Measurement 122 (2018) 648–657

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Automated algorithm for impact force identification using cosine similarity searching

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ARTICLE INFO

Keywords:
Composite panel
Cosine similarity searching
Impact force identification
Inverse problem
Piezoelectric

ABSTRACT

A similarity searching technique is adopted to identify the impact force applied on a rectangular carbon fibre-epoxy honeycomb composite panel. The purpose of this study is to simultaneously identify both the location and magnitude of an unknown impact using the measured dynamic response collected by only a single piezoelectric sensor. The algorithm assumes that a set of impact forces are concurrently applied on a set of pre-defined locations. However, the magnitude of all the impact forces except one is considered to be zero. The impact force at all potential locations is then reconstructed through an l_2-norm-based regularisation via two strategies: even-determined approach and under-determined approach. In an even-determined approach, the reconstruction process is performed independently for each pair of sensor and potential impact location. However, in an under-determined approach, the captured vibration signal is the superposition of the responses of the simultaneous 'assumed' impacts at the potential locations. Using either approach, a reconstructed impact force is obtained for each potential impact location. The reconstructed impact forces at spurious locations are expected to have zero magnitude as no impact has actually occurred at these locations. However, there might be some non-zero reconstructed impact forces at spurious locations. Therefore, it is worth designing an automated algorithm capable of detecting the most probable location. Cosine similarity searching is adopted to measure the intensity of the relationship between the reconstructed forces and an impact-like signal with various scale parameters. The largest value of cosine among all reconstructed forces corresponds to the most probable impact location. The results illustrate successful identification of the impact force location and magnitude for both even-determined and under-determined approaches.

1. Introduction

Composite structures, broadly used in aerospace industry, are vulnerable to damage due to various impact loadings. As a major event in aviation, bird strikes are a substantial and inevitable safety threat to aircrafts [1]. It has been reported that bird strikes can impose more than $1.2 billion on the aviation industry for aircraft repairs and delays and cancellations of flights [2].

Common impact-induced failures in composite structures, such as de-bonding of core and skins, delamination of carbon fibre/epoxy laminate skins and core crushing in honeycomb sandwich panels demonstrate the vital need for efficient and low-cost structural health monitoring (SHM) systems. The localisation of damage by identification of impact locations and magnitude can create a speedy SHM system.

Inverse estimation of an impact force would be favourable when information as to the applied force is required but the location of the impact is unknown or inaccessible for direct measurement. Inverse algorithms take advantage of impact responses, such as acceleration or strain, which are measurable by typical sensors like accelerometers or strain gauges attached distant from the impact location. Successful application of non-contact sensors using microphone has also been reported in the literature to measure the sound waves induced by impact [3].

Comprehensive identification of an impact force is achieved by determination of both its location and magnitude (force history). Deconvolving the response signals from the transfer function of the system is the essential key for reconstructing the impact force history [4]. This approach is typically known as deconvolution. Deconvolution can be performed in both time and frequency domains. However, a review of past research up to 2005 reveals that the vast majority of inverse

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https://doi.org/10.1016/j.measurement.2018.01.016
Received 31 July 2017; Received in revised form 9 November 2017; Accepted 10 January 2018
Available online 14 March 2018

methods for impact force reconstruction have focused on the frequency domain [5], possibly because of the lower computational cost of the frequency domain compared to the time domain. A frequency domain method was first applied by Bartlett and Flannelly [6] to determine hub forces in a helicopter model. Some research into force identification in the frequency domain can be found in [7–15]. Nowadays, powerful computers have motivated researchers to work in the time domain. The physical behaviour of the system can be better sensed in the time domain [5]. A time-frequency domain method that applies the wavelet transform has also been implemented for force reconstruction [16].

Besides deconvolution methods, neural networks have also attracted much attention for impact identification [17–19]. These techniques entail a considerable amount of training, which limits their application to real large structures [20].

Inverse reconstruction problems are not straightforwardly attainable in reality. The problem stems from the ill-posed nature of the transfer function of the structure. Assume that the impact force, $f(t)$, on a structure is mapped to the impact-induced response, $r(t)$, by a linear operator, $\bar{\lambda}$, as

$$\bar{\lambda}[f(t)] = r(t) \tag{1}$$

Through a perturbation analysis, it can be shown that [5]

$$\frac{\|\Delta f(t)\|}{\|f(t)\|} \leqslant \mathrm{cond}(\bar{\lambda})\frac{\|\Delta r(t)\|}{\|r(t)\|}, \tag{2}$$

where $\mathrm{cond}(\bar{\lambda})$ is the condition number of the linear operator. This number is indicative of the magnification of error in the linear equation. As a result, any tiny perturbation in the data, $\Delta r(t)$, is multiplied by the condition number of $\bar{\lambda}$, which is usually a very large number. Therefore, the problem must be regularised to avoid a large deviation in the reconstructed force $\Delta f(t)$. It should be noted that $\bar{\lambda}$ is a convolution operator in impact force problems.

Several l_2-norm-based regularisation methods, including the Tikhonov, truncated singular value decomposition (TSVD), damped SVD, and iterative regularisation methods, have been proposed to overcome the difficulties of ill-posed problems in the time domain [21,22]. Recently, a general sparse methodology based on minimizing l_1-norm was developed to solve large-scale ill-posed inverse problems for impact force reconstruction [23,24]. The Wiener filter was also adopted for regularisation of impact force reconstruction problems in the frequency domain [25,26].

In this study, deconvolution is employed to identify the location and magnitude of impact forces exerted on a rectangular carbon fibre-epoxy honeycomb composite sandwich panel. A number of particular locations on the panel are specified as potential places for the occurrence of impact and a single piezoelectric sensor is attached on the underside of the panel to collect the vibration responses. It is assumed that impact forces are simultaneously exerted on all potential locations, but the magnitude of all forces except one is zero. The impression behind this scheme is that an impact has occurred at only one of the potential locations. The purpose is to identify the actual impact location as well as its magnitude through a least-squares problem together with regularisation. Two schemes for problem solving are considered: the even-determined approach and the under-determined approach. In the even-determined approach, the identification of impact location and time history is achieved at the same time, however, a large number of equations equal to the number of potential impact locations is required to be solved. In the under-determined approach, a two-stage procedure is adopted by first localising the impact force using a single equation and then reconstructing the impact force history through a simple deconvolution.

As a result of both schemes, a force history is reconstructed for each potential impact location. However, chances are high that non-zero reconstructed forces appear at spurious locations where no impact has actually occurred at these locations. Cosine similarity searching is utilised to find the actual impact location based on measuring the cosine of the angle between the reconstructed force vectors and an impact-like vector. It is demonstrated that the reconstructed force at the actual location is characterised by the highest similarity index. Several case studies using a panel with eight potential impact locations are investigated.

2. Inverse problem

For an impact force problem, Eq. (1) can be expressed by using a convolution operator as [27]

$$\int_0^t g(\vartheta,\varsigma,t-\tau)f(\vartheta,\tau)d\tau = r(\varsigma,t), \tag{3}$$

where $g(\vartheta,\varsigma,t-\tau)$ is the transfer function in the time domain between impact location ϑ and measurement point ς. By applying Riemann's approximation, Eq. (3) is given by

$$\sum_{i=0}^{n-1} g_{i+1}f_{n-i} = r_n, (n = 1,\ldots,p), \tag{4}$$

where $r_n (n = 1,\ldots,p)$ is the response at time $t_n = n\cdot\Delta t$, Δt is the sampling time and p is the number of samples. Eq. (4) can be expressed in matrix form as

$$GF = R, \tag{5}$$

where

$$G = \begin{bmatrix} g_1 & 0 & \ldots & \ldots & 0 \\ g_2 & g_1 & \ddots & \ddots & \vdots \\ g_3 & g_2 & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & 0 \\ g_p & g_{p-1} & \cdots & \cdots & g_1 \end{bmatrix}, F = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_p \end{bmatrix}, R = \begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ \vdots \\ r_p \end{bmatrix}. \tag{6}$$

Assuming a number of impact forces at different locations $F_i (i = 1\ldots X)$ simultaneously applied to a structure, the corresponding dynamic strain signal at a given single measurement point R is a superposition of the responses caused by each single force.

$$G^1F_1 + G^2F_2 + \ldots + G^XF_X = \sum_{i=1}^{X} G^iF_i = R \tag{7}$$

where G^i is the transfer function between the force location i and the sensor location. Eq. (7) is written in matrix-vector form as

$$[G^1 \ \ G^2 \ \ \cdots \ \ G^X]\begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_X \end{bmatrix} = [R], \tag{8}$$

where X is the number of impact locations. For a problem with one impact location, Eq. (8) represents an even-determined problem and is the same as Eq. (5). However, for a problem with more than one impact location, Eq. (8) produces an under-determined problem. For simplicity, Eq. (8) is represented by $GF = R$. The solution is then obtained using the least-squares problem as

$$\min\|GF-R\|_2^2. \tag{9}$$

Since R is practically contaminated by experimental errors and G is a matrix with a very large condition number, the problem must be regularised. Tikhonov regularisation seeks a good approximation of F by replacing Eq. (9) with a penalised least-squares problem of the form

$$\min\{\|GF-R\|_2^2 + \beta\|IF\|_2^2\} \tag{10}$$

where I is the identity matrix and $\beta \geqslant 0$ is the regularisation parameter, which can be determined by the generalised cross-validation (GCV) method [21]. The optimal regularisation parameter can also be determined as a solution of a maximisation problem [28].