Development of a New Bio-Inspired Mobile Sensing System

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ABSTRACT

Sensing system (such as fiber, strain gauge, piezoelectric wafer) is a core component for a health monitoring system. Generally, sensors in any sensing system that transmit and /or receive diagnostic information are often adhered on the surface of structure, or embedded into the structure. Therefore, once established, the sensing system can not be changed. Both installation methods have the following problems: 1) the location of sensors are predefined and fixed, which means that lots of sensors are required to monitoring the whole structure area and results in the increase of structural weight and the system cost. 2) The life of sensors bonded on or embedded into the structure would be shorter than that of the structure, which would lead to the loss of monitoring capability in the service life. 3) The structural integrity would be affected, especially in the service process.

To overcome above shortcomings, this study focuses on the guided wave structural health monitoring to develop a new concept of mobile flexible sensing system based on piezoelectric wafer. This new idea is inspired by the nature species, such as that the gecko can randomly fixed on and flexibly move in a vertical wall on the basis of the negative pressure. The presented mobile sensing system is fitted for the inspection or monitoring of large structures, especially, a large aircraft structure such as wing, fuselage, and tailplane. This study discusses three key issues on designing mobile sensing system. The first issue involves with how to design a structure with vacuum absorbability or negative pressure. The second issue is how to make the piezoelectric wafer couple with the hot structure to excite the uniform diagnostic wave. The last issue is concerned with how to make the device to flexibly move. The preliminary experimental results show that the proposed mobile sensing system is feasible in an Aluminium plate. The contribution of this study is that the mobile sensing system can flexibly move on the structural surface anytime, and fixed at the desired location anywhere, meanwhile, the proposed mobile structural health monitoring system can be used not only in the flight process, but also in the ground maintenance stage to improve inspection efficiency.

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INTRODUCTION

Structural health monitoring (SHM) is a collective term for cutting-edge technologies using permanently attached sensor networks to enable the continuous inspection of the reliability of structures [1]. In the past two decades, SHM has received increasing interest in the academic and industrial community [2] and significant advances have been made towards the development of sensors, data collect system and damage algorithms that are specific for different fields, such as civil infrastructure, aerospace system. Generally speaking, an ideal SHM system should include the following four components: a sensing system, a data diagnosis and prognosis engine, information transmission network and a decision support system[3]. Sensing system (such as fiber, strain gauge, and piezoelectric wafer) is an essential core component of SHM system. This study focuses on the sensing system.

A number of SHM solutions have been already presented on laboratory scale, and even partially implemented in real aircraft [4]. The guided wave-based SHM (GWSHM) is widely acknowledged as one of the most encouraging ways of quantitative identification of damage in aircraft structures, especially in composite structures. In principle, GWSHM enables a testing of large area plate-like structures (fuselage, wing, and blade) on demand without time consuming scanning, but with a small attenuation and interact with defects. The damage detection based on guided wave can be realized in a way of either pulse-echo method or pitch-catch method. The sensing system of GWSHM system is used to excite and receive the guided wave (propagating in the plate-like structure called as lamb wave). Due to the limitation of lamb wave attenuation and detection precision, the sensing system is required to cover the structure as large as possible. There are different techniques for GWSHM, such as single-transmitter multiple-receiver sensor network and multiple-transmitter multiple-receiver sensor network. These sensors are often permanently adhered on the surface of structure, or embedded into the structure. Therefore, once established, the sensing system is expected to work as long as the structure service life. Unfortunately, the life of a sensing system are often much shorter than that of the structure due to lots of factors, such as the sensor performance degradation, the external impact, the ambient temperature, the humidity, and the corrosive liquid or atmosphere. The question that is in front of us is: to avoid above problem, is there an alternative solution to flexible sensors installation instead of permanent installation? To answer this question, this study draws lessons from the nature species, such as that the gecko can randomly fixed on and flexibly move in a vertical wall on the basis of the negative pressure, and develop a new concept of mobile flexible sensing system based on piezoelectric wafer.

The remainder of this paper contains four sections. Section 2 discusses and analyzes the current sensing system of GWSHM; In Section 3, some key issues on how to design a mobile sensing system are discussed. Moreover, some preliminary experimental study is presented in Section 4. Finally, the last section concludes the paper.

ANALYSIS OF THE SENSING SYSTEM OF GWSHM SYSTEM

This section discusses and describes the potential problems of the current sensing system of GWSHM system. Guided waves can be actively excited and collected by a variety of means, roughly grouped under six categorizes and compared with other NDE transducers listed in Table 1. The merits and shortcomings of these sensors have been analyzed in the Ref. [5].

Table 1. *Comparison of Lamb wave transducers with other NDE transducers*.

	Sensor	Applications/features	Install style
	Ultrasonic probe	Distance and thickness detection, exact, time-consume	Contact, fluid coupled
	Laser interferometer	Displacement measurement, high precision, expensive	Contactless
SHM	Piezoceramics	Active, high-frequency response, low driving force, cheap	Attaching, embedding
	Piezoelectric paint and PVDF	Easy application for non-flat shapes, cheap	Attaching, embedding
	Optical fiber	Line sensing, high precision, expensive	Attaching, embedding
	Accelerometer	Acceleration detection, high-frequency response	Attaching,
	Magnetic sensor	Crack with magnetic leakage, soft magnetic piece, magnetic field	Contact, attaching
NDE	AE sensor	Changes in physical property only, passive sensor	Attaching, embedding
	Eddy-current transducer	Electromagnetic impedance detection, complicated, expensive	Attaching
	Strain gauge	Low-frequency response, cheap	Attaching
	Shape memory alloy	Active sensor, large force, low-frequency response	Attaching, embedding

This study focuses on the piezoelectric element due to its excellent performance in lamb wave generation and acquisition. Meanwhile, this kind of sensors is particularly suitable for integration into a host structure as an in-situ actuator/sensor, for its neglectable mass/volume, easy integration, wide frequency responses, low power consumption and acoustic impedance, as well as low cost. In additionally, the electrical impedance of piezoelectric elements can be directly related to the mechanical impedance of a host structural component where the piezoelectric elements are attached. It has been proved that piezoelectric sensor installation on the host structure is an important step that may have significant influence on the success of the health monitoring process [6]. A common way is to bond the piezoelectric sensors on the structure surface using an appropriate adhesive. However, this installation method is just limited in the laboratory experiments. The bond layer, as a media bridge between sensors and structures, affects the lamb wave propagations. The service life of this kind of bonding sensing system depends on the durability and survivability of bond layer. Therefore, Lin and Chang [7] described the Stanford-Multi-Actuator-Receiver-Transduction (SMART) Layer concept to embed the piezoelectric sensors into the composite structures or bond on the structure surface. This new concept involved the use of printed circuit technology to produce a thin flexible, dielectric film with an array of networked piezoceramic actuators/sensors. Although, it was shown that the layer does not significantly degrade the mechanical behavior of the composite, the end-users and the structure manufacturers don't really put their mind at ease, they may ask that whether this special structure is safe, especially for aircraft structures under a complex load and critical environment. This is the same with that we will always feel uncomfortable when something foreign is embedded into our bodies. No matter bonding or embedding sensors, both installation methods have the following concerns: 1) the location of sensors are predefined and fixed, which means that lots of sensors are required to monitoring the whole structure area and results in the increase of structural weight and the system cost. 2) The life of sensors bonded on or embedded into the structure might be shorter than that of the structure, which would lead to the loss of monitoring capability in the service life. 3) The structural integrity would be affected, especially in the service process.

Many researchers have investigated the durability and survivability of sensors in different aspects. Wang et al.(2003) [8] have studied the piezoelectric ceramics stress corrosion cracking in water, methanol, and formamide at a constant load test. Park et al. (2006) [9] studied the degradation or failure of Piezoelectric Wafer Active Sensors (PWAS) and how the bond layer may affect the impedance readings and the Lamb-wave propagations. Qing et al. (2006, 2008) determine the survivability and functionality of a lead zirconate titanate (PZT) SMART tape at cryogenic temperature [10, 11]. To a certain extent, it can be concluded that these uncertain factors limit the real world application of GWSHM. Therefore, we propose a new concept of installing sensors to excite and receive guided waves in a mobile and flexible way. The proposed mobile sensing system can provide an alternative solution for the combined SHM strategy of guided wave and electromechanical impedance method [12]. This new idea is inspired by the nature species, such as that the gecko can randomly fixed on and flexibly move in a vertical wall on the basis of the negative pressure. The presented mobile sensing system is fitted for the inspection or monitoring of large structures, especially, a large aircraft structure such as wing, fuselage, and tailplane. The contribution of this study is that the mobile sensing system can flexibly move on the structural surface anytime, and fixed at the desired location anywhere, and then characterizing and optimizing notions of service-on-demand provided by an adaptive sensor network in a dynamic environment can be realized in a way of the mobile sensors. Therefore, the proposed mobile structural health monitoring system can be used not only in the flight process, but also in the ground maintenance stage to improve inspection efficiency.

SENSOR DEVICE WITH ABSORBABILITY

Different from the permanently attached sensor system in the current SHM field, the proposed mobile sensing system is composed of a series of sensors that can be not only easily installed on the structure surface but also be easily removed. To realize this novel installation, we design a new device that can contain one sensor or sensor array, and also can adsorb on the surface of the monitored structure. But how make the device adsorb the structure in a flexible and adjustable way? We are inspired by the nature species, such as that the gecko can randomly fixed on and flexibly move in a vertical wall on the basis of the negative pressure. Therefore, we design a novel device to absorb on the surface according to the principle of negative pressure similar to the gecko suck. The whole structure of the proposed device is illustrated in Fig 1. The device is composed of the following components: the hard component denoted by 1, the deformable component denoted by 2, the sensor by 3, the sensor container by 4, the spring by 5, the power cable by 6, the gas nozzle by 7, the movable hollow shaft by 8, the sealing ring by 9, the sealing sleeve by 14, the seal slider by 15. The sensor container can be equipped with at least one sensor to form different sensor arrays. The installation process of the mobile sensor system is described as follows: When the device is pushed on the surface without covering the gas nozzle, the space of deformable component become smaller, the air is escaped through the hollow hole of the shaft, and the spring is compressed. Then the end of the hollow shaft is sealed by the gas nozzle, at this time the space of the deformable component get larger to form a negative pressure. If the negative pressure is larger than the spring pressure, then the device is installed on the structure surface. In this balance state, the compression load produced by the spring is applied on the sensors in the sensor container to form a work mode of dry couplant. It should be noted that the proposed device can be manufactured through the reconfiguration of off-the-shelf suck shown in Fig 2.

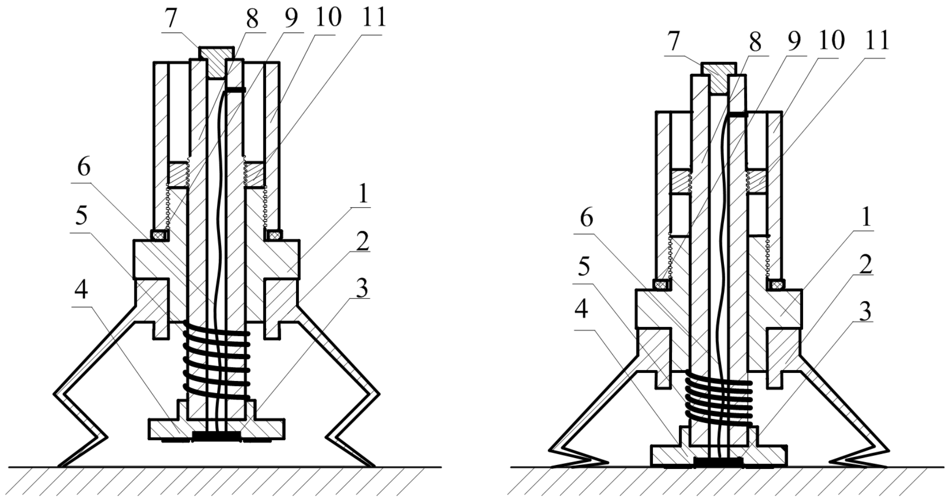


Figure 1.a (left), The structure without absorbability; Figure 1.b (right), The structure with absorbability.

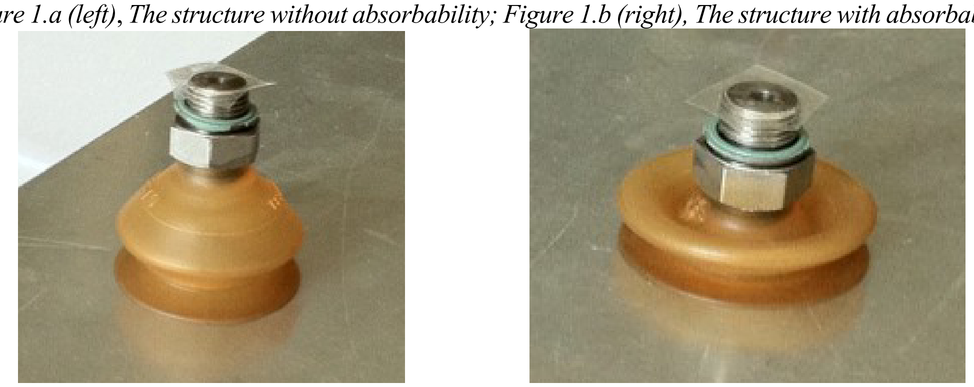


Figure 2.a (left), The off-the-shelf suck; Figure 2.b (right), The off-the-shelf suck with absorbability.

As stated above, when the sensor system can be installed at anytime and anywhere, the couplant is not necessary. Therefore, the piezoelectric elements react with the monitored structure in a way of dry couplant. To realize the dry couplant of sensors, the spring is used to apply a force onto the sensor. The compress force on the sensor is adjusted through the length of the compressed spring. To illustrate the feasibility of the proposed dry couplant, some experiments are conducted to reveal the relationship between the signal amplitude and the compress force, the relationship between the impedance and the compressed force.

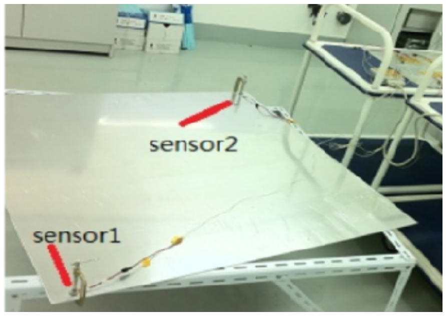
PRELIMINARY EXPERIMENTS AND RESULT ANALYSIS

To verify the effectiveness of the proposed mobile sensing system, some experiments are carried on in a way of dry couplant between sensors and the structures.

(1) Both sensors are dry coupled.

The experimental system is illustrated in Fig.3.a. The 10 burst, 180 kHz signal was generated by sensor 1 and received by sensor 2. The first received signal is in Fig.3. b. It can be seen from that the signal can be received. The first S_0 waves should arrive at 0.269 ms according to dispersion curve. There should be no signal before S_0 waves;

however there is unknown signal in Fig.3.b. The signal was actuated again under the same condition.



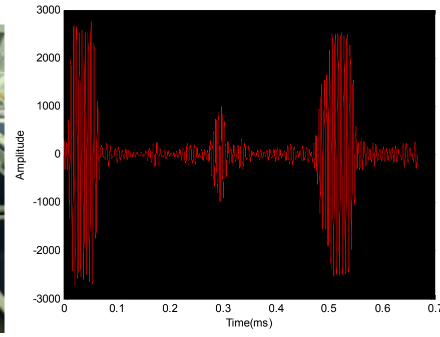
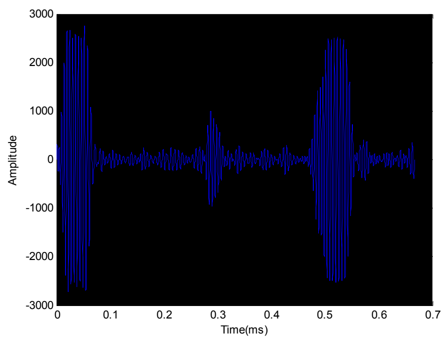


Figure 3.a (left) The photo of on test system; Figure 3.b (right), Signal recoded at first time.

The second signal is in Fig. 4.a. The difference between the first and the second signal is in Fig. 4.b.



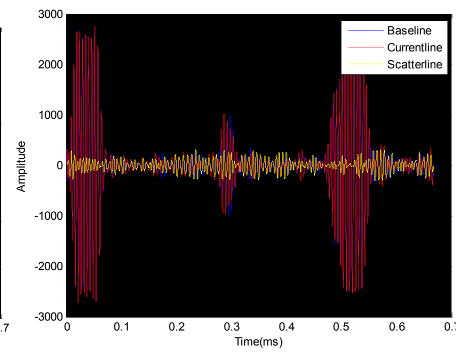
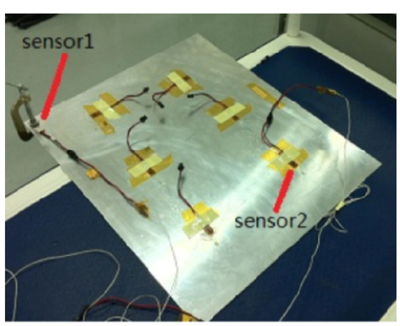


Figure 4.a (left) Signal recored at second time; Figure 4.b (right), Comparison between two signals.

The difference of the received signal under the same condition should be quite small; however, the difference was obvious in Fig. 4.b. Therefore, the signal was unstable with dry coupling.

(2) One sensor dry coupled and another bonded on aluminum plate as shown in Fig.5.a.

The 10 burst, 200 kHz signal was generated by sensor 1 and received by sensor 2. The received signal is in Fig. 5.b. The first S_0 waves should arrive at 0.12ms according to dispersion curve. The received signal agreed with the dispersion curve.



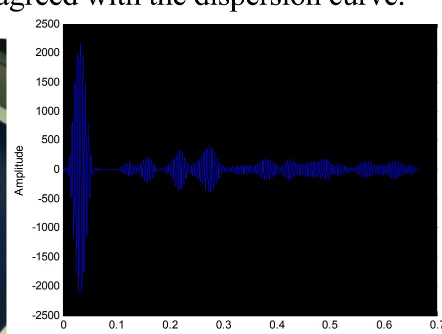


Figure 5.a (left) The photo of second cases; Figure 5.b (right), Signal recoded at first time.

The 10 burst, 200 kHz signal was generated by sensor 2 and received by sensor 1. The received signal is in Fig. 6, the difference betwee the first and the second signal is showed in Fig. 6 (b).

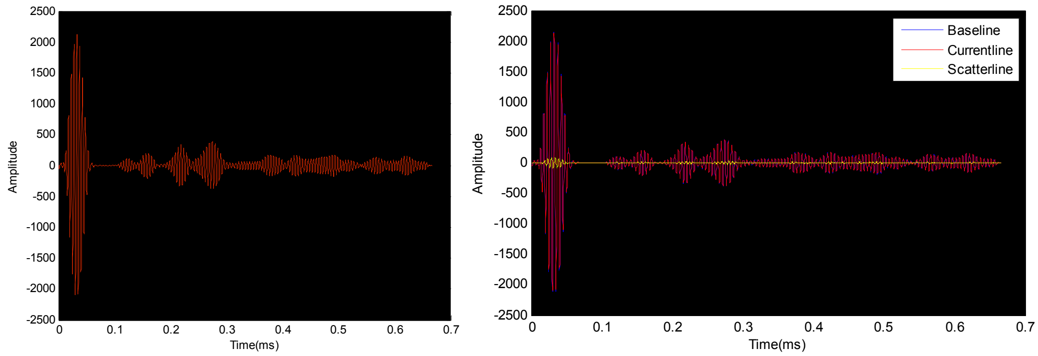


Figure 6.a (left) Signal recored at second time; Figure 6.b (right), Comparison between two signals.

It can be seen that the signal was quite stable. The signal was unstable when both sensors were dry coupled, which may be due to inconsistence of compressing forces and need further investigation.

(3) Impedance of sensor under a different compress force.

The curve of frequency and impedance under different compression force is illustrated in Fig. 7. It can be seen that the difference length of the spring, namely, the different load, has obvious impact on the impedance of the sensor. However, it should be further studied to understand the relationship among impedance, frequency, and load.

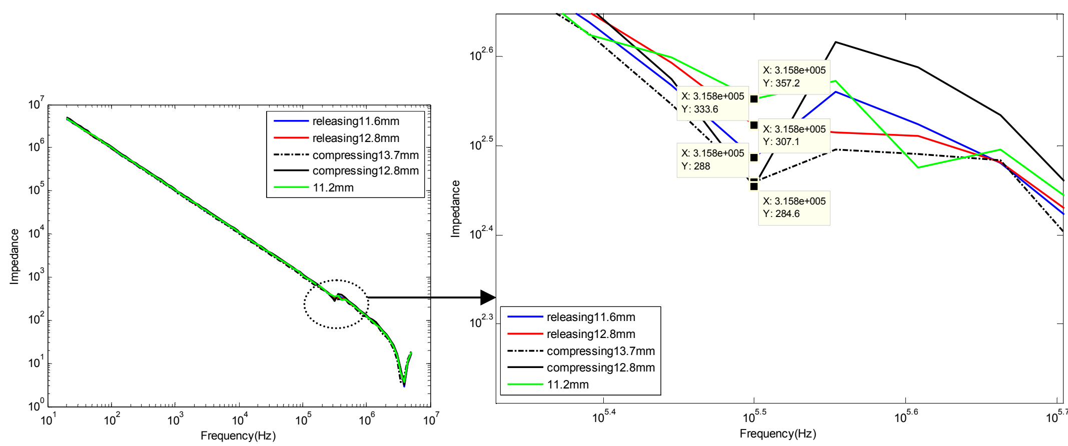


Figure 7. The curve of frequency and impedance under different compression force.

CONCLUSIONS

This study focuses on the guided wave structural health monitoring to develop a new concept of mobile flexible sensing system based on piezoelectric wafer. This new idea is inspired by the nature species, such as that the gecko can randomly fixed on and flexibly move in a vertical wall on the basis of the negative pressure. The presented mobile sensing system is fitted for the inspection or monitoring of large structures, especially, a large aircraft structure such as wing, fuselage, and tailplane. This study discusses three key issues on designing mobile sensing system. The first issue involves with how to design a structure with vacuum absorbability or negative pressure. The second issue is how to make the piezoelectric wafer couple with the hot structure to excite the uniform diagnostic wave. The preliminary experimental results show that the proposed mobile sensing system is feasible in an Aluminium plate. The contribution of this study is that the mobile sensing system can flexibly move on the structural surface anytime, and fixed at the desired location anywhere, meanwhile, the proposed mobile structural health monitoring system can be used not only in the flight process, but also in the ground maintenance stage to improve inspection efficiency.

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