An On-Line Wireless Impact Monitoring System for Large Scale Composite Structures

Hanfei Mei, Shenfang Yuan, Lei Qiu, Yuanqiang Ren

AN ON-LINE WIRELESS IMPACT MONITORING SYSTEM FOR LARGE SCALE COMPOSITE STRUCTURES

Hanfei Mei[1], Shenfang Yuan[1*], Lei Qiu[1] and Yuanqiang Ren[1]

[1] *The State Key Lab of Mechanics and Control of Mechanical Structures, The Aeronautic Key Lab for Smart Materials and Structures, Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Nanjing, 210016, People's Republic of China*
ysf@nuaa.edu.cn

ABSTRACT

One of the major concerns in the whole lifetime of aircraft composite structures is their susceptibility to impact damage. Aiming at the impact monitoring of large scale composite structures, this paper puts forward an on-line wireless impact monitoring system based on a kind of wireless digital impact monitor developed. Different from traditional processing methods, the new one is fulfilled in a digital way by turning the outputs of PZT sensors directly into digital queues and localizing the impact occurring sub-region based on the digital queues obtained. Meanwhile, validation experiments are implemented on an unmanned aerial vehicle (UAV) composite wing. The results show promising performance of the proposed system for on-line structural health monitoring (SHM) applications on large scale aircraft composite structures.

KEYWORDS: *structural health monitoring, wireless, impact monitoring, composite structures*

INTRODUCTION

Owing to many advantages compared to conventional metallic materials, composite materials have been widely used in many areas of engineering applications, especially in aerospace applications. Their excellent strength-to-weight ratios, resistance to fatigue/corrosion and flexibility in design are particularly attractive for high performance light weight aircraft structures. The latest Airbus A380, taken as an example, is composed of 22% composites [1], and the Boeing B787 aircraft uses 50% of composite materials [2]. However, one of the deficiencies of such materials is their susceptibility to impact damage. Impact usually causes inner damages in composite material which in general cannot be found easily. This undetected, hidden damage is also known in aerospace applications as Barely Visible Impact Damage (BVID), which can cause significant loss of strength or stiffness. Because of this, impact monitoring has always been an important monitoring object in the research area of composite SHM [3, 4].

For damage monitoring, it may not be requested to be performed on line. But impact is an instant event, and aircraft structure may suffer from impacts during both its service and maintenance. These impact events have to be monitored on line. The on-line monitoring system applied to aircraft structures should meet the following requests: (1) low power – this is relevant for aerospace vehicles since impact may occur during periods when the airframe is powered down. In this case, the system can only work on batteries; (2) light weight and small size – adding extra weight is always an issue on aerospace vehicles; (3) networking – for less cabling requirements and thus lower total weight; (4) local data logging and storage – to reduce network bus traffic; (5) strong electromagnetic compatibility – not influencing with each other by other electric devices.

Aiming at on-line and on board applications, a new digital impact localization method is put forward by the authors [5-7]. Different from traditional processing methods, the new one is achieved in a digital way by turning the outputs of the PZT sensors directly into digital queues and localizing the impact occurring sub-region by analyzing the digital queues obtained. According to this new concept, the digital impact monitors with advantages of miniaturized size, low weight and low energy consumption have been developed. With the advantages of compactness and high efficiency, the digital impact monitor shows its potential for on-board impact monitoring. However, for real-world aerospace engineering applications, several impact monitors should be utilized to form a monitoring network to fulfil the large scale structure monitoring.

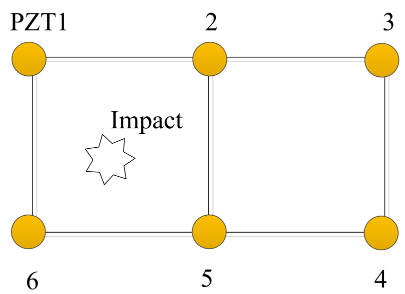
To meet the needs to monitor impact on-line and on board for large scale aircraft composite structures, this paper puts forward an on-line wireless impact monitoring system. In this system, each impact monitor takes charge of the records of impact occurring sub-region on-line and on board. When the impact times of certain sub-region exceeds some pre-set values, damage inspection methods, including traditional NDT methods, can be scheduled to this specific sub-region to search impact damage. Consequently this can save a lot of time, make the inspection highly efficient and significantly reduce the maintenance cost of aircraft structure.

1 DIGITAL IMPACT SUB-REGION LOCALIZATION ALGORITHM

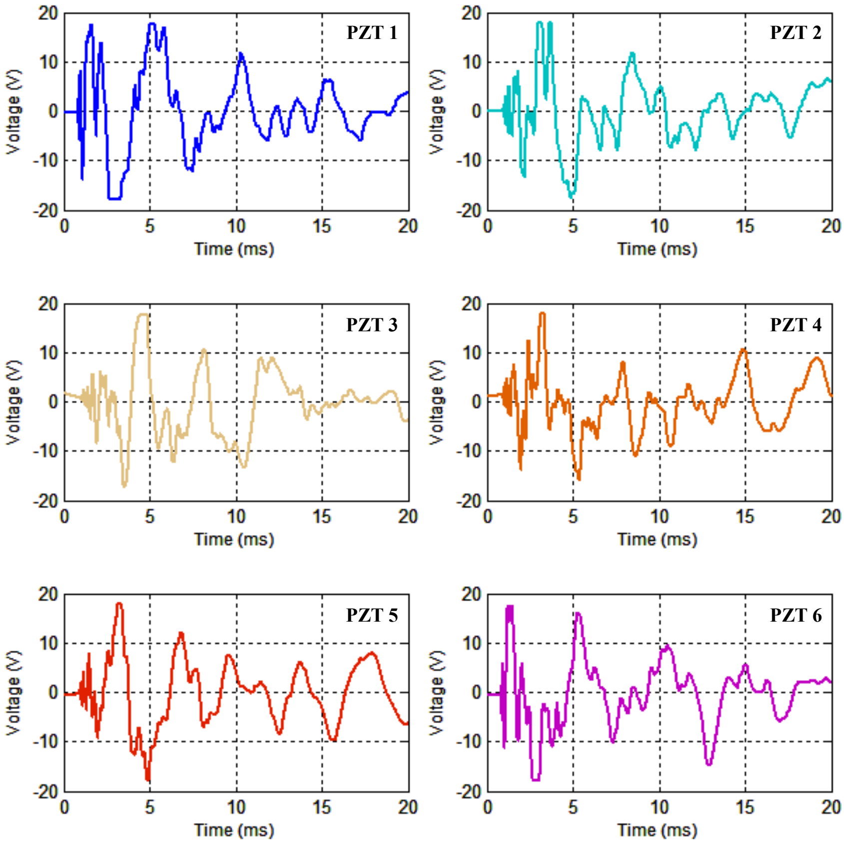
When an impact occurs on an elastic structure, acoustic signals are caused to propagate radically across the surface of the structure from the point of impact. The acoustic signals can be caught by the PZT sensors bonded on the structure surface or built into the structure. Based on the signatures, such as arrival time, traditional SHM methods by using different localization methods try to locate the position of the impact accurately. These methods rely on complex monitoring system [8-10]. To simplify the system hardware, a digital impact sub-region localization algorithm is presented.

The algorithm can be explained by a simple example, shown in figure 1(a). Six PZT sensors are bonded on the structure, forming two monitoring sub-regions. With the conventional impact monitoring system, impact response signals from the PZT sensors can be obtained as shown in figure 1(b). However, these signals are not sampled directly. Instead, they are taken into comparison with a pre-set trigger value, achieving six digital queues as a result in figure 1(c). According to the arrival time of the first rising edge appeared in each queue, the first three response PZT sensors (PZT1, PZT2, PZT6) can be recognized. Accordingly it can be determined that the impact occurred in the left sub-region surrounded by PZT1, PZT2, PZT5 and PZT6. This algorithm can be applied on a large scale structure just by increasing the number of PZT sensors. And the algorithm doesn't have strict restrictions on the monitoring objects, making it feasible for a large number of different structures.

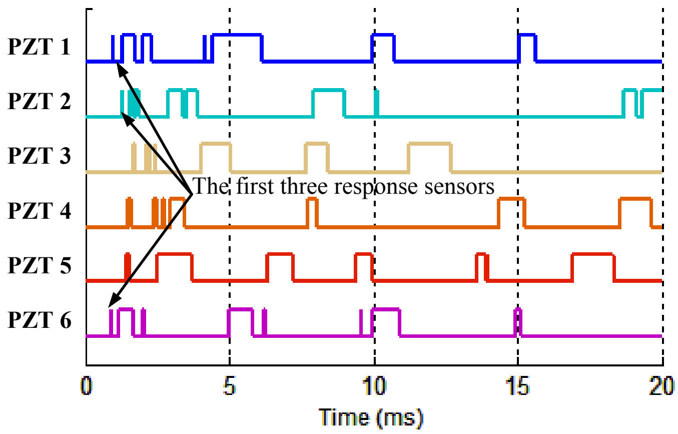
Although no strict requirements exist for the composite structures, two suggestions about the layout of PZT sensors are offered based on a large number of impact monitoring experiments on composite structures: (1) square is preferred as the shape of a divided sub-region; (2) the dimension choice for a sub-region is based on the structure to be monitored. 150mm×150mm has been tested as an appropriate area for relatively complex composite structures, and larger area is available for simpler ones.



(a) Schematic layout of PZT sensors



(b) Response signals of PZT sensors



(c) Digital queues of PZT sensors

Figure 1: Illustration of digital impact sub-region localization algorithm

2 DEVELOPMENT OF DIGITAL IMPACT MONITOR

Aiming at providing a appropriate impact location, the impact monitor has be capable of handling the data acquisition, processing, analysis, and storage for massive number of PZT sensors. Besides, in order to satisfy the requests for on-line applications in aerospace vehicles, the impact monitor need be minimal weight, size and power requirements. Figure 2 shows the schematic structure of the digital impact monitor, which mainly consists of sensing interface, processing core and communication interface.

The sensing interface takes response for acquiring measurement data from PZT sensors, in which a comparator array with preset thresholds is used to transform the response signals from the PZT sensor array into digital queues. The comparator chip chosen here is the LM139 with low power consumption from Texas Instruments Inc (TI).

The processing core is designed to analyze the digitalized signals, store and upload the results. An Altera Cyclone series Field Programmable Gate Array (FPGA) of EP1C3T100I7 is chosen as the processing core. Complicated logical and arithmetical algorithms can be implemented in FPGA with parallel computation for good performance.

The communication interface is used to transmit the impact results to the central system, in which the wireless communication and standard serial port communication are adpoted.

Figure 3 shows the developed impact monitor circuit board and two well-packaged monitor (one for wireless communication and the other one for serial port communication). The impact monitors are capable of: (1) small size (8×6×3cm^3), light weight (120g) and low-power request (less than 100mW); (2) access up to 24 PZT sensors; (3) real-time response and rapid impact sub-region location and storage; (4) serial port or wireless transmission and network monitoring; (5) dual power supply (28V aviation power or battery supply).

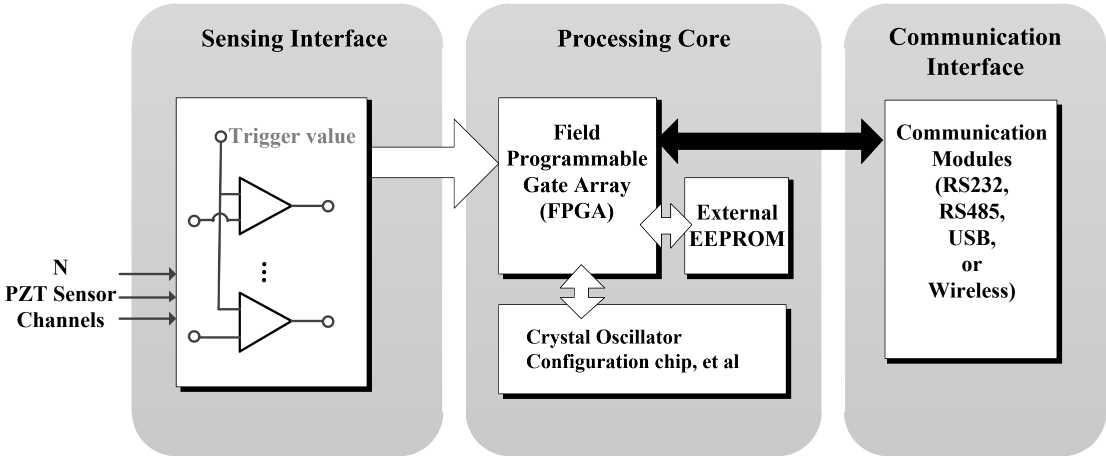
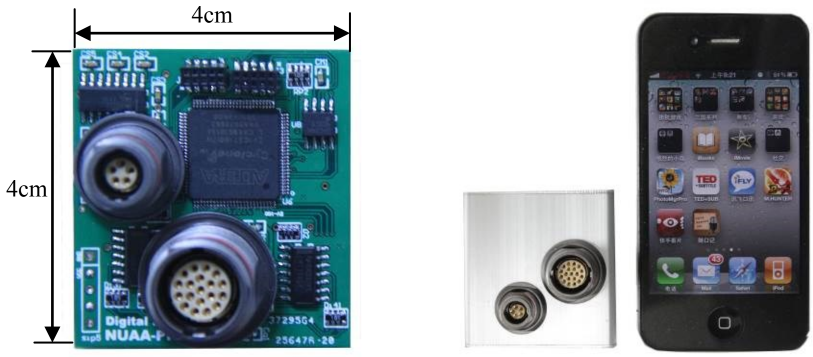


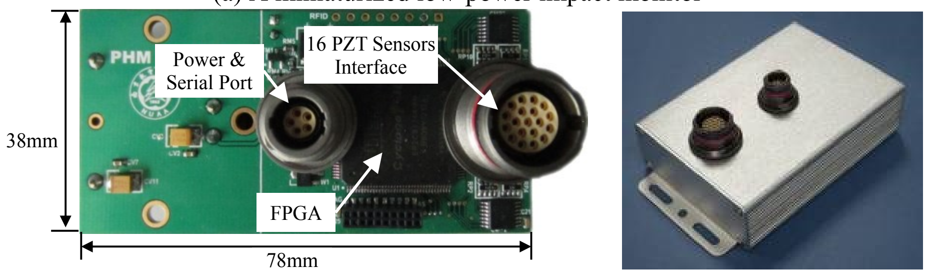
Figure 2: Architecture of the digital impact monitor

Figure 3: The miniaturized PZT-based impact monitors

In addition, in order to make the digital impact monitor equipped with the character of ultra low-power consumption, high reliability and extreme small size for on-line monitoring, two kinds of the latest impact monitors are developed. First, a miniaturized low-power impact monitor developed is shown in figure 4(a), which is more compact (4×4×2 cm^3) and less power consumption (less than 50mW) than the ones in Figure 3 and supports access to 16 PZT sensors. Second, figure 4(b) shows an airborne oriented impact monitor, in which passive filters and comparators are used to turn the impact response signals directly into digital queues. Moreover, all the two kinds of the impact monitors replace all their interfaces with strong anti-vibration ones.



(a) A miniaturized low-power impact monitor



(b) An airborne oriented impact monitor

Figure 4: Two kinds of the latest miniaturized impact monitors

3 THE ON-LINE WIRELESS IMPACT MONITORING SYSTEM DESIGN METHOD

For impact monitoring of real aircraft, several impact monitors should be utilized to form a monitoring network to fulfil the large scale structure monitoring. To realize this, an on-line wireless impact monitoring system is designed. In this paper, the wireless digital impact monitor developed is chosen here to perform on-line impact monitoring and form a monitoring network.

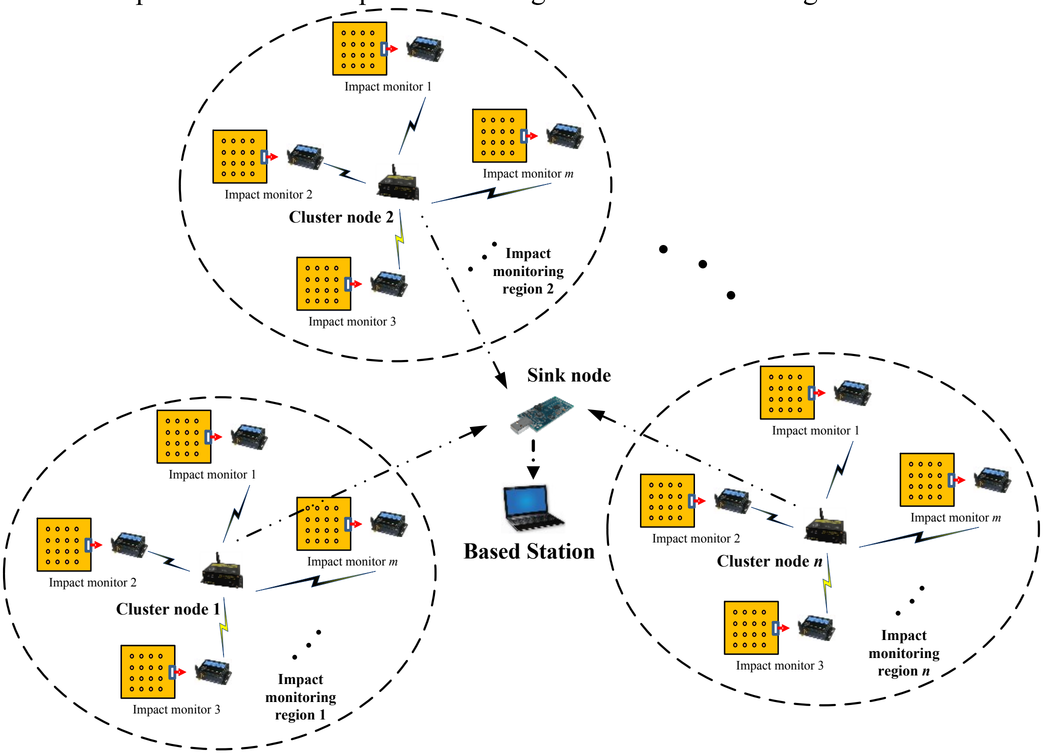


Figure 5: Illustration of the on-line wireless impact monitoring system

In this system, each impact monitor records the impact event on-line and in an on board way. The information is stored locally in each monitor. These results can be read and stored as impact history records by a base station periodically when the aircraft lands. When the impact times of certain sub-region exceeds some pre-set values, damage inspection methods, including traditional NDT methods, can be scheduled to this specific sub-region to search impact damage. Consequently this can save a lot of time, make the inspection highly efficient and significantly reduce the maintenance cost of aircraft structure.

Figure 5 shows the illustration to construct the on-line wireless impact monitoring system based on the wireless digital impact monitor. The wireless digital impact monitors are arranged into several clusters in different monitoring regions on the large scale composite structures, which form a monitoring network. In each cluster, one cluster node and *m* impact monitors are adopted. Each monitor takes charge of one region of the structure and records the impact events independently. They send their recorded information to the cluster node periodically.

The base station with a sink node connected is designed to read the impact history records from each cluster. The sink node works in a query mode, which uses channel switching mechanism to access multiple communication channels dynamically and receives the impact history records from each cluster. The base station performs this process at a fixed interval which is specified by the real engineering application request. The base station does not need to be installed on the aircraft which can reduce the additional burden of the monitoring system to the aircraft which is very important since the aerospace application has very strict limitation on the weight caused by the monitoring system.

4 PERFORMANCE VERIFICATION ON COMPLEX COMPOSITE STRUCTURE

To verify the feasibility and stability of the on-line wireless impact monitoring system proposed in this paper, validation experiments are implemented on an UAV composite wing.

4.1 Evaluation setup

The dimension of the UAV composite wing is 1200×2000×200mm^3. The composite skin and the PZT sensors arrangement are shown in figure 6. 36 PZT sensors bonded on the inner surface of the composite wing form 20 sub-regions with a dimension of 170×150mm^2 marked in figure 6. The impact monitor 1 and 2 are installed on the side of the UAV composite wing and connected with the 18 PZT sensors, respectively. Another TelosB node is used as the cluster node. The base station with a sink node connected and the user interface are shown in figure 7.

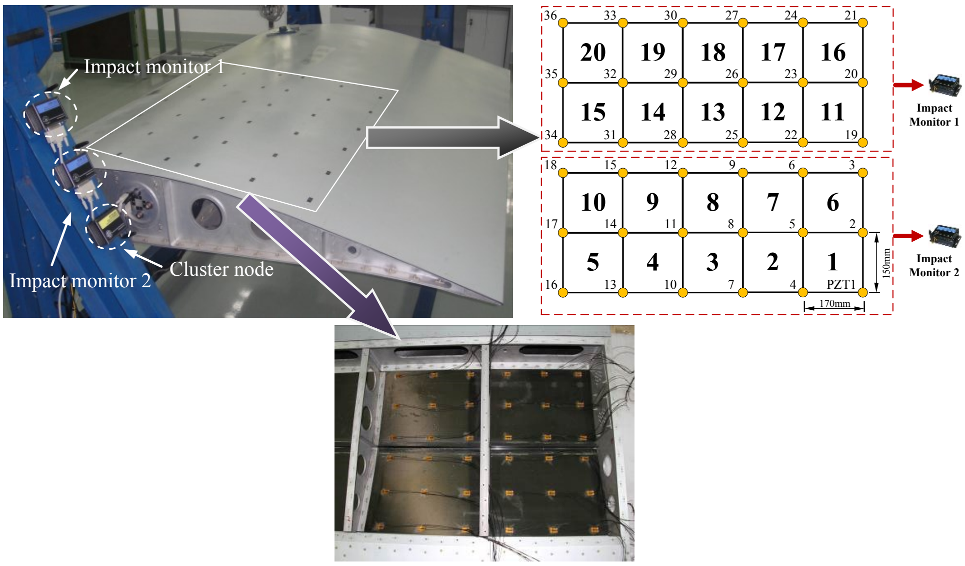


Figure 6: UAV composite wing setup

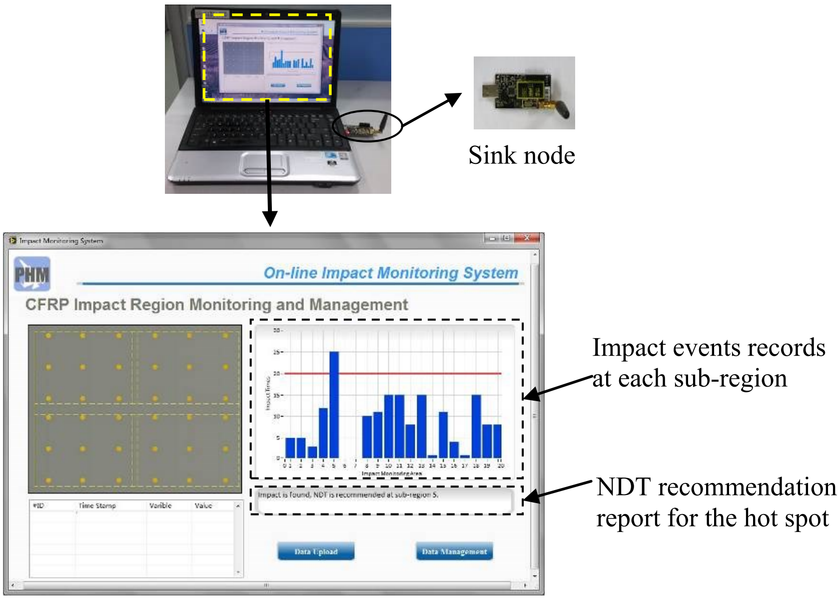


Figure 7: Evaluation system setup

4.2 Evaluation results

A series of 130 impacts with three different energy levels (0.2J, 0.5J and 1J) produced by an impact hammer are performed at various sub-regions on the UAV composite wing. By comparing the records with the actual impact history listed in Table 1, almost all the impact events occurred on the UAV composite wing have been recorded by the two impact monitors and the accuracy rate of the sub-region location turns out to be approximately 96%.

Table 1: Evaluation results on the UAV composites wing

	Sub-region No.											
	1	3	5	6	8	10	11	13	15	16	18	20
Actual impact times	5	4	23	13	17	11	7	19	6	9	3	13
Recorded impact times	5	4	22	13	16	11	7	18	6	8	3	12

CONCLUSION

This paper puts forward an on-line wireless impact monitoring system based on a kind of wireless digital impact monitor aiming at the impact monitoring of large scale composite structures. With this method, multi-region impacts of large scale composite structures can be monitored on line. To verify the feasibility and stability of the system proposed, validation experiments are implemented on the UAV composite wing. Experimental results show that the accuracy rate of the impact sub-region localization is about 96%, which show promising performance of the presented system for on-line applications in aerospace vehicles.

ACKNOWLEDGMENTS

This work is supported by the National Science Fund for Distinguished Young Scholars (Grant No.51225502), the National Natural Science Foundation of China (Grant No.51205189), and Seventh Framework Program (Grant No. FP7-PEOPLE-2010-IRSES－269202).

REFERENCES

[1] M. Kupke, M. Kolax. CFRP-fuselage–ensuring future competitiveness. *SAMPE Europe international conference*, Paris, 2004.

[2] E. Hanlon. The New--technology Boeing 787 Dreamliner. *Aviation Week & Space Technology Market Supplement*, 18:15-19, March 2005.
[3] R. Seydel, F. K. Chang. Impact identification of stiffened composite panels: II. Implementation studies. *Smart materials and structures*, 10:370-379, April 2001.
[4] W. J. Staszewski, S. Mahzan, R. Traynor. Health monitoring of aerospace composite structures–Active and passive approach. *Composites Science and Technology*, 69:1678-1685, September 2009.
[5] S. F. Yuan, P. P. Liu, L. Qiu. A miniaturized composite impact monitor and its evaluation research. *Sensors and Actuators A: Physical*, 184:182-192, September 2012.
[6] P. P. Liu, S. F. Yuan, L. Qiu. Development of a PZT-based wireless digital monitor for composite impact monitoring. *Smart Materials and Structures*, 21:035018, March 2012.
[7] L. Qiu, S. F. Yuan, P. P. Liu, W. F. Qian. Design of an all-digital impact monitoring system for large-scale composite structures. *IEEE Transactions on Instrumentation and Measurement,* 62:990–2002, July 2013.
[8] R. Seydel, F. K. Chang, Impact identification of stiffened composite panels: I. System development, *Smart Materials and Structures,* 10:354–369, April 2001.
[9] L. Qiu, S. F. Yuan. On development of a multi-channel PZT array scanning system and its evaluating application on UAV wing box. *Sensors and Actuators A: physical*, 151:220-230, April 2009.
[10] X. P. Qing, S. Beard, S. B. Shen, S. Banerjee, I. Bradley, M. M. Salama, F. K. Chang. Development of a real-time active pipeline integrity detection system, *Smart Materials and Structures,* 18: 15010, November 2009.