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Smart lightning protection skin for real-time load monitoring of composite aircraft structures under multiple impacts

Yoshiro Suzuki *, Toyoaki Suzuki, Akira Todoroki, Yoshihiro Mizutani

Tokyo Institute of Technology, Department of Mechanical Sciences and Engineering, Box I1-50, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, Japan

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ABSTRACT

We experimentally test a previously reported lightning protection sheet (LPS) sensor to detect impacts within a short collision interval. The exact loading position is achieved using a two-step method. Our sensor sheet is flexible and can easily be attached to different shaped structures. Current flows in the sensor only during loading and our quick switching system identifies the real-time *x*, *y* coordinates of the loading position. Using this method multiple impacts can be detected when the time difference between two impacts is larger than 10 ms. The position of a single impact is estimated within 16 mm. This means that detailed inspection needs to be conducted only over a circular area with a radius about a few centimeters. Our method is ideally suited for aircraft components and it reduces costs and saves time as only small specific areas require inspection using ultrasonic or electrical resistance techniques.

1. Introduction

Carbon-fiber-reinforced polymers (CFRPs) have been used as a structural material in commercial airplanes. For instance, the Boeing 787 Dreamliner and Airbus A350 XWB use 50% and 53% CFRP by weight, respectively. The reliability of real-time inspections for CFRP components has become important. Delamination damage due to an external impact is a major concern in the design of CFRP structures. In laminated CFRPs, an out-of-plane impact can cause layers to separate with significant loss of the load-carrying capability of the structures, particularly compressive strength [1–3]. Delamination can be caused by the following impact loads.

- Hailstorm during flight and bird strike during takeoff and landing.
- Tailstrike during takeoff and landing that is an event in which the rear end of an airplane hits the runway.
- Minor collision with other vehicles in airport such as passenger steps vehicle, cargo loader, refueling car, belt loader, towing tractor, scissor car, water wagon and so on.
- Tool drop and minor collision with a working bench in hangar when the aircraft is in maintenance.

Delamination is an internal damage and difficult to detect visually. Therefore ultrasonic [4], coin tapping, infrared thermography [5,6], and X-ray inspections must be performed over the entire structure; these methods are time consuming and require putting the airplane out of service. A real-time system that can detect an impact and specify the position automatically would benefit flight safety and economic efficiency. As fiber-reinforced polymer (FRP) materials have lower electrical conductivity than ordinary metal, they are easy to be damaged by heat generated by a large current from lightning strikes [7,8]. High electrical conductivity and thermal conductivity could help restrain the damage by spreading current and heat from the lightning strike. To enhance both the conductivities of the FRPs, various methods are presented for adding and dispersing tiny conductive fibers or particles (e.g., carbon nanotubes [9]) in the FRPs, however, they are unpractical at least for the commercial aircraft because of the low reliability. Present composite structures of commercial aircraft are covered with a thin metal mesh or film (usually copper or aluminum) that provides lightning protection [10–12] to the airplane as shown in Fig. 1.

In a previous study [13,14], we developed an in-situ method for detecting and locating impact loading by implementing resistive touchpad techniques [15–19] on a lightning protection shield (LPS). The LPS is an integral part of the load sensor circuitry and there has been little discussion so far on the repurposing of LPSs [20,21]. Our proposed sensor is a flexible thin sheet that can be attached to a curved surface. It requires no special equipment, uses a voltmeter and a limited number of power supplies, and can be replaced easily if broken. Notifying the aircrew in real time during flight that the airplane structure has been impacted would help

* Corresponding author. Tel./fax: +81 3 5734 3184.
E-mail address: ysuzuki@ginza.mes.titech.ac.jp (Y. Suzuki).

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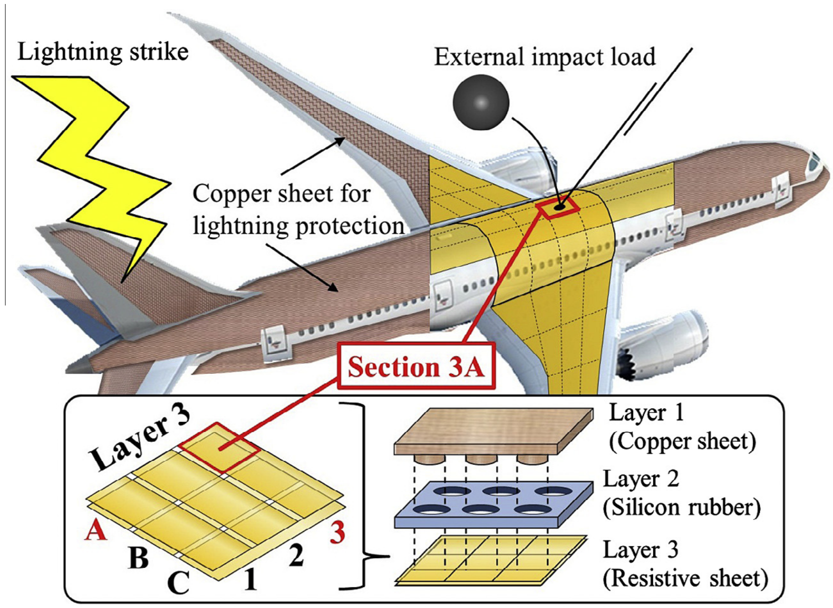

Fig. 1. Schematic of the proposed sensor sheet that has two functions: lightning protection and load sensing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prevent serious accidents. The sensor also works on ground. For instance, it can detect a minor collision with other vehicles in airport and a tool drop when the aircraft is in maintenance. Our approach only detect an impact applied to the structure and does not detect internal damage, so other methods such as ultrasonic or electrical resistance methods [20–22] are required for detailed inspection of internal damage after detecting the impact by the proposed sensor. However, as only specified areas require inspection, this reduces the total costs and total time of the inspection. In the previous study [13,14], the position of a static indentation load applied to the sensor was estimated with an average error of 9 mm. However, the sensor has not yet been experimentally tested under real-time impacts. For practical use, the sensor sheet must locate impact loading in large FRP structures within a short collision interval. The sensor must also detect several loads if there are multiple impacts within a short time range. The present study employs the sensing method for real-time identification of positions of multiple-impact loads. To identify the real-time x, y coordinates of the loading position, we use a quick switching system. The differences between the proposed sensor in this manuscript and the sensor in our previous articles [13,14] are summarized as follows.

- Real-time position estimation for a dynamic impact load applied to the sensor has not been tested in the previous study; however, it will be experimentally investigated in this manuscript (Section 4.2. Single-impact loading).
- Although the previous sensor detects only single load, the new sensor can detect multiple impact loads hitting almost simultaneously (Section 4.3. Multiple-impact loading).
- The previous sensor sheet, which is $100\,\text{mm} \times 300\,\text{mm}$ in size, estimates the load position with an average error of 9 mm. The new sensor sheet, which is $1000\,\text{mm} \times 1000\,\text{mm}$ in size, identifies the load position with an average error of 16 mm (See Section 4.2). As the new sensing system consists of a two-step estimation technique for the load position (Sections 2.2.1 and 2.2.2) and therefore hardly reduces the estimation accuracy even when the sensing area (i.e., area of an inspection object) becomes large. Conversely, the previous sensor has just one-step position estimation and generates a position error that would be proportional to the length of the sensing area.

2. Principle of position specification for impact loading

2.1. Configuration of the sensor

Fig. 1 shows the proposed sensor sheet composed of the following three layers.

- Layer 1 is a thin copper sheet, acting as both the LPS and the signal path between the load point and voltmeter. This layer has cylindrical projections that protrude downward.
- Layer 2 is a nonconductive silicone rubber sheet performing as load support and insulator between layers 1 and 3. The sheet is equipped with circular holes with diameter slightly larger than that of the cylindrical protrusion.
- Layer 3 is a circuit board consisting of resistive rectangles arranged orthogonal to each other.
- Layer 4 (not shown in Fig. 1) is a thin nonconductive layer that electrically insulates layers 1–3 from an FRP aircraft structure. The nonconductive layer prevents a lightning current from entering the FRP structure [10] and makes the sensor properly estimate position of an impact load.

2.2. Procedure for position specification

As shown in a flowchart of the proposed method (Fig. 2), the task of position estimation is divided into two steps: specification of the loaded section and estimation of the exact position in the specified section. This two-step method results in a high degree of accuracy over large areas such as those of aircraft components.

2.2.1. Step 1: Specification of a loaded section in the entire structure

Fig. 3 is a schematic of layer 3 and the switching circuit. The resistive sheets are arranged in rectangles orthogonal to each other, named 1, 2, 3,... and A, B, C,.... For example, section 3A is where rectangles 3 and A overlap. When an impact load is applied