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A self-healing system for a new type fiber optic smart structure based on fuzzy control algorithm

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A self-healing system for fiber optic smart structure based on fuzzy control algorithm is presented. The system consists of light source, the liquid-core fiber optic smart structure, photoelectric detection circuit, A/D convertor, relay and micro controller. Light source contains communication light and repair light. The smart structure is made up of the composite embedded with the homemade liquid-core fiber. It plays a vital role in the system. The liquid is mix of oligomer, reactive diluent, photo initiator and auxiliary. Photoelectric detection circuit is used to convert the light signal into electrical signal. Micro-controller is responsible for collecting and processing photoelectric signal. The system software is designed using fuzzy inference algorithm to derive electromagnetic relay to control the switch between the communication light and repair light. Experiments are carried out by destroying the composite structures. The results show that the system is stable and reliable. It realizes the aim of damage self-repairing for composites.

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Keywords: Micro-controller, Optical fiber sensor, Fuzzy algorithm, Smart structure, Self-healing

1. Introduction

The structure health monitoring for composites has long been a hot research topic [1], because composites health has a high impact, especially in the aerospace business. Composites have been widely used in aircraft. It is difficult to avoid being suffered from all kinds of shock for an working aircraft such as a wing plane crashed with flying birds, gunshots, the influences of the pulley in the launching or taking-off process on the runway and so on. A small injury may bring a fatal disaster. So it is very necessary to locate the damage position and repair the damage. Composites damage location and judgment of damage degree have become the research hot topic in recent years. Of course, it also made a lot of scientific research achievements [2,3]. The function of smart structure should contain the content of the two parts, one is self-diagnose and the other is self-repair. Optical fiber self-diagnosis application in intelligent composites had been more in-depth research and it achieved remarkable results [4]. Currently the sensor applied in the intelligent monitoring system for composite materials at most is a Fiber Bragg grating (FBG) sensor. But FBG as the sensing element could only monitor the health status of composite material. While damage occurred, it is impossible to realize self-repair for materials, and when the material is damaged, fiber will also be destroyed. That is to say, sensors will lose the function of communication and self-diagnosis.

In this paper, the self-repair system is designed based on a built-capsule bionic self-healing mechanism. The bionic self-repair mechanism is embedding the hollow capsules into composites. The hollow capsules were injected with repair agent. Once composites cracked under the action of external force, part of the capsule is broken, and adhesive liquid flow out then deep into crack. The adhesive can make composites crack be repaired. The concept of self-healing for liquid-core fiber was put forward based on the embedded liquid-core fibers [4]. The fibers released the repair materials and crack cured. The work on the research of liquid-core optical fiber was conducted early abroad. In 1987, Germany LUMA TEC successfully developed the first practical liquid core optical fiber in the world [5]. But the loss of the developed is larger. At the time of the research condition, it was not very realistic for the liquid core to be used for communication. While the silica optical fiber is in ferment, the production technology of optical fiber improved soon. The loss of produced quartz optical fiber is close to the theoretical loss value.

In recently years, compared to the solid optical fiber, the consumption of liquid-core optical fiber during a specific waveband is smaller. It is critical for the light transmission. There are many varieties of fibers, such as glass fiber, quartz fiber, plastic optical fiber, liquid-core optical fiber [6]. Researches and applications of quartz fiber and glass fiber in the field of communication have been very extensive [7]. They have better information security, and large information storage capacity to prevent signal interference, light weight and other characteristics. While comparing to the liquid-core optical fiber, anti-bending performance is not very well, the using toughness is not very high, and it has a low radiation resistance [8]. Plastic optical fiber not only has the low cost, toughness, resistance to bending good performance characteristics, but also has advantages of anti-impact, easy reproduction, coupling and simple. Yet the translucent of material is not well [9]. It is not conducive to the transmission of the signal as the large loss. Liquid optical waveguide has the different particular structure with the ordinary optical fiber. It has a number of unique characteristics: a large core diameter, high spectral transmission quality, scope broader spectrum transmission, the numerical aperture and long life features [10]. It is particularly worth mentioning that when glass or quartz fiber-optic beam is often used, the excessive bending can cause breakage of monofilament fiber and will decrease light transmission efficiency. But the problem of liquid-core optical fiber is non-existent since the liquid-core optical fiber interior is entirely made of a material composition. It is possible to prevent the gap as the light beam pass as ordinary optical fiber between the fiber wire coupling loss caused by the transmission and the large power of optical energy will not be lost [11]. With the optical fiber transmission field growing popularity, applications of fiber optic technology combining with electronics, optics, control and sensor also gradually increase [12]. Although it is not used for communication, it is successfully applied to mechanical, thermal, and electrical parameters measured as a special kind of liquid waveguide fiber. And it plays an important role in the sensor field. Liquid-core optical fiber is a new construction of light propagation medium, especially for fluorescence measurement and analysis, ray sterilization treatment of disease, criminal investigation, the UV curable liquid materials and scientific research [13, 14]. Fiber optic technology have become more popular in the medical, chemical, bridge construction, automotive, shipbuilding, aerospace and other range.

Generally the self-repair system contains the function of self-diagnostic. The liquid-core optical fiber not only has sensing function, but also has the repair function. Therefore the light source in the system includes the communication light and the repair light. While two light sources don't work simultaneously. Repair light works when the fibers are destroyed and it is detected by the micro-processor. In this paper, relay is chosen as the controlled switch element.

Based on the above, a system for a special liquid-core optical fiber is proposed in this paper. The system combines the light-curing technology, optical fiber sensing technology, photoelectric detection technique and fuzzy control technology. The designed system tries to solve the above problem and achieves some results. We choose the liquid-core optical fiber as the sensor. Relay is the key element of the system. When the smart material structure is destroyed and failure, the system will control the light source switched and the damage will be repaired in time.

2. Fuzzy control theory

Fuzzy control is a control theory rising in the 1970s [15]. The control is implemented on subjects that are difficult to establish a precise mathematical model, which is based on fuzzy reasoning, imitating people's way of thinking. It is the product of fuzzy control theory combined with the product. And it's an important part of the Intelligent Control. Fuzzy control is the exact amount of input fuzzy, then by fuzzy reasoning, and finally through a clear process to obtain the control amount to construct a nonlinear control. The control block diagram is shown in Fig. 1.

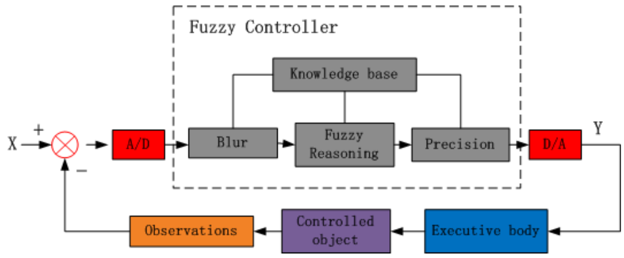

Fig. 1. The control block diagram.

As the core of fuzzy control system, the figure in the dotted line frame is composed by the fuzzy algorithm software. [16]

Step 1: According to the sampling of the output value of the system, compute system's input variables;

Step 2: The input variables are multiplied by the quantitative factor, then blurring the input variables, transforming into fuzzy quantity;

Step 3: According to the fuzzy rule, calculate the control amount (fuzzy quantity);

Step 4: the fuzzy quantity should be accurate, multiplied by the scale factor and transmitted to the executive mechanism, which controls the object controlled by the actuators. Its outstanding features are [17]:

(1) It is not required to know the precise mathematical model of controlled object to designing the control system, only need to provide empirical knowledge and operating data on-site operator.

(2) The control system has a strong robustness. It is suitable for solving nonlinear, time-varying and delay system problem.

(3) It simulates human thinking in fuzzy reasoning process, and it is able to handle complex and even the "sick" system.

3. System

3.1. Hardware

The self-healing system for fiber optic smart structure based on fuzzy control algorithm is shown in Figure 2.

The system hardware mainly consists of light source (communication light and repair light), homemade liquid-core optical sensors, photoelectric detection circuit, A/D convertor, buzzer, relay and micro processor.

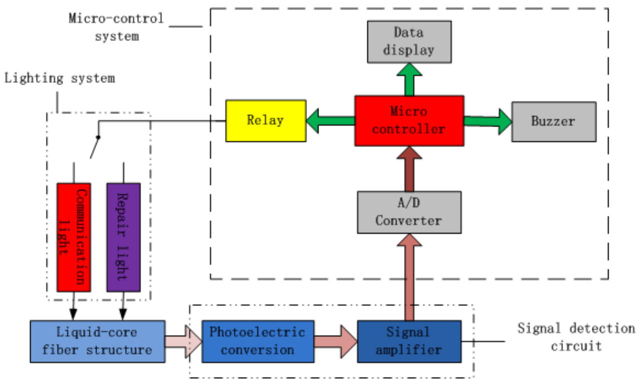

Fig. 2. The hardware system

3.1.1. Light source

There are two light sources with different wavelengths. We chose the wavelength of 632nm light as the communication light source of system. It is used for lighting liquid core optical fiber sensors and sensing composite structure health status information. And the wavelength of repair light is 320nm, which is the same as the curing agent and the repair light is mainly used for lighting curing agent. While the composite structures are destroyed, the embedded sensor is destroyed and the liquid core will flow out. The repair source will be open and light the sensor under control of the micro-controller. And the damage will be repaired.

3.1.2. Liquid-core optical fiber smart structures

Liquid-core optical fiber as the sensor is used in the designed structure. The structures are shown in Fig. 3. The liquid-core in the fiber is made up of solidification liquid. And the solidification liquid consists of a mix of oligomer, reactive diluent, photo initiator and auxiliary. Then the liquid-core fiber is embedded into composites. It is the liquid-core optical fiber smart structure.

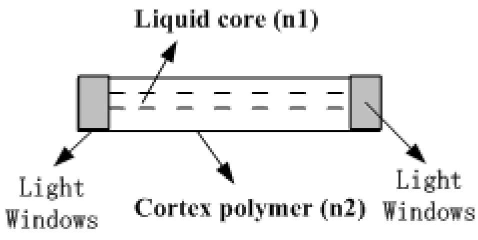

Fig. 3. Liquid-core optical fiber structures

3.1.3. Photoelectric detection circuit

The circuit contains two parts: photoelectric converter circuit and the signal amplification circuit. We chose silicon-photodiode as the photoelectric converter. It has high sensitivity. It is used for converting optical signals into electrical signals. The circuit is shown in Fig. 4.

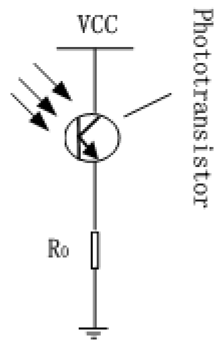

Fig. 4. The photoelectric conversion circuit diagrams

As shown in Fig. 5, the differential amplifier is AD626 [18]. And its internal connection is shown Fig. 6. In Fig. 5, there are two inputs and on output. And the C3 = C4=0.1μF.

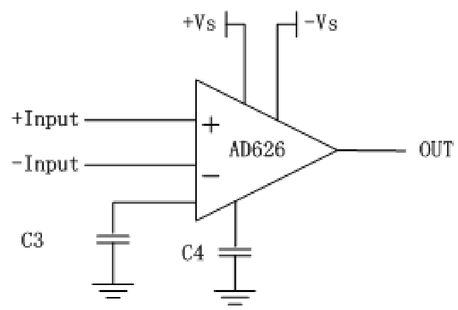

Fig. 5. Signal amplifying circuit diagram

In Fig. 6, the input signal is first applied to the double active attenuator R1~R4. It reduces the maximum common-mode voltage of the input preamplifier. The preamplifier is composed feedback level low drift operational amplifier A1. Thus the differential input voltage is six times greater than the input voltage. Minimize the common-mode error through the study of precision laser trimming for R3 and R4. So the common-mode rejection ratio of AD626 will be the minimum 10000:1 (80 db). There is RF signal in the input end because of the rectifying action. And in order to reduce the effect of rectification RF, small filter capacitor C1 and C2 will be chosen. The source impedance is set below to decrease the gain error. Meanwhile, we set the gain through setting the feedback network of the around amplifier A2. The job gain of the output buffer A2 is 2 and the front calibration gain of AD626 is 10.

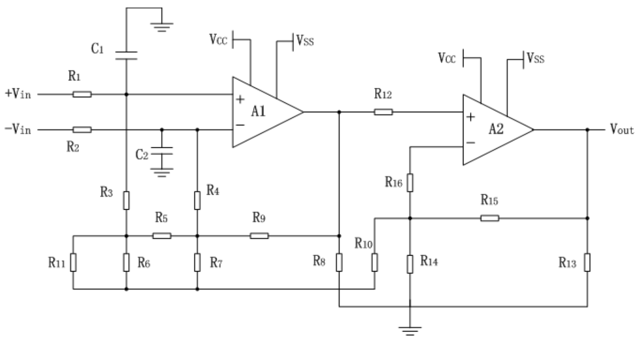

Fig. 6. AD626 Internal Connection

3.1.4. Micro-controller

The general processor AT89S51 of 8051 series is the core of the system in this paper. There are 256 bytes in user available RAM. The Block diagram of microcontroller is shown in figure 7. Its peripheral circuit mainly includes power, photoelectric detector, data display, buzzer, relay, A/D converter. Controller conducts the fuzzy operators based on the optical fiber real-time output light intensity value and the optical fiber output value of the structure in health. The operation results determine the delay whether the delay is open or closed and the opening and closing time. Thus it controls the switch between the communication light and repair light.

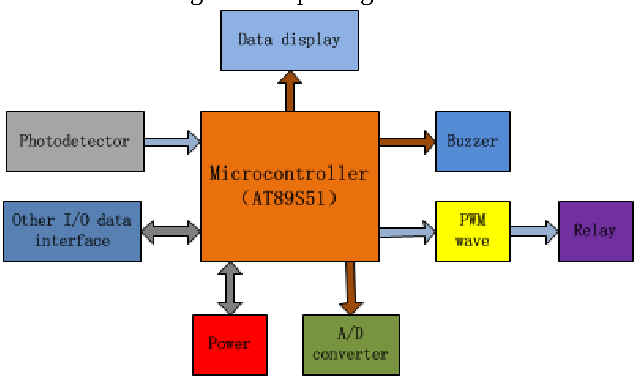

Fig. 7. The block diagram of micro controller

3.1.4.1. A/D converter

A/D converter is used to convert the amplified analog signals into the digital signal which can be recognized by the micro controller. It is a 10 bytes converter. Set the value of the amplified signals be V, according to the following formula to calculate the A/D converted value Y:

$$Y=\frac{V}{V_c}\times 2^{10} \tag{1}$$

Where, Vc = 5v is the reference voltgage.

3.1.4.2. Buzzer and digital display

Buzzer is as an alarm when the composite structures are destroyed. Digital display is used to display the measured data. Here there are three seven-segment LEDs as a monitor based on the total Yang connection and static display.

3.1.4.3. Relay

Electromagnetic relay is chosen to control the switch between the communication light and the repair light. The circuit diagram of relay is shown in Figure 8. And in figure 8, when the composite material damage occurs, relay coil will be energized. A powerful electromagnetic force will be produced in the coil. It pulls up armature, drives the reeds and makes the contact 2, 5 disconnected, 2, 4 connected. Thus the repair light is connected. It realizes that the communication light is switched to the repair light. When the repair liquid outflows and was cured under lighting of repair light, the coil will be de-energized and reset spring the reeds. It makes contact 2, 4 disconnected and 2, 5 connected. The switch from repair light to communication light is completed. So the damage will be repaired in time.

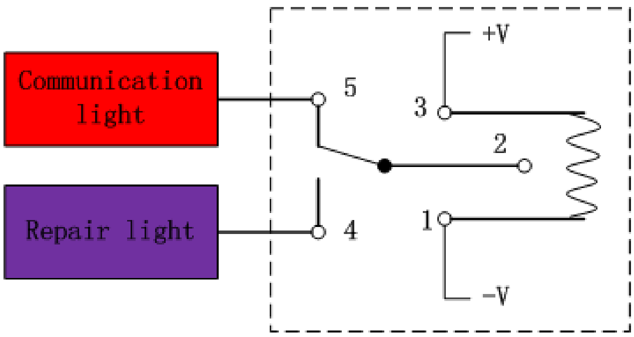

Fig. 8. Relay circuit

3.2. Software

In the system, the voltage is 0.22-0.25v after the light from optical fiber is being transformed by photoelectric conversion. And through the signal amplifier, the voltage is amplified to 2.2-2.5v. Because it is an analog signal, it must be converted into digital signal. A/D conversion module in the microcontroller is 10 bytes. According to the expression 3.1, the theoretical output light intensity is in 409-512. Then we used the fuzzy algorithm to process the data ulteriorly. The software flow chat is shown in Fig. 9.

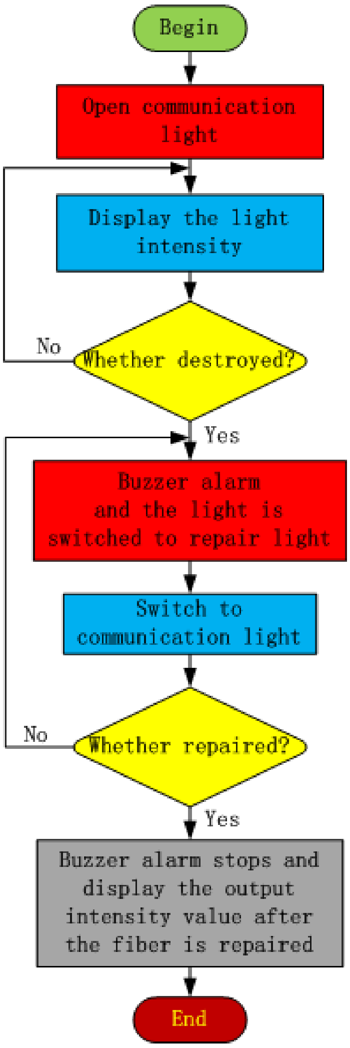

Fig. 9. Software design flow chat

There are two inputs in fuzzy arithmetic, named E and EC. E expresses the difference value between the real time measurement value of optical fiber output light intensity and fiber sensor output in health. EC represents the difference between the measuring light intensity and the intensity measured at last time. The universe of E is [-512, 0]. And the universe of EC is [0, 310]. The fuzzy subsets of E are {NB, NM, NS, ZO}. And the fuzzy subsets of EC are {PB, PM, PS, ZO}. Where, “B”, “M” and “S” represents Large, Middle and Small respectively. “N” shows negative and “P” shows positive. For example, “NL” expresses the large negative intensity difference between the real time measurement value of optical fiber output light intensity and fiber sensor output in health. “PM” shows the middle positive intensity difference between the measuring light intensity and the intensity measured at last time. “ZO” represents the almost equal intensity. The fuzzy input and transformation of E and EC are shown in table 1, 2 respectively. The maximum membership degree method is used this paper. It can be known that from table 1 and table 2, for E, “ZO” represents the intensity difference between the real time measurement value of optical fiber output light intensity and fiber sensor output in health is in [-50, 0]. “NS” represents the intensity difference is in [-300, -50]. “NM” represents the intensity difference is in [-300, -512]. “NL” represents the intensity difference is in $[-\infty,-512]$. For EC, “ZO” represents the difference between the measuring light intensity and the intensity measured at last time is in [0, 50]. “PS” represents the intensity difference is in [50, 125]. “PM” represents the intensity difference is in [125, 300]. “PL” represents the intensity difference is in $[300,+\infty]$.

Table 1. Fuzzy input and transformation of E

Fuzzy subset \ Membership \ Range	$[-\infty,-512]$	[-512,-300]	[-300,-50]	[-50,0]
NL	1	0	0	0
NM	0	1	0	0
NS	0	0	1	0
ZO	0	0	0	1

Table 2. Fuzzy input and transformation of EC

Fuzzy subset \ Membership \ Range	[0,50]	[50,125]	[125,310]	[300,+∞]
PL	1	0	0	0
PM	0	1	0	0
PS	0	0	1	0
ZO	0	0	0	1

"U" expresses the output of the fuzzy arithmetic. It determines whether the relay is open or closed and the open or closed time. The size is showed by the duty cycle of PWM. The fuzzy subsets of U are {OL, OM, OS, ZO, CS, CM, CL}. Where, "O" shows opening and "C" shows closing. For example, "OL" expresses opening the relay. That is connecting the repair light and keeping a longer time. "OM" means keeping a long time connecting. "OS" means keeping a short time connecting. "CL" expresses closing the relay. That is connecting the communication light and keeping a longer time. "CM" means keeping a long time connecting. "CS" means keeping a short time connecting. "ZO" means keeping the original state. The fuzzy decision table is shown in Table 3.

Table 3. Fuzzy decision table

EC \ U \ E	NL	NM	NS	ZO
PL	OL	CM	CS	OL
PM	CM	CM	OL	OS
PS	CS	OL	CS	OL
ZO	CL	CL	OL	ZO

4. Experimental results and discussions

Here we choose the enhanced epoxy resin composites commonly used in aircraft as the basis material. The self-designed fiber as the sensor is embedded into composites. Before the fiber sensor is embedded into composites, it is smeared with black carbon. Black carbon can absorb the ultraviolet and visible light. And it is able to provide the well bonding performance between repair fiber and composites. The experimental setup is shown in Figure 10. The micro-controller mainly contains photoelectric detection, microprocessor and relay. The lighting system contains communication light and repair light source which are controlled by the relay. The repair light is a plane light source. It can light all the fiber.

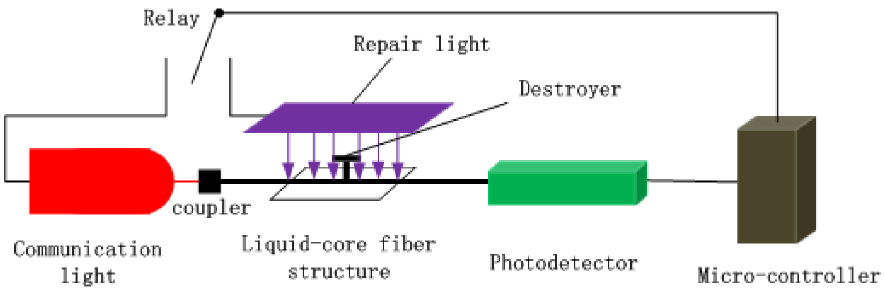

Fig. 10. Experimental set-up

The experiment process is as follows:

At first, connect the experimental setup and then loading and destroying experiments are carried on the composites. Then when there is no loader or destroyer carried on composites, a group of data could be displayed on digital tube and recorded (the first line in table 4). Finally, destroyed experiments are operated on composites and record the data meanwhile (the second line in table 4). After more than ten minutes, we record the stable data in the end.

Table 4. Experimental data

Times / Intensity	1	2	3
In health	434	425	441
After destroyed	24	37	15
After repaired	257	238	279

In the process of the experiment, the buzzer alerted when the damage occurred. From table 4, we could know that the output light intensity was normal with the data between 409 and 512 when the composites were not subjected to destroying. While the damage occurred, the intensity value decreased sharply and the fiber lost the optical communication function. The displaying data was not zero as it might be affected by other external factors. Under the work of the whole system, the light was switched to the repair light when damage occurred. The outflow liquid was cured under the lighting by the repair light and the damage fiber was repaired. The light path was connected again. The data increased. While the fiber had been destroyed, it lost the former communication capabilities. Thus, the value was smaller than in health. The research results showed that the communication and repair light can be switched in time and effectively. It realized the aim of damage self-repairing for composite structures.

5. Conclusions

This paper proposes a self-healing system for fiber optic smart structure based on fuzzy control algorithm. Damage self-healing for composite structures has been a major problem in the field of structural health monitoring. The designed system in this paper tries to solve the problem and achieved good results. The core idea comes from the bionic self-repair mechanism. The system combines the light-curing technology, optical fiber sensing technology, photoelectric detection technique and fuzzy control technology. Through controlling the opening and closing of relay, it realizes the switch between the communication light and repair light. The damage of composite structures can be repaired in time. The experimental results show that the system is stable and reliable. It has a great signification for aviation safety.

Acknowledgements

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