Materials Research Proceedings **27** (2023) 271-278 https://doi.org/10.21741/9781644902455-35

Design of compact and portable structural health monitoring system for piezoelectric guided wave

Qiyun Xu[1,a], Shenfang Yuan[1,b*], Lei Qiu[1,c*]

[1] Research Center of Structural Health Monitoring and Prognosis, State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China

[a]xuqiyun@nuaa.edu.cn, [b]ysf@nuaa.edu.cn, [c]lei.qiu@nuaa.edu.cn

Keywords: SHM, Guided Wave, System Integration, Compact, Portable

Abstract. Structural health monitoring (SHM) is an important technology to realize structural reliability evaluation, which can increase the safety and reduce the maintenance costs of engineering structures. Piezoelectric guided wave SHM technology has broad application prospects because it is sensitive to small damage and can realize multi parameter monitoring such as damage and impact. However, the reported piezoelectric guided wave SHM system is large, which is not conducive to engineering applications. In this paper, aiming at the ground rapid monitoring application of aircraft structure, a compact and portable SHM system for piezoelectric guided wave is developed. Firstly, an overall architecture of hierarchical design is proposed, and then the software and hardware design of the system is studied. The volume of the system is only $273\times184\times59mm^3$, the mass is less than 3kg, it can support 32 sensor channels, the excitation voltage amplitude can reach $140V_{pp}$, and the maximum sampling rate can reach 60MS/s. Finally, a verification experiment is carried out to realize the accurate location of the damage of carbon fiber composite structure. The results show that the system is a high-performance portable system suitable for aircraft ground applications.

Introduction

Structural health monitoring technology is based on the sensor integrated with the structure, structural health monitoring system and advanced damage diagnosis algorithm to identify the cracks, corrosion and other damage discrimination, which can greatly improve the safety of engineering structures and reduce maintenance costs. Many countries in the world have successively put forward a series of strategic plans for the application of structural health monitoring technology in aircraft. For example, NASA's SBIR&STTR plan [1] specifies that future manned space missions will need spacecraft and launch vehicles that can monitor the structural health of aircraft, diagnose and report the performance degradation of aircraft. Airbus, Honeywell and other companies estimate that the global aircraft health monitoring market will receive an investment of $5.5 billion in 2020-2025 [2], so as to enhance the real-time information of aircraft health management and reduce aircraft maintenance costs. Horizon Europe, Europe's scientific research funding framework for the next seven years (2021-2027), clearly points out that health monitoring systems are one of the mature signs of intelligent technology in space research strategies [3]. The vision of China's science and technology and society in 2049 published by the Chinese Aeronautical Society: Aeronautical Science and technology and future aviation mentioned that the intelligent structure of aircraft in the future can detect, locate and evaluate the structural damage caused by fatigue, impact, corrosion, temperature changes, etc. At the same time, the prediction and health management (PHM) system will become an important airborne system and be widely used by aircraft in the future [4].

SHM technology based on piezoelectric guided wave has the advantages of high sensitivity, independent of structural load, multi parameter monitoring such as damage and impact, sensitive

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to small damage, large monitoring range, both online monitoring and offline processing, and applicable to metal and composite structures. Therefore, SHM technology based on piezoelectric guided wave has great application prospects [4-9].

The function of the structural health monitoring system is to excite the guided wave signal, acquire the sensing signal and use the damage identification algorithm to process and analyze the obtained guided wave signal, so it is one of the core links of SHM technology for piezoelectric guided wave. Some fully integrated [10-12] and semi-integrated [13-17] structural health monitoring systems have been applied and studied. Professor yuan from Nanjing University of Aeronautics and Astronautics has designed and developed an airborne miniaturized piezoelectric guided wave structural health monitoring system, which supports the access of 32 channel sensors, with a volume of only 127×90×45mm^3, mass 472g, excitation voltage up to 140Vpp, maximum sampling rate of 60MS/s. However, the system needs to be equipped with an independent power module and an external computer to realize damage diagnosis, so the integration is not high. Acellent Corporation of the United States launched the ScanGenie Mini system [18], which supports the access of 32 channel sensors, with a volume of 102 × 112 × 40mm^3, the mass is about 200g, the excitation voltage is 90Vpp, and the maximum sampling rate can reach 48MS/s, but it needs to send the acquired data to the external data download and processing module for processing. Honeywell International has designed a structural health monitoring system [19] in which the control module (SCU) and the channel switching module (SSU) are separated. The size of the control module is 120×80×70mm^3, the mass is 50g, excitation voltage up to 150V, single channel switching module can access 32 channels of piezoelectric sensors, its size is 97×79×69mm^3, weighing 400g. Although the system has achieved miniaturization, the separation design leads to the low integration of the system. Therefore, the system integration can be further improved, and the data processing module and the image display module can be integrated internally to meet the actual engineering application requirements.

In this paper, aiming at the ground rapid monitoring application of aircraft structure, a compact and portable SHM system is developed which has the advantages of integrated, miniaturized design, simple operation, and convenient carrying. Finally, the effectiveness of the system is verified by experiments.

System Architecture Design

This paper proposes the architecture design of the structure health monitoring system for piezoelectric guided wave, which is divided into human-computer interaction layer, system application layer, task working layer, hardware control layer and functional hardware layer, as shown in Fig. 1.

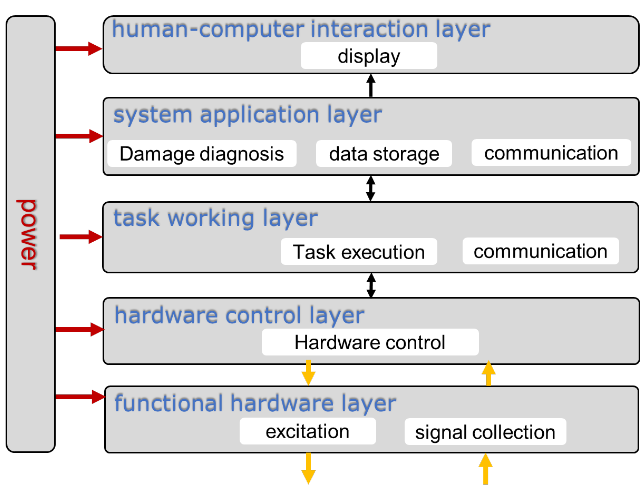

Fig. 1 system architecture design

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The main function of human-computer interaction layer is to display monitoring results and touch response. The system application layer is responsible for monitoring mission control. According to the user instructions of the human-computer interaction layer, it sends the work enable signal, monitoring parameters, etc. to the task working layer, and stores the monitoring signals. At the same time, it provides damage diagnosis tools, and outputs the diagnosis results to the graphical display of the human-computer interaction layer. The main function of task working layer is to perform monitoring tasks according to the instructions issued by the system application layer, including starting signal acquisition and uploading monitoring signals. The hardware control layer realizes the bottom hardware control, initializes the hardware circuit according to the working parameters transmitted from the task working layer, and realizes the precise timing control of each hardware module. The functional hardware layer realizes guided wave excitation and guided wave acquisition. The required guided wave excitation signal is generated according to the control signal of the hardware control layer, and the guided wave sensing signal is acquired according to the set acquisition parameters.

System Hardware Design

According to the architecture design of the system, the hardware of the system is divided into five modules to realize miniaturization design, including guided wave module, control and processing module, image interaction module, power module and interface module, as shown in Fig. 2.

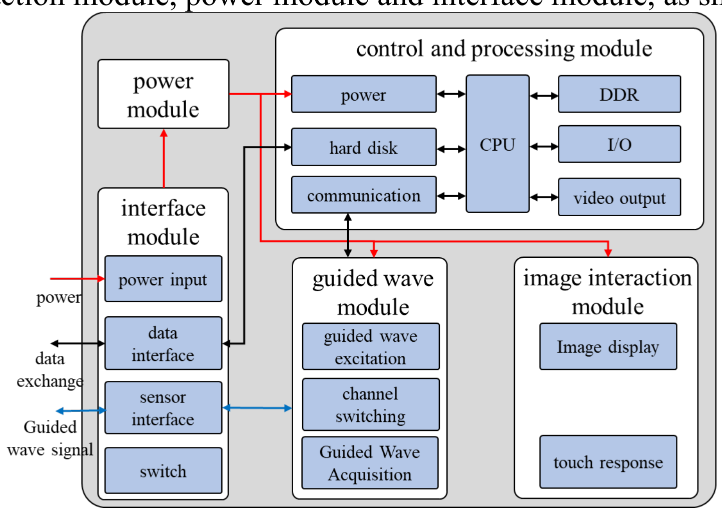

Fig. 2 system hardware architecture

The guided wave module is the operation platform of task working layer, hardware control layer and functional hardware layer. It can realize guided wave excitation signal output, channel switching and guided wave data acquisition, and upload the monitoring signal to the control and processing module through Ethernet communication. Guided wave module takes embedded microprocessor as the core, including communication unit, guided wave signal acquisition unit, guided wave excitation unit, channel switching unit and storage unit. Small volume electronic components and high-density component layout are selected to realize the miniaturization design of the waveguide module, with a volume of only $140 \times 70 \times 38 mm^3$, the mass is less than 400g. The finally designed guided wave module supports 32 piezoelectric sensors. The maximum excitation voltage amplitude can reach 140Vpp and the maximum sampling rate can reach 60MS/s.

The control and processing module is the operation platform of the system application layer, which controls the start and stop of the guided wave task, and realizes the monitoring signal storage and damage diagnosis. This module is based on the industrial embedded single board computer, adopts the advanced hardware integration method, takes the CPU as the core, integrates all the necessary components of the computer on a circuit board, and designs many I/O interfaces to meet the needs of the industrial field. It has the advantages of high performance, small volume, low

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power consumption, etc. the maximum main frequency is 2.5GHz, supports 8G of memory, and the volume after adding the heat sink is $145\times102\times28mm^3$, the system is powered by +12V single power supply, static power consumption no more than 6W, maximum no more than 15W, and its data processing capacity can meet the operation requirements of damage diagnosis algorithm, such as path imaging and delay accumulation imaging algorithm.

The image interaction module is the human-computer interaction interface platform. It’s main function is to display the monitoring results graphically and respond to the touch to realize the visual operation of the system. The module is realized by the touch screen group after the integration of the touch screen and the image display screen. The display screen is responsible for the image display, and the touch screen is responsible for the touch response. The final selected touch screen group is $247\times166mm^2$, display area is $217\times136mm^2$, the display interface is VGA, and the display resolution is 1280×800dpi, what’s more, the power consumption is less than 4.56W.

The final realized system is shown in Fig. 3, and the technical indicators are shown in Table 1.

Fig.3 compact and portable piezoelectric guided wave structure health monitoring system

Table 1 system technical indicators

category	technical indicators	specification
hardware	excitation voltage	>140 Vpp
	bandwidth	10kHz~700kHz
	sampling Rate	60MS/s
	number of channels	32
computing performance	main frequency	2.5 GHz
	memory	8 GB
volume and weight	volume	$273\times184\times59mm^3$
	weight	<3kg

System Software Design

User application software includes two main functions. (1) Acquisition function of guided wave monitoring signal: it is required to control the system hardware and set parameters to obtain the guided wave monitoring signal stably and reliably. It also includes sub functions such as signal display, display storage, signal analysis and signal export. (2) Alarm and location function of structural damage: responsible for running the damage diagnosis algorithm to give the diagnosis results, including such sub functions as damage alarm and damage location. In addition, the user application software also includes a self-test function for communication detection, and a one touch shutdown function for realizing quick shutdown.

The user application software is implemented based on the labview2017 programming platform. The main interface of the designed software is shown in Fig. 4, including eight function buttons

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and communication connection status indicators which greatly improves the monitoring efficiency of the system.

Fig.4 main interface of user application software

Experimental Verification

The damage monitoring effect of the designed portable system is verified by the simulated damage arranged in the area of the piezoelectric smart sandwich integrated with carbon fiber composites [14]. The monitoring structure selects a carbon fiber composite material specimen of 1000mm×1000mm×3mm. As shown in Fig. 5, two piezoelectric smart interlayers are arranged on the specimen to form two monitoring areas: area 1, area 2, The piezoelectric smart interlayers are integrated on the surface of the structure through the surface-mounted co-curing process, and has the characteristics of oil-proof, waterproof and moisture-proof.

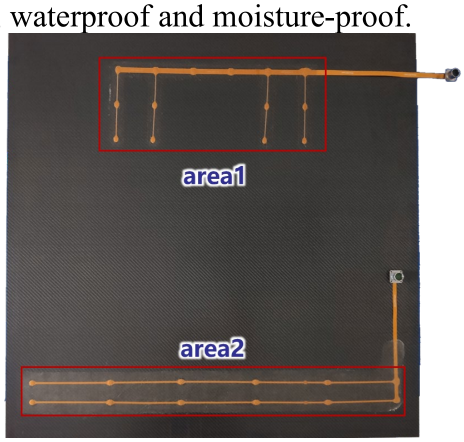

Fig. 5 carbon fiber composite material

The experimental setup is shown in Fig. 6, including the carbon fiber composite material structure, the signal cable, and compact and portable piezoelectric guided wave structure health monitoring system.

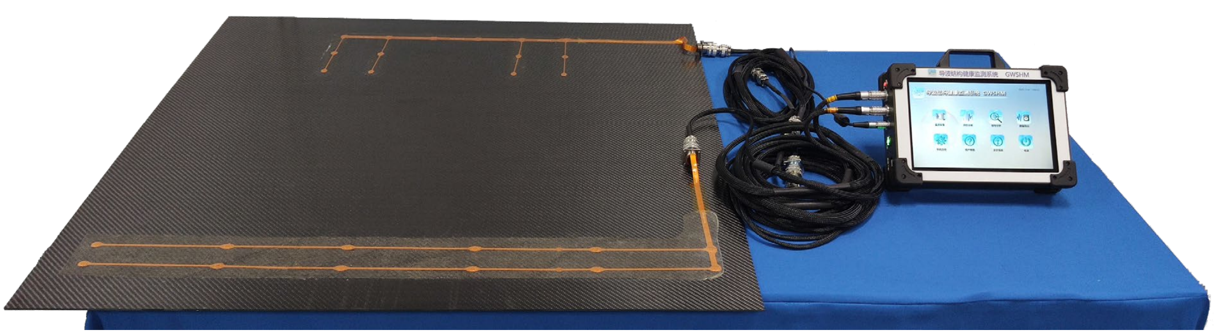

Fig. 6 experimental setup

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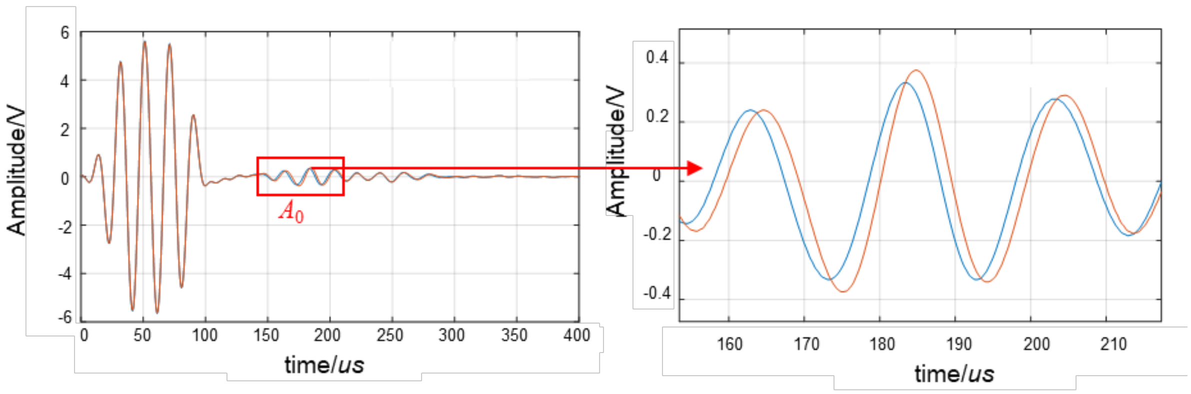
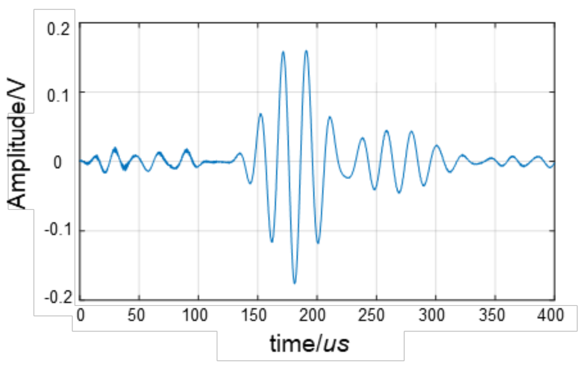
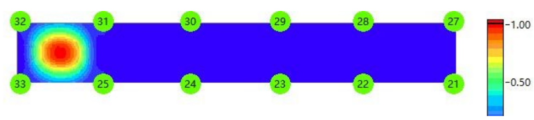
First select the guided wave monitoring frequency as 50kHz, the excitation voltage as 140Vpp, the sampling rate as 10MS/s, and the average of 100 times as the acquisition parameters.

In this experiment, the health signal of the current structure is first acquired as the benchmark, and then the damage of the structure is simulated by arranging the simulated damage - wave absorbing adhesive, which is an acoustic damping material, and will change the propagation characteristics of the guided wave. The simulated damage traverses each monitoring sub region, and gives the typical signal, damage difference signal, and damage imaging cloud image in Fig. 7.



(a) typical signal





(b) damage difference signal (c) damage imaging cloud image

Fig. 7 experimental result

The amplitude of the difference signal can reach more than 150mV, which can clearly reflect the impact of the damage on the guided wave propagation.

The statistical table of damage location error is shown in Table 2. The damage location error of 5 areas is less than 5mm.

Table 2 statistics of damage location error

Monitoring location	Actual damage coordinates (mm, mm	Damage location coordinates mm, mm	error
1	82 24	82 23	1mm
2	249 23	251 23	2mm
3	424 23	423 22	1mm
4	594 23	598 19	4mm
5	766 23	765 22	1mm

According to the damage monitoring results of the carbon fiber composite, the system designed in this paper can accurately identify the damage of the composite structure and give the accurate damage location, which ensures the damage monitoring effect while achieving portability.

Summary

In this paper, a compact and portable structural health monitoring system for piezoelectric guided wave is designed and implemented for the ground rapid monitoring application of aircraft structure. A simple and fast user monitoring software is developed for this system. The size of the system is only 273×184×59mm^3, and the mass is less than 3kg, supports 32 sensor channels, the excitation voltage amplitude can reach 140Vpp, and the maximum sampling rate can reach 60MS/s. What's more, the system integrates touch screen and data processing module, and the embedded diagnosis algorithm supports real-time damage diagnosis, which can accurately monitor the damage of the carbon fiber composite structure. It is a high-performance portable system suitable for rapid monitoring applications of multiple parts of the aircraft.

Acknowledgment

This work is sponsored by the National Natural Science Foundation of China (Nos. 51921003, and 51975292), the Outstanding Youth Foundation of Jiangsu Province of China (No. BK20211519).

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