A Multi-Response-Based Wireless Impact Monitoring Network for Aircraft Composite Structures

Shenfang Yuan, Yuanqiang Ren, Lei Qiu, and Hanfei Mei

Abstract—Composite structures may be subjected to internal damages caused by impact events, which can seriously degrade the property of the structures. Hence, impact monitoring is of great importance to ensure the applications of composite, especially in aerospace engineering. This paper puts forward, for the first time, a new multi-response-based wireless sensor network (WSN) to realize the large-scale impact monitoring with the weight and complexity of the monitoring system reduced greatly. A novel multi-response-based global impact localization method that can unite multiple leaf nodes to solve the problems of localization confliction and mid-region localization is proposed for the WSN. Evaluations performed on large-scale complex composite structures have shown the advantages of the presented new methods.

Index Terms—Composite structures, impact monitoring, localization method, piezoelectric transducer (PZT), wireless sensor network (WSN).

I. INTRODUCTION

Composite materials have been widely used in many areas, such as aerospace engineering, wind energy industry, ship engineering, and civil buildings because of their superior characteristics over conventional materials, such as excellent strength-to-weight ratio, resistance to fatigue/corrosion, and flexibility in design [1], [2]. However, impact may occur during manufacturing, service, and maintenance in the whole lifetime of composites, which causes barely visible impact damage in the materials, giving rise to the overconservative design of composite structures and expensive and time-consuming nondestructive testing (NDT) maintenance [3].

How to monitor the impact online to instruct maintenance and, hence, reduce the maintenance cost has been a hot research topic for the last 20 years with numerous papers published [4]–[7]. But till now, the real applications for online and on-board monitoring, especially in aerospace engineering, are very few. This is because the aerospace engineering application has strict limitations on the weight of the structural health monitoring (SHM) system. And, usually, large scale and multiple parts of aircraft structures need to be monitored, such as the wing, vertical fin, and fuselage. Few researches have been effectively conducted to address the low-weight and large-scale online impact monitoring problems.

As one of the most researched technologies in the last decade, a wireless sensor network (WSN) offers numerous advantages over conventional wired systems, such as low weight and cost, scalability, flexibility, and ease of deployment, that enable its use in a wide range of diverse domains [8], including agriculture [9], industry [10], environmental monitoring [11], and space and extreme environments [12]. Besides these applications, many researchers have been interested in taking advantages of WSN to realize SHM of composite structures in aerospace engineering [13]–[16], including impact monitoring. Delebarre et al. [17] developed a piezoelectric transducer (PZT) based WSN to detect the impact for aeronautical composite structures. Marchi et al. [18] designed a wireless impact node to monitor impact events. Bouzid et al. [19] proposed an in situ wireless SHM system to conduct acoustic sources localization for wind turbine blades.

However, the numbers of sensors adopted in the impact related literatures mentioned above are very limited, resulting in a small scale of monitoring scope. To solve this problem, Liu et al. [20] reported a digital wireless impact monitoring node with the characteristics of low power, wireless communication, small size, and light weight and can access up to 24 PZT sensors. Different from traditional methods, the new node turns the analog response signals of the PZT sensors directly into digital sequences and locates the impact-occurring sub-regions by analyzing these digital sequences. Since the signals are digitalized at the front end, only simple field programmable gate array (FPGA) circuits are needed to realize the hardware and a simple impact localization algorithm is proposed to locate the impact-occurring sub-regions. By recording the impact history during the whole lifetime of the structures, further damage inspection can be instructed to the detected impact sub-regions instead of the entire structure by ordinary NDT methods, which can effectively reduce the maintenance cost. Although the preliminary...
research has proved the potential of the proposed digital wireless impact monitoring nodes, so far, the research primarily concentrates on the development of the nodes and most of the evaluations have been performed using small-scale sensors on simple structures.

In order to meet the needs to monitor impact online for large-scale composite structures, especially for aircraft structures with low weight requested, a large number of sensors have to be adopted. Hence, multiple nodes should be organized to realize a WSN for large-scale monitoring. However, several problems still exist and need to be addressed while designing the WSN, though the node has shown its potential.

First, it is found that the elastic waves caused by the impact can propagate for a certain distance in the structures. One impact may cause several nodes to respond when they are arranged closely, as shown in Fig. 1. Impact occurring in a sub-region monitored by Node 1 can also cause the response of Node 2. In this case, several nodes will give different localization results and lead to confliction. Another problem is that by using different nodes to monitor different regions, there exists a special kind of sub-region called mid-region, which does not belong to any node and thus cannot be located, as shown in Fig. 1. However, impacts may also occur in these mid-regions and cause responses of the circumjacent nodes. A specific method has to be proposed to deal with these problems.

Second, since large-scale and multiple parts of the structures need to be monitored, the organization method of the WSN needs to be addressed as well. As a fundamental performance benchmark of WSN, the organization method has been widely researched, with numerous papers published. Chen et al. [21] presented a hybrid memetic framework for sensing coverage optimization of WSNs. Nguyen et al. [22] developed a cooperative clustering protocol to prolong the lifetime of a WSN. Faye et al. [23] studied and characterized the probable topologies of WSNs for managing urban road traffic. However, these methods are too complex and may decrease the network reliability, considering the online large-scale impact networking monitoring studied in this work. A simple organization method with enough reliability and efficiency is needed.

To meet the online and large-scale monitoring requests, a multi-response-based wireless impact monitoring network is put forward for the first time. A novel impact localization algorithm that estimates the multi-response from multiple impact monitoring nodes to solve the localization confliction and locate the mid-regions is proposed. Based on these methods, a WSN-based multi-channel impact monitoring network with 84 PZT sensors adopted is build and evaluated on a composite unmanned aerial vehicle (UAV) wing and an aircraft composite wing box at the same time.

The rest of this paper is organized as follows. Section II briefly describes the digital wireless impact monitoring node and its original localization method. The multi-channel impact monitoring WSN and the new global multi-response-based impact localization method are proposed in Section III. The time synchronization mechanism of the WSN is presented in Section IV. Section V introduces the performance verification. Section VI gives the conclusions.

II. DIGITAL WIRELESS IMPACT MONITORING NODE AND ITS ORIGINAL LOCALIZATION METHOD

In the digital wireless impact monitoring nodes [20], [24], different from the traditional methods, the localization method makes a tradeoff between the localization accuracy and the hardware and software complexity. The method just locates the impact-occurring sub-region instead of the specific position, which can greatly help in reducing the hardware weight and software complexity. Fig. 2 shows the hardware architecture of the digital wireless impact monitoring node. The circuit board and the well-packaged node are illustrated in Fig. 3.

Fig. 4 offers an example to specifically explain the definition of the impact monitoring sub-region and the conversion from analog response signals to digital sequences. As shown in Fig. 4(a), six PZT sensors are attached on a composite structure, forming two sub-regions. Fig. 4(b) gives out the analog response signals of the six sensors caused by the impact occurring in sub-region 1, denoted as $V_1(t)$ to $V_6(t)$. By comparators designed in
the node, all these analog signals are taken in comparison with a predefined threshold that is preset depending on the amplitude level of the impacts under monitoring. In this paper, the threshold is 3 V. The comparator outputs a high digital level “1” if the voltage value of the signal is larger than the threshold. Otherwise, it outputs a low digital level “0.” Fig. 4(c) shows the achieved six digital sequences. According to the arrival time of the first rising edge in each digital sequence, the original localization method recognizes the first three responding sensors (namely PZT1, PZT4, and PZT3 in this case) to locate impact. Hence, sub-region 1, which is surrounded by PZT1, PZT2, PZT3, and PZT4, is determined as the impact-occurring sub-region.

When a number of nodes are organized to monitor impact together instead of only one, two main problems exist with the original localization method mentioned above.

1) If the regions monitored by different nodes are close, impact-occurring in one region may cause the nearby nodes to respond. As shown in Fig. 1, impact occurring in the region monitored by Node 1 can also trigger Node 2. In this case, both the two nodes give their own localization results separately, leading to localization confliction. Node 3 is not triggered since it is arranged far away enough.

2) If the region monitored by Node 1 is next to the region of Node 2, then there exist mid-regions among the two nodes, which need to be monitored as well. When an impact occurs in the mid-region, both Node 1 and Node 2 will be triggered to respond and none of their localization results are correct, which is also a wrong case.

Hence, the original impact localization method which is realized within a single node is no longer applicable. A new algorithm should be proposed when the WSN technology is adopted to organize the large-scale impact monitoring network.

III. MULTI-CHANNEL IMPACT MONITORING WSN

In recent years, multi-channel communication is proposed as an efficient method to alleviate the effects of interference and maximize parallel transmission capacity of WSN [25]–[27].

To take advantages of the multi-channel communication, a multi-radio sink node [28] is adopted. A high data throughput of 1020 Kbps can be obtained by using the eight-radio sink node to obtain eight parallel communication channels provided by the IEEE 802.15.4 protocol. In this paper, the digital wireless impact monitoring node and the multi-radio sink are used together to realize the multi-channel impact monitoring WSN.

A. Multi-Radio Sink Node

Fig. 5 shows the hardware framework of the multi-radio sink node, which mainly contains \( K \) radio frequency (RF) modules, an FPGA module, a power management module, and a universal serial bus (USB) module [28].

Controlled by the FPGA module, the \( K \) RF modules receive data packets from different communication channels independently and simultaneously. After reading the received packets from the RF modules, the FPGA module packages these packets and uploads to the monitoring center in real time through a USB2.0 port. Fig. 6 shows a sink node of size 18 cm \( \times \) 11.5 cm containing eight RF modules.

B. Architecture of the Multi-Channel Impact Monitoring WSN

As shown in Fig. 7, the architecture of the multi-channel impact monitoring WSN is proposed. There are four kinds of devices in the network: leaf node, cluster node, multi-radio sink node, and monitoring center.

The clusters are responsible for monitoring impacts of different parts of the aircraft on board. Each cluster contains one cluster node and several leaf nodes. The digital wireless impact monitoring nodes are used as leaf nodes, taking charge of...
monitoring the structures independently, responding to the impacts, generating impact records and transmitting them to the cluster nodes. A commercial TelosB node [29] with a low-power design is taken as the cluster node. It is used to receive impact records generated by the leaf nodes, locate impact-occurring sub-regions, and upload localization results to the base station when requested according to the maintenance inspection.

Multi-channel sink based ground base station contains the multi-radio sink node and the monitoring center, taking charge of recording impact localization results and instructing further impact damage inspection. Each cluster can communicate with the multi-radio sink node in its own communication channel. The sink can receive impact localization results from multiple clusters simultaneously and deliver them to the monitoring center. A LabVIEW platform based integrated software is developed as the user interface in the monitoring center. When the impact times of a certain sub-region recorded by the monitoring center exceeds the preset value, an NDT-based damage inspection can be instructed to this specific sub-region to search impact damage. Since this process can be carried out on ground, there is no need to install the base station on the aircraft, which is very important and helpful to reduce the weight and energy consumption of the on-board WSN system.

Besides adopting the multi-channel communication mechanism, several measures are also adopted in the implementation of the proposed WSN to ensure the communication reliability, including the clear channel assessment (CCA) [30], the acknowledgement (ACK) mechanism [31], and the automatic repeat request (ARQ) scheme [32]. Before transmitting impact record, the leaf node first enables CCA and checks the current channel. If the channel is idle, it sends a request packet to the cluster node immediately. Otherwise, it waits for a random period decided by the CCA protocol before repeating the channel assessment again. The cluster node sends an ACK back after receiving the request. A reliable communication link is built between the leaf node and the cluster node when the former receives the ACK. Then, the leaf node transmits the impact record and the cluster node returns an ACK again after receiving the record. In addition, the ARQ scheme is used to further decrease the possibility of packet loss. If the leaf node does not receive the ACK the cluster node returns, it retransmits the impact record after a predefined timeout of 5 ms and repeats this process until it receives the ACK. The timeout is supposed to fully cover the communication time between the leaf node and the cluster node, which is about 2 ms in this paper. Using the multi-channel WSN architecture has the following advantages.

1) Several parts of the aircraft may have impact events at the same time in real applications; letting different clusters work in different communication channels can reduce the interference to each other. And, adopting the multi-channel communication mechanism does not add any cost or design complexity for the on-board WSN clusters.

2) All the impact localization results are stored in the cluster nodes, which will be scanned by the multi-channel sink connected to a computer on ground. By using the sink, the scanning time can be greatly reduced, which can improve the maintenance efficiency. Although integrating multiple RF transceivers results in the cost increase of the sink, with only one sink adopted, the increment is acceptable compared with the advantage of improving efficiency.

C. Multi-Response-Based Global Impact Localization

Two feature parameters extracted from the digital sequences have been proved to be effective to locate impact when only one node is adopted [20]. They are the duration of the rise (DR) and the index of the first rising edge (IFRE), as shown in Fig. 8. DR is the total lasting time of the high digital level “1” of the digital sequence and is measured in milliseconds. In Fig. 8, there are two parts of high digital level “1” in the digital sequence, one lasts 0.513 ms and the other lasts 1.206 ms. DR is the sum of them, which is 1.719 ms. IFRE describes the order of the arrival time of the first rising edge among all the sensors which connect to the same node. For example, the DRs of PZT1, PZT3, and PZT4 in Fig. 4(c) are 2.722, 2.161, and 3.667 ms, and their IFRES among all the six PZTs are 1, 3, and 2, respectively.

DR represents the energy a PZT sensor obtains from impact. Theoretically, the closer the distance between a sensor and the impact is, the bigger its DR is. IFRE characterizes the order of the triggering time of a sensor compared with other sensors that connect to the same node. The sensor nearest to the impact is supposed to be first triggered and has the minimal IFRE. Due to the complexity of the aircraft structures and the environmental noise, to increase the estimation reliability, the two feature parameters are used in the combination of CCA, ACK, and ARQ.
parameters are combined to form a new energy-weighted factor (EWF) to perform impact localization, as follows:

\[
\text{EWF} = \frac{\text{DR}}{\text{IFRE}}. \tag{1}
\]

In (1), 1/IFRE is treated as the weight to correct DR. The EWF is capable of describing the impact influence on every sensor within the whole monitoring scope.

Since EWF is the only parameter used to locate impact, it is very important to ensure its accuracy. Both DR and IFRE rely on the rising and dropping edges of the digital sequence. The accuracy involves three aspects: the PZT sensor, the comparator chip, and the sampling rate of the processing core in FPGA. PZT sensors usually have good dynamic frequency performance within the band of the impact induced elastic waves. Hence, the other 2 aspects should be carefully designed to ensure the accuracy. During the development of the impact monitoring node, the comparator chip LM139 from Texas Instruments (TI) is chosen, which has a 1.3 \(\mu\)s short response time. Using the measured average group velocity of the impact induced waves in the evaluation introduced in Section V as an example, the velocity is 800 m/s, which means the waves can propagate about 1 mm after 1.3 \(\mu\)s. The processing core in FPGA acquires the digital signals with a sampling rate of 1 MHz. The time difference between two adjacent sample points is 1 \(\mu\)s. Hence, the wave propagation distance difference can be distinguished by the node is 1 mm, which is reasonable small for impact localization.

Based on the proposed EWF, a new multi-response-based impact localization method is put forward, which locates the impact in a global way, as shown in Fig. 9.

When multiple leaf nodes are triggered by the impact to respond, these nodes record their own impact-occurring times, turn the response signals of the PZT sensors they connect into digital sequences, count DRs and IFREs, and calculate the EWF of every sensor. Then, each of the responding nodes picks out the top \(N\) among all the EWFs it calculates, packages them with the corresponding sensor indexes and impact-occurring time and then transmits to the cluster node. \(N\) is the number of PZT sensors in each sub-region.

After receiving data from all the responding nodes, the cluster node first calculates time differences among these nodes. If the maximal time difference \(T_\Delta\) of these nodes is small enough to be less than a preset parameter \(T_\delta\), which is decided by the propagation distance of the impact-induced elastic waves and the placement of the sensor array and will be discussed later, these nodes are considered as being triggered by one impact. In this situation, the cluster node applies once the new proposed localization method to locate this impact. If \(T_\Delta\) is larger than \(T_\delta\), the cluster node treats these nodes as responding to different impacts, each of which may correspond to one or several responding nodes. These impacts will be distinguished according to \(T_\delta\) and located, respectively, still by using the new method as follows.

The cluster node reserves the top \(N\) EWFs among all the reported sensors, sets the others to 0 and does not care whether the \(N\) EWFs belong to the sensors of one sub-region. After these steps and with the sensor placement information stored beforehand, the cluster node now calculates the impact influence on every sub-region which is expressed as \(EWF^s\). Assuming that there are in total \(M\) sub-regions under monitoring, the \(EWF^s\) of each sub-region can be defined as

\[
EWF^s = \sum_{i=1}^{N} EWF_i, i = 1, \ldots, N; s = 1, \ldots, M \tag{2}
\]

where \(EWF_i\) presents the EWF value of the \(i\)th PZT of the sub-region.

Considering that the \(N\) PZT sensors of the impact-occurring sub-region should have much larger EWFs than sensors in other sub-regions, the one with the maximum \(EWF^s\) is considered as the impact-occurring sub-region, shown as

\[
EWF^{\text{impact}} = \max \{ EWF^1, EWF^2, \ldots, EWF^M \}. \tag{3}
\]

In order to further explain the new method, taking each sub-region contains four sensors (\(N = 4\)) as an example, three possible kinds of impact-occurring cases are introduced. Besides, the performance of the original localization method proposed in Section II under the three cases are also analyzed to demonstrate the effectiveness of the new method. The PZT sensor index is expressed as \(I_{c,i,j}\), where \(c\) is the cluster number, \(l\) represents
The leaf node number, and j is the serial number of this sensor among all the sensors that one leaf node connects.

Case 1: Normal situation. As shown in Fig. 10(a), when an impact occurs in sub-region 5, only leaf node 1 is triggered. PZT sensors with the top four EWFs picked out by leaf node 1 of cluster 1 are \( P_{1,1}, P_{1,7}, P_{1,10}, \) and \( P_{1,6} \). Since only leaf node 1 responds, the four PZT sensors with top EWFs that cluster node 1 reserves are still \( P_{1,1}, P_{1,7}, P_{1,10}, \) and \( P_{1,6} \), the EWFs of other sensors are set to 0. After calculating the EWF of each sub-region, as shown in Fig. 10(b), EWF is the maximum one, which means sub-region 5 is the impact-occurring sub-region. As for the original method, since only leaf node 1 is triggered, the first three responding sensors recognized by the method should be three of \( P_{1,1}, P_{1,7}, P_{1,10}, \) and \( P_{1,6} \), then sub-region 5 can be correctly considered as the impact-occurring sub-region. For the original method, since only leaf node 1 is triggered, the first three responding sensors recognized by the method should be three of \( P_{1,1}, P_{1,7}, P_{1,10}, \) and \( P_{1,6} \), then sub-region 5 can be correctly considered as the impact-occurring sub-region.

Case 2: Confliction situation. As shown in Fig. 11(a), when an impact occurs in sub-region 1, both leaf node 1 and leaf node 2 are triggered. The four sensors with the top EWFs of leaf node 1 are \( P_{1,2}, P_{1,4}, P_{1,5}, \) and \( P_{1,4} \). The four sensors of leaf node 2 are \( P_{2,1}, P_{2,2}, P_{2,4}, \) and \( P_{2,3} \). After receiving the data transmitted by the two nodes, cluster node 1 reserves the four EWFs of leaf node 1 and sets the others to 0, since the four EWFs of leaf node 1 are larger. Fig. 11(b) shows the EWF of each sub-region, EWF is the largest one. The localization confliction is solved. However, by using the original method, both node 1 and node 2 respond and they locate the sub-region 1 for leaf node 1 and sub-region 3 for leaf node 2, respectively. There is no mechanism to tell which one is correct, leading to the localization confliction problem.

Case 3: Mid-region situation. Impact occurs in a mid-region. As shown in Fig. 12(a), when an impact occurs in mid-region 2, both leaf node 1 and leaf node 2 are triggered. The four sensors with the top EWFs of leaf node 1 are \( P_{1,5}, P_{1,4}, P_{1,1}, \) and \( P_{1,6} \). The four sensors of leaf node 2 are \( P_{2,1}, P_{2,2}, P_{2,5}, \) and \( P_{2,4} \). Fig. 12(b) shows the top four EWFs of the cluster, which are \( P_{1,5}, P_{1,4}, P_{2,2}, \) and \( P_{1,6} \). It is obvious that mid-region 2 has the maximum EWF and can be considered as the impact-occurring sub-region, the mid-region is correctly located. Similarly to Case 2, two localization results are given by the original method. The difference is that none of them is correct, since the actual impact-occurring sub-region is a mid-region and does not belong to any of the two nodes.

Different from the original localization method, the new method unites multiple leaf nodes and consolidates their own sensor networks to cover all the sub-regions under monitoring, including the mid-regions. And with the parameter EWF, the impact influence on all the sub-regions can be estimated globally. In this way, the localization confliction can be eliminated and the mid-regions can be located as well.

IV. Time Synchronization Mechanism of the Multi-Channel Impact Monitoring WSN

Based on the proposed multi-channel WSN architecture and the new impact localization algorithm, this section further explains the time synchronization mechanism of the WSN.

During the realization of impact localization, in order to determine whether all the responding leaf nodes are triggered by the same impact, the cluster node needs to compare the impact-occurring times involved in the impact records of these nodes.
The time synchronization mechanism of the WSN has to take this need into consideration. When triggered by an impact, the leaf node needs to record the impact-occurring time. Every leaf node has a crystal-based local timer to achieve this. Unlike general WSNs that perform the structural evaluation according to the monitoring data from a lot of distributed sensor nodes together and need high synchronization accuracy, the multi-channel impact monitoring WSN only needs a time synchronization mechanism to distinguish the responding leaf nodes for one impact and maintain the normal working of the WSN, which is not a high requirement.

The time synchronization mechanism adopted in this paper is as follows. The cluster node sends out a synchronization packet with its own clock time stamp $T_{01}$. Each leaf node working in this cluster receives this packet and records its own clock time stamp $T_{11}$. When the next synchronization action is performed, similarly, the time stamp of the cluster node $T_{02}$ and the corresponding time stamp of the leaf node $T_{12}$ are recorded. Then, the clock time difference between the cluster node $T_{CN}$ and the leaf node $T_{LN}$ can be calculated as

$$T_{CN} - T_{LN} = (T_{02} - T_{01}) - (T_{12} - T_{11}). \quad (4)$$

The leaf node corrects its timer according to (4). Experiments conducted on a 2 mm composite structure have shown that the elastic waves caused by the impact will attenuate below 3 V after propagating a distance about 1000 mm. In this case, the elastic waves cannot trigger other leaf nodes anymore. With a group velocity of 800 m/s, the propagation takes 1.25 ms, which is the maximal time difference of the adjacent leaf nodes that can be triggered by the same impact, namely $T_δ$ mentioned in Section III-C. Since the frequency stability of the crystal adopted in the leaf node is 20 ppm, the possible maximal crystal drift will add up to 400 $\mu$s after 20 s. Hence, the synchronization interval of the multi-channel impact monitoring WSN is chosen to be 20 s to maintain a synchronization accuracy of 400 $\mu$s.

V. EXPERIMENTAL EVALUATION

To verify the feasibility and stability of the presented multi-channel impact monitoring WSN, an evaluation with 84 PZT sensors adopted is conducted on a composite UAV wing and a wing box together, which are both complex carbon fiber composite structures.

A. Evaluation Setup

This evaluation adopts one eight-radio sink node and four clusters with different communication channels. Cluster 1 and cluster 2 take charge of monitoring the UAV wing structure. Clusters 3 and 4 are responsible for the wing box structure.

Considering the laying cable of the PZT sensors, a special piezoelectric transducer layer (PSL) [33] is adopted in this evaluation to reduce the wire burden. The connection cables of conventional PZTs are replaced by circuits printed in the flexible interlayer to reduce the cables weight.

Fig. 13(a) gives out the experimental arrangement of the UAV wing. Cluster 1 includes cluster node 1, leaf node 1, and leaf node 2, working in communication channel 11 provided by IEEE 802.15.4 protocol. Cluster 2 includes cluster node 2, leaf node 3, and leaf node 4, working in channel 13. A wing rib and a stiffener vertical to it form a cross within the whole monitoring area. A total of 12 PSLs which contain 36 PZT sensors are attached to the inner surface of the wing, as shown in Fig. 13(b). Fig. 13(c) illustrates the sensor placement of Cluster 1, $P_{1,1}$ to $P_{1,9}$ are
Fig. 14. Wing box. (a) Structure, clusters, and PSL placement. (b) Sensor placement of cluster 3. (c) Sensor placement of cluster 4.

connected to leaf node 1 and $P_{12}$ are connected to leaf node 2, forming eight regular sub-regions and two mid-regions. The remaining 18 sensors have the similar placement, as shown in Fig. 13(d). The regular sub-region and the mid-region have the same size, which is $170 \text{ mm} \times 150 \text{ mm}$, and the area of the UAV wing is $1200 \text{ mm} \times 2000 \text{ mm}$.

The arrangement of the wing box is shown in Fig. 14. There are in total six T-shaped stiffeners with a distance of 130 mm between them, and five lines of bolt holes vertical to the stiffeners with an interval of 280 mm, as shown in Fig. 14(a). Cluster node 3, leaf node 5, and leaf node 6 belong to cluster 3, working in channel 17. Cluster 4 includes cluster node 4, leaf node 7, and leaf node 8, working in channel 19. Sixteen PSLs with 48 PZT sensors are attached to the inner side of the top panel. Each leaf node connects 12 PZT sensors, forming 24 regular sub-regions and 6 mid-regions in total, as shown in Fig. 14(b) and (c). The regular sub-region and the mid-region have the same size of $150 \text{ mm} \times 150 \text{ mm}$, and the area of the wing box is $1000 \text{ mm} \times 1800 \text{ mm}$. Fig. 15 shows the base station, including the eight-radio sink node and the monitoring center.

B. Evaluation Results

In this evaluation, by using an impact hammer, 150 impacts are averagely applied in 15 sub-regions. Six sub-regions distribute on the UAV wing, including sub-regions 1, 8, 14, and 20 and mid-regions 6 and 15, as shown in Fig. 13(c) and (d). The other nine sub-regions belong to the wing box, including sub-regions 3, 7, 8, 12, 17, 22, and 25, and mid-regions 14 and 30, as shown in Fig. 14(b) and (c).

1) Impact Localization Confliction Solving Results:

Since the two leaf nodes in each of the four clusters are all arranged closely, they all have the confliction problem during the impact monitoring. The evaluation shows the effectiveness of the proposed multi-response-based impact localization algorithm. As a typical example, when an impact occurs in sub-region 1 of the UAV wing, both leaf node 1 and leaf node 2 in cluster 1 are triggered to respond. Fig. 16(a) gives out the digital sequences of the nine PZT sensors of leaf node 1, based on which the DRs and IFREs of the nine sensors can be obtained. Similarly, the digital sequences of the nine sensors of leaf node 2 are shown in Fig. 16(b). In order to solve the localization confliction, DRs and IFREs are combined to calculate EWFs of all the 18 sensors. As can be seen from Fig. 16, PZT sensors of leaf node 1 have far larger DRs than sensors of leaf node 2. The four sensors with the
TABLE I

<table>
<thead>
<tr>
<th>Sub-Region No.</th>
<th>UAV Wing</th>
<th>Wing Box</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 6 8 14 15 20</td>
<td>3 7 8 12 14 17 22 25 30</td>
</tr>
<tr>
<td>Actual impact times</td>
<td>10 10 10 10 10</td>
<td>10 10 10 10 10</td>
</tr>
<tr>
<td>Correct localization times</td>
<td>10 10 9 10 9</td>
<td>10 9 10 10 9</td>
</tr>
</tbody>
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Fig. 17. Typical response signals and digital sequences. (a) Typical response signals. (b) Typical digital sequences.

Fig. 18. $EWF^*$ of each sub-region of cluster 3.

Fig. 19. Six false records. (a) Caused by impact position. (b) Caused by structural complexity. (c) Caused by the combination of the aforementioned two situations.

1) Impact-occurring position is very close to the boundary of two adjacent sub-regions, such as the wrong estimated impact applied in sub-region 8 of the UAV wing, as shown in Fig. 19(a). In this case, the distance between the impact-occurring position and $P_{2,6}$ or $P_{2,3}$ of sub-region 8 is close to the distance of $P_{2,4}$ or $P_{2,1}$ of sub-region 7. The four sensors have similar DRs and may influence the localization result. Moreover, it is hard to strictly distinguish the arrival times of the first rising edges of different sensors when they almost have the same distance from the impact-occurring position, which means their IFREs
may be not as accurate as the theoretical values. Hence, the EWFs of $P_{1.2}$ or $P_{2.3}$ may be less than $P_{3.4}$ or $P_{4.1}$, resulting in the maximum EWF instead of $EWF^8$.

2) There exists a stiffener or a wing rib in the sub-region in which impact is applied, for instance, sub-region 3 and mid-region 14 of the wing box, as shown in Fig. 19(b). When impact is applied in such sub-regions, the stiffener or rib may change the propagation characteristics of the elastic waves caused by the impact, leading to the abnormal DRs of PZT sensors of the impact-occurring sub-region and the false localization record eventually.

3) The third situation involves a combination of the above two situations, including mid-region 15 of the UAV wing, sub-region 7, and sub-region 17 of the wing box, as shown in Fig. 19(c). As mentioned above, both the deviation of the impact-occurring position and the complexity of the structure offer the possibility of false localization. However, what should be noted is that there is only one false localization record among the ten impacts applied in each of the three sub-regions, as shown in Table 1, the accuracy of the new proposed localization method is barely influenced.

Although there exist several false localization records, the overall accuracy turns out to be 96%, which is acceptable. It is also noticed that almost all the false localization records are adjacent to the actual impact-occurring sub-regions. Since the purpose of this paper is to instruct NDT-based damage inspection by giving out a probable region that has suffered from the impact overmuch, these false localization records can still help in reducing the inspection area by using ordinary NDT methods. In summary, the feasibility and stability of the multi-channel impact monitoring WSN have been proved.

VI. CONCLUSION

To monitor the impact online and on-board for large-scale composite structures, a novel multi-response-based wireless impact monitoring network was proposed to perform reliable impact localization. Evaluations on a composite UAV wing and an aircraft composite wing box with a total of 84 PZT sensors adopted show the reliable impact localization accuracy of 96%. Although, in this paper, the main monitoring object is the aerospace composite structures, the methods can be used in other engineering areas where the composite materials are widely used, such as blades of wind farm turbines and ship hulls.

REFERENCES


Shenfang Yuan received the B.S. degree in measurement technology and instruments, the M.S. degree in experimental mechanics, and the Ph.D. degree in measurement technology and instruments from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 1990, 1993, and 1996, respectively.

She is currently a Changjiang Chair Professor and the Director of the Research Center of Structural Health Monitoring and Prognosis, NUAA. Her main research interests include smart materials and structures, structural health monitoring, structural prognosis and management, wireless sensor networks, and signal and information processing.

Yuanqiang Ren received the B.S. degree in aircraft design and engineering in 2012 from Nanjing University of Aeronautics and Astronautics, Nanjing, China, where he is currently working toward the Ph.D. degree in measurement technology and instruments.

His current research interests include impact monitoring and wireless sensor networks.

Lei Qiu received the B.S. and Ph.D. degrees in measurement technology and instruments from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2006 and 2012, respectively.

He is currently an Associate Professor at NUAA, a Hong Kong Scholar, and a Humboldt Research Fellow. His main research interests include structural health monitoring and management, signal processing, smart sensors, and system integration.

Hanfei Mei received the B.S. degree in aircraft design and engineering in 2012 from Nanjing University of Aeronautics and Astronautics, Nanjing, China, where he is currently working toward the Ph.D. degree in measurement technology and instruments.

His current research interests include impact monitoring and guided-wave-based reliable damage evaluation methods.