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Identification of impact force acting on composite laminated plates using the radiated sound measured with microphones

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ABSTRACT

Foreign object impact events are serious threats to composite laminates because impact damage leads to significant degradation of the mechanical properties of the structure. Identification of the location and force history of the impact that was applied to the structure can provide useful information for assessing the structural integrity. This study proposes a method for identifying impact forces acting on CFRP (carbon fiber reinforced plastic) laminated plates on the basis of the sound radiated from the impacted structure. Identification of the impact location and force history is performed using the sound pressure measured with microphones. To devise a method for identifying the impact location from the difference in the arrival times of the sound wave detected with the microphones, the propagation path of the sound wave from the impacted point to the sensor is examined. For the identification of the force history, an experimentally constructed transfer matrix is employed to relate the force history to the corresponding sound pressure. To verify the validity of the proposed method, impact tests are conducted by using a CFRP cross-ply laminate as the specimen, and an impulse hammer as the impactor. The experimental results confirm the validity of the present method for identifying the impact location from the arrival time of the sound wave detected with the microphones. Moreover, the results of force history identification show the feasibility of identifying the force history accurately from the measured sound pressure using the experimental transfer matrix.

1. Introduction

In recent years composite materials such as CFRP and GFRP (glass fiber reinforced plastic) have been extensively applied to various structural components with the objective of weight reduction because they show excellent mechanical properties, i.e., high specific stiffness and high specific strength. On the other hand, composite structures that are manufactured by stacking unidirectional prepregs or woven fabrics are susceptible to impact damage [1]. Thus, foreign object impact events that structures may encounter during the manufacturing process, operation, or the maintenance process are threats to composite structures, because significant degradation of the mechanical properties can occur as a result of the impact-induced damage

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such as delaminations, matrix cracks, and fiber breakages. Moreover, impact damage in composite materials is critical because it is difficult to detect by visual inspection. Therefore, smart technologies for automatically monitoring structural integrity from measurement data obtained with built-in sensor networks are very attractive for ensuring the safety of composite structures and preventing catastrophic accidents. Recently, various technologies for Structural Health Monitoring (SHM) have been developed by many researchers [2].

For monitoring impact damage, the location and time history of the applied impact force are useful for diagnosing structural integrity. Thus, impact force identification has been one of the major research topics related to SHM for several decades [3,4]. In previous studies, strain gauges [5–7], accelerometers [8–12], piezoelectric sensors [13–21] and fiber-optic sensors [22–24] were extensively used to obtain measurement data for impact force identification. Although the aforementioned sensors are suitable for measuring the response of the impacted structure, the bonding/embedding of sensors could affect the mechanical properties of the structure considerably and may also lead to some difficulties in the manufacturing or maintenance processes. Hence, methods for identifying the impact force using noncontact sensors, such as microphones, have also been examined thus far.

In the studies reported by Tsuji et al. [25–28], the sound radiated from the impacted structure was measured with microphones and utilized to identify the impact force. A method for identifying the force history was devised in Ref. [25], where experimental transfer functions are used to relate the impact force to the radiated sound. Subsequently, a similar identification method was proposed by employing the relation between the impact force and the radiated sound determined on the basis of the finite element method (FEM) [26]. In Refs. [27,28], a method for identifying the impact location was additionally developed and verified experimentally by using an aluminum plate and an aluminum bar as the target and the impactor, respectively. Here, an iterative method was adopted to identify the impact location by minimizing the deviation between the sound pressure calculated from a FEM model and the sound pressure measured with the microphone. On the other hand, Canistraro and Jordan [29] devised a simple method for determining the projectile's impact location utilizing multiple microphones and the difference in the arrival times of the sound wave, by assuming that the sound waves from the impacted structure will radiate spherically from the impact location. Then, determination of the impact position of a golf ball on a canvas screen was demonstrated to develop a technology for an interactive indoor golf simulator.

A method for identifying the location and force history of an impact acting on a CFRP laminated plate utilizing the radiated sound has also been proposed by the authors in a previous study [30]. For the force history identification, an experimentally constructed transfer matrix that relates the time histories of the impact force and the corresponding sound pressure was employed. For impact location identification, the difference in the arrival times of the sound wave was utilized by considering the same sound radiation mechanism that was assumed in Ref. [29]. Referring to the studies reported by Wåhlin et al. [31], Ross and Ostiguy [32], and Troccaz et al. [33], the flexural waves induced by the impact force are crucially important sources of transient acoustic waves, in the case of plate structures. In particular, when discussing the arrival time of the sound waves, the high-frequency flexural wave is important because it generates acoustic waves by propagating through the structure much faster than the speed of sound in air. Therefore, to accurately identify the impact location using the arrival time of the sound waves, it is essential to consider the characteristics of the sound radiated from the impacted structure, instead of assuming that the sound waves radiate spherically from the impacted point.

This paper proposes a novel method for identifying an impact force acting on a CFRP laminated plate that uses the radiated sound measured with microphones. First, the characteristics of the sound radiated from an impacted plate are examined by focusing on the propagation path of the first sound wave to reach the microphone, in order to obtain the information essential for determining the arrival time of the sound wave, which will be utilized to identify the impact location. The method for identifying the impact location and the force history is then proposed. The force history is identified from the measured sound pressures with the identification method on the basis of experimental transfer matrices constructed by conducting preliminary impact tests [34]. For the verification of the validity of the proposed method, impact force identification is performed experimentally by applying an impact force to a CFRP laminated plate by using an impulse hammer. Moreover, to demonstrate the effectiveness of the proposed method, the identification is also conducted with the method previously reported in Ref. [30] for comparison.

2. Sound radiation from an impacted plate

The aim of this study is to establish a method for identifying the location and force history of an impact acting on a CFRP laminated plate by using the radiated sound measured with microphones. In this section, the propagation path of the sound wave from the impacted location to the microphone is examined, in order to estimate the time at which the first sound wave reaches the sensor. The obtained information is utilized in the next section to propose a method for identifying the impact location from the arrival time of the sound wave detected with the microphone.

2.1. Propagation path of sound wave

Fig. 1 depicts the sound radiated from a CFRP laminated plate subjected to an impact force. A Cartesian coordinate system (x, y, z) is adopted so that the $x-y$ plane coincides with the surface of the plate. The impact force $f(t)$ is assumed to act perpendicularly on the plate surface at $(x_F, y_F, 0)$, and the sound pressure $p(t)$ is measured with a microphone placed at