A Flexible-Integrated Impact Monitoring System for Aircraft Composite Structures

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Abstract

In recent years, large-scale composite structures have been widely applied on large aircrafts. However, the poor impact resistance of composite structures may lead to barely visible impact damage and result in stiffness degradation and a significant loss of structural integrity. Therefore, impact monitoring of aircraft composite structures is an important issue in the field of structural health monitoring. The impact of a structure is an instantaneous event so that it needs to be monitored on-line continuously during the whole service lifetime of the structure. Thus considering the strict restrictions of aerospace application, an impact monitoring system is required to be low weight, low power consumption and high reliability. In this paper, a Flexible-Integrated Impact Monitoring System (FIIMS) with advantages of compactness, ultra-thin, light weight, low power consumption and high efficiency is developed to meet the strict requests of on-line application. Differently from conventional impact monitoring systems, the complex analog circuits are removed and the whole impact monitoring process is achieved in a digital way by turning the output of the PZT sensors directly into digital sequences through a two-level mechanism which is realized by combing diode array with a Field Programmable Gate Array (FPGA). A simple but efficient impact-region localization method is implemented in the FPGA. In addition, the FIIMS is realized in a flexible way so that it can be embedded onto the composite structure to be a mechatronic system to realize impact monitoring on-line continuously. To illustrate the capability of the FIIMS, it is integrated with a flexible PZT sensor array to construct a large-scale impact monitoring network. The network is embedded onto the surface of a large-scale carbon fiber reinforced plate with stiffeners by using a co-curing process and the impact monitoring ability of the FIIMS is validated.

1. Introduction

Composite materials have been widely used in many areas of engineering applications due to many advantages compared to conventional metallic materials, 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, and the Boeing B787 aircraft uses 50% of
composite materials [1]. However, a major concern that has to be considered following the widespread implementation of composites is their safety during service.

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 Structural Health Monitoring (SHM) for aircraft composite structures.

In recent twenty years, many literatures have reported to use PZT sensor array based methods to monitor composite impact. Acellent Corporation in USA has developed a series of integrated SHM systems named SMART Suitcase [2-3], including an IMGenie instrument to detect impact events. The authors’ team also developed a PZT network-based integrated multi-channel scanning system called PXI-ISS [4-5]. Since conventional PZT-based impact monitoring systems are developed aiming at fulfilling a high-precision impact localization in composite structures, these systems have to consist of many modules, such as charge amplifiers, data acquisition boards, computer systems and work depending on complex algorithms. These kinds of monitoring system are usually bulky, heavy, high power consumption and rely on complex algorithms, which are usually used in lab research.

For damage monitoring, it may not be requested to be performed on line. But impact is an instant event, and the aircraft structure may suffer from impacts during both its service and maintenance, which are caused mainly by bird strikes, tool drop, runway stones or ballistic impacts. These impact events have to be monitored on line. On-line aircraft application of SHM does not allow too much additional weight, size and power consumption attachment caused by the SHM systems. The on-line SHM system applied to aircraft structures should meet following requirements: (1) Small size, light weight. (2) Low power consumption. (3) Strong Electro Magnetic Compatibility (EMC). (4) Large-scale structure monitoring.

Based on the requirements for on-line applications, some relevant works have been reported. Metis Design Corporation in US has developed an impact monitoring system both with active and passive [6], it is rounded and the diameter is only 40mm. However, the analog signal acquired by it must be uploaded to PC for further processing. The authors’ team also developed a miniaturized digital impact monitoring system, it has the feature of small size (80×40×20mm³), light weight (180g) and low power consumption (90mW) [7-9]. In spite of this, the size, weight and even the power still have the space of optimization. Comparator array is used in the digital impact monitoring system to realize the transformation of analog signal to digital sequence, which needs power supply and 16 PZT sensors need to use 4 comparator chips. Besides, Altera FPGA is used as the core processing chip and it is not a low power FPGA.

This paper develops an impact monitoring system of micro size, light weight and low power consumption. It can support large numbers of piezoelectric (PZT) sensors to monitor large-scale structures. The comparator array and the Altera FPGA is replaced by a diode and a low power FPGA. A simple but efficient impact region localization method is implemented in the low power FPGA of the micro and low power impact monitoring system to detect and record the impact events. Furthermore, the FIIMS is realized in a flexible way so that it can be embedded onto the composite structure to be a mechatronic system to realize impact monitoring on-line continuously.
2. The architecture design of the FIIMS and impact region localization algorithm

2.1 The architecture design of the FIIMS

When an impact occurs on an elastic structure, a stress wave will be caused to propagate radially across the surface of the structure from the point of impact. The stress wave can be caught by the PZT sensors bonded on the structure surface or built into the structure. Based on it, the existing PZT-based SHM systems for impact monitoring are mostly working in a passive way and the structure of these systems is illustrated in Figure 1(a). Generally, the outputs of PZT sensors have to be pre-processed through the signal filtering, amplification and AD converting circuit boards, occupying a large part of the system and limiting the number of sensor channels in the systems. And these impact monitoring systems are often bus-based and only some traditional interfaces are attached. Meanwhile, some impact monitoring methods are developed in these systems to obtain impact monitoring results [10-15]. All these methods aim at high-precision impact localization results in specific structures and are realized with complex algorithms. Besides, most of these methods require a significant amount of information like full impact data or structure characteristics.

In this paper, the requirements in on-line impact monitoring systems make the method here quite different from the traditional development methods. This method focuses on achieving approximate location results other than high-precision ones. The architecture of the new impact monitoring system FIIMS is illustrated in Figure 1(b).
In the FIIMS, the signal filtering, amplification and AD converting circuits in existing impact monitoring systems are replaced by filter array and comparator circuit. The response signal from a PZT sensor is directly changed into a digital sequence by comparing it with a pre-set trigger value. Although it reduces a large amount of information from each sensor, it can access to more sensors and reduce the system volume, weight and power-demand at the same time. Besides, it also improves the ability of anti-electromagnetic interference by greatly minimizing the proportion of analog circuits in it.

The Altera Field Programmable Gate Array (FPGA) is chosen in the development method. Unlike ordinary CPU/MCU, FPGA has no given processor structure but offers large amounts of logic gates, registers, SRAM, and routing resources, which makes it more flexible and lower power request. Complicated logical and arithmetical algorithms can be readily implemented in FPGA with parallel computation for much better performance. Typically, thousands of operations can be performed in parallel in FPGA during every clock cycle. And its compact physical size also makes it applicable in online impact monitoring system.

2.2 The impact region localization algorithm

An illustration of the impact region localization algorithm adopted by the FIIMS is shown in Figure 2. In Figure 2 (a), nine PZT sensors are placed on a composite structure, forming four impact monitoring regions. With the conventional SHM system, we can get the signals from the PZT sensors as shown in Figure 2(b). Then all these signals are sent into filter, comparator array and FPGA. Achieving nine digital sequences as a result as shown in Figure 2(c). According to the arrival time of the first rising edge appeared in each sequence, the first three PZT sensors (PZT1, PZT2, PZT8) can be recognized. So we can determine that the impact occurred in the left region surrounded by PZT1, PZT2, PZT8 and PZT9. 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.
For more precise impact localization, the algorithm based on energy-weighted region location [16] can be used. The algorithm defines a characteristic parameter called Impact Effect Factor (IEF) generated by the sensor digital sequence to characterize the extent to which the sensor is affected by impact. IEF is calculated as equations (1), (2) and (3) below, where DT is the high level duration time and ORE is the order of the first rising edge. After calculating the IEF values of all digital sequences in the sensor array, add the values of the four sensors that consist an impact monitoring region to characterize the extent to which the region is affected by impact. The region which has the largest $E_{area}$ is the algorithm-defined area of impact. The flow chart is shown in Figure 3.

\[
DT = \sum_{i=1}^{a} DT_i \tag{1}
\]

\[
IEF = \frac{DT}{ORE} \tag{2}
\]

\[
E_{area} = \sum_{j=1}^{4} IEF_j \tag{3}
\]

![Flow Chart](image)

Figure 3. The implementation process of the impact region localization method based on energy-weighted region location

3. Hardware and software design of the FIIMS

Figure 4 shows the detail hardware structure of the FIIMS, which mainly consists of filter and diode array module, core processing module, serial communication module and storage module and power supply module.
3.1 Filter and diode array

A second-order passive high-pass filter array is reserved to reduce the load and aerodynamic noise of low frequency. Comparator array is realized by a diode array because the advantage of zero power consumption and small size. 25 diodes are included in FIIMS to enable the access up to 25 PZT sensors. The outputs of the diode array are provided as the inputs to the low power FPGA, through low power FPGA pin level standard to transfer the analog signal into digital sequence, and then do impact region localization.

3.2 Processing core

At the center of the FIIMS is the processing core which contains function modules for data collection, processing and communication control. A low power FPGA is selected as the main chip in processing core. A 10MHz crystal oscillator is adopted to provide the system clock to the processing core and is divided in FPGA for different modules such as storage module and serial module as shown in Figure 5. The FLASH-based FPGA adopted in FIIMS will not lose all the configuration information after power down, so external configuration chip is not needed, which reducing the power consumption. An easy reset circuit is used for resting the program and giving the initial value. Besides, the low power FPGA offers unique Flash*Freeze technology, allowing the device to enter and exit ultra-low power Flash*Freeze mode when no power is consumed by the I/O banks, clocks, JTAG pins, or PLL, and the device consumes as little as 2µW in this mode.

3.3 Storage and serial communication

An external 64k byte CMOS-based EEPROM is added to the FIIMS design for the storage of impact monitoring results. The EEPROM transmits and receives data via an I2C port with the FPGA, in which an I2C IP core is created with a rate of 300kbits per second. And the package of the EEPROM chip is nano DFN, with the size of 2×3×0.75mm. And the serial module is used to communicate with the PC for the download of impact monitoring results.
3.4 The FIIMS

Figure 6 shows the developed FIIMS. The FIIMS is capable of: (1) Micro size and flexible (66.5×28×3mm$^3$), light weight (3g) and low power consumption (30mW). (2) Access up to 25 PZT sensors. (3) Real-time response and rapid impact region localization and storage.

4. Functional validation of the FIIMS

To illustrate the capability of the FIIMS, it is integrated with a flexible PZT sensor array to construct a large-scale impact monitoring network. The network is embedded onto the surface of a large-scale carbon fiber reinforced plate with stiffeners by using a co-
curing process, which is shown in Figure 7. The impact monitoring ability of the FIIMS is validated by applying multiple impacts in each monitoring regions and comparing monitoring results with actual impacts. The monitoring regions and the impact locations in each region are shown in Figure 8. Apply 5 impacts in each location. Thus there are 25 impact times in each region and 400 impact times on the whole structure.

Figure 7. Carbon fiber reinforced plate and large-scale impact monitoring network

Figure 8. Illustration of impact monitoring regions and impact locations

Figure 9(a)-Figure 9(b) shows the impact response digital sequences and $E_{\text{area}}$ of each region when impact was in region 1. It is clear that the order of the first rising edge of digital sequences (CH2, CH1 and CH7) is correspond to the impact location. Meanwhile the region which has the largest $E_{\text{area}}$ is the same as the actual impact region. Figure 10(a)-Figure 10(b) shows the impact response digital sequences and $E_{\text{area}}$ of each region when impact was in region 11. It is also clear that the order of the first rising edge of digital sequences (CH13, CH14, CH18 and CH19) is correspond to the impact location. Meanwhile the region which has the largest $E_{\text{area}}$ is the same as the actual impact region.

Table 1 shows the impact localization results. The accuracy rate on the whole structure is around 95.5%. The results show that the FIIMS has the ability to realize large-scale impact monitoring for composite structures when integrated with a PZT sensor array and the accuracy rate of the impact monitoring is high.
Figure 9. Impact localization results

Figure 10. Impact localization results

Table 1. Impact localization results and accuracy rate

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5. Conclusions

In FIIMS, all the complex analog circuits are turned into digital sequences by diode array and FPGA pin level standard. A low power FPGA is adopted as the processing core to detect and record the impact events. All these characters in the FIIMS show its potential for real applications in aircraft with advantages of compactness, light weight, low power consumption and high efficiency. Our current effort is to acquire more information such as the impact force level from the digital sequences besides the impact region location results. And improvement is needed in the ruggedness and robustness of the FIIMS for real applications. In addition, more tests are also needed to fully validate the FIIMS.

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References