objective, the importance of understanding the system dynamics prior to choosing an SHM strategy, has been demonstrated. If the performance of an SHM strategy could be evaluated beforehand based on the differences mentioned earlier, the "blinded" choice for the SHM approach can be avoided. To achieve this, means to compare the performance of SHM techniques to each other should be designed. The future work will involve development of a framework which enables SHM performance comparison given the specific damage modes and structure by varying the sensor arrangements and feature extraction methods.

8 Acknowledgement

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