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► **To cite this version:**

Liang Si, Horst Baier. An Advanced Ensemble Impact Monitoring and Identification Technique for Aerospace Composite Cantilever Structures. EWSHM - 7th European Workshop on Structural Health Monitoring, IFFSTTAR, Inria, Université de Nantes, Jul 2014, Nantes, France. hal-01022086

HAL Id: hal-01022086

<https://inria.hal.science/hal-01022086>

Submitted on 10 Jul 2014

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AN ADVANCED ENSEMBLE IMPACT MONITORING AND IDENTIFICATION TECHNIQUE FOR AEROSPACE COMPOSITE CANTILEVER STRUCTURES

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ABSTRACT

An investigation was performed to develop a real-time automatic health monitoring technique for the identification and prediction of the location and the force magnitude of foreign object impact on composite structures with distributed sensor network. In the smart ensemble impact identification (EII) technique proposed, it consists of four sequential procedures, which are the sensor signal preprocessing (SSP), the forward system modeling (FSM), the inverse model operator (IMO) and the impact positioning. Subsequently, in our experimental cases, we considered the disturbed factor – random interfering noises, and added the cantilever support condition into our experimental tests of a CFRP plate structure, meanwhile, we also used the small balls with the different materials and masses as the impactors. However under the various impact situations and external noise environment, the predictions for the accuracy of impact forces and locations using the EII technique were validated, and the evaluated errors all fell well within the satisfactory limited range, and also interpreted the EII technique that is competent to reconstruct precisely the input-force signal due to stochastic impact event and estimate the impact location effectively in complex practical environment.

KEYWORDS : *real-time, ensemble impact identification, genetic algorithm (GA), distributed sensor network, cantilever composite structure, random interfering noise*

1. INTRODUCTION

Aerospace structures can often encounter impacts from a variety of sources over their lifetime. Especially for carbon fiber composite structures, damage due to impact events may not be visible to surface inspection but still can cause significant loss of structural integrity. However, for the traditional NDT detection solution, it's so difficult for aerospace transportation vehicle to identify real-time this kind of damage on board. Therefore, an efficient technique that can automatically monitor and report the event's occurrence, the occurred location and force magnitude generated from impact event would be very helpful in maintaining the structures at reducing cost.

In recent years, there have been an extensive amount of research associated with the development of health monitoring methods including impact identification aspect for aerospace structure systems, but the most investigations [1–3] just have been taken into account their tested structure systems only under “pure external environment condition” without any interfering factor, for instance, the existing background (interfering) noises from the multiple environments of the practical aerospace engineering. However, in case that we can add external noise condition into our experimental research and utilize successfully the ensemble impact identification technique to implement efficiently and precisely positioning and force reconstruction due to random impact event, it will be very significant to solve the practical aerospace engineering problems.

Nevertheless, in our research, we proposed adding the new experimental condition of noise, and applied the novel impact identification technique we developed to establish accurate system model and

inverse model for monitoring any impact event on structure. The forward model is constructed in terms of impulse response functions (IRFs) on the basis of the relation between input and output, which can be applicable to various configurations of structures and can handle various types of impact objects. While, because it provides a simple inverse model formulations to reconstruct input force, thus the entire impact identification procedure become much simpler and faster than the traditional model-based identification technique [3–6]. In this paper, there include the two main aspects: theoretical development and experimental verification. Then, a theoretical basis was found to determine unknown impacts from sensor measurements using the ensemble impact identification (EII) technique proposed. In the sections of experimental tests and results, the novel identification technique was verified and evaluated by various experiments.

2. METHOD OF APPROACH

This impact identification approach developed by us is an advanced technique based on global sensor measurements, which can be qualified for various configurations of structures and various types of impact objects. However, it consists of four sequential procedures, which are the sensor signal preprocessing (SSP), the forward system modeling (FSM), the inverse model operator (IMO) and the impact positioning. And then they will be discussed in detail as follows.

2.1 Denoising Method

In order to denoise from original sensor signals, we adopted the mode decomposition method to eliminate the interferences (e.g. random interfering noises) and transfer smoothly the nonlinear effects from non-stationary output signals due to the weak vibration to the linear dependence; that is, discovering and extracting the effective linear relation between the input and the output from the structure system response subject to the corresponding impact, which is hidden in the nonlinear condition.

Thus, a sensor output signal $s(t)$ has to be transformed as an analytic signal $z(t)$ in time domain, which is expressed as follows,

$$z(t) = s(t) + iH[s(t)] = a(t)e^{i\theta(t)} \quad (1)$$

Where,

$$H[x(t)] = \frac{1}{\pi} \int_{t_0}^{t_1} \frac{s(u)}{t-u} du \quad (2)$$

$$a(t) = \sqrt{s^2(t) + H^2[s(t)]} \quad (3)$$

$$\theta(t) = \arctan\left(\frac{H[s(t)]}{s(t)}\right) \quad (4)$$

Where we define that $a(t)$ is an envelope function that describes the instantaneous amplitudes of the original sensor signal $s(t)$, and $\theta(t)$ is a phase function that describes the instantaneous Hilbert phase of the signal $s(t)$ versus time.

The sifting (filtering) process is then performed to decompose the related temporal signals $s(t)$ and generate the corresponding intrinsic mode functions (IMFs), meanwhile, through Hilbert transformation of each IMF component, the instantaneous frequency at any moment can be estimated, and with the instantaneous frequencies of IMFs, the segments within the frequency band can be extracted, finally, the output signals after filtering can be obtained from a combination of those IMF segments.

2.2 Forward System Model

In the procedure of establishing an accurate forward system model (FSM), there accomplish mainly three functions, which are as follows,

1) Determination of the forward system model structure; 2) Selection of the optimized model order; 3) Minimization of prediction error and generation of the optimized system parameters (a_i, b_j) .

2.2.1 Determination of System Model Structure

Consider a structure system model can be applicable to any complex structure, we defined and used the structure system model of multi-degree of freedom (MOF) by a discrete-time state-space expression.

However, the impulse response expression given by Eq. (5) can be derived from the MOF structural system model.

$$s(k) = \sum_{i=0}^k g(i)u(k-i) \quad k = 1, 2, \dots \quad (5)$$

Where,

$$g(0) = D \quad g(i) = CA^{i-1}B \quad i = 1, 2, \dots \quad (6)$$

Therefore, now we are interested in the relationship between the input force signals $u(k)$ and the output sensor signals $s(k)$, In other words, our goal is to describe $s(k)$ as a function of previous outputs and inputs, and together with noises. Thus, a set of models [7] are postulated, within which the best description of the true structure system will be searched for.

$$s(k) = [1 - A(q)]s(k) + B(q)u(k) + e(k) \quad (7)$$

Where $e(k)$ is an sequence of uncorrelated random noises. Because that $e(k)$ is an unpredicted white noise at all, thus for the impulse response representation related between input and output, it can be modeled through the following equation (8).

$$\hat{s}(k|\theta) = \sum_{i=1}^n a_i s(k-i) + \sum_{j=1}^m b_j u(k-j) \quad (8)$$

Equation (8) is called a predictor of output $s(k)$, that is, known as the forward system model.

2.2.2 GAE Assisted Model Order Selection and IRF Generator

In here, we defined a criterion of model order selection, which is to minimize the prediction error from the different outputs between the system model and the real structure system. Therefore, to select the appropriate model order, the following selection criterion is used:

- a) Start with a smallest model possible (normally the model order $n \geq 3$);
- b) Increase model order until the recursive coefficient Ω^2 is high enough and close to 1;

$$\tilde{\varepsilon}(k) = \varepsilon(k, \tilde{\theta}) = \varphi(k)^T \tilde{\theta} - s(k) \quad (9)$$

$$\Omega^2 = 1 - \frac{\sum_{k=1}^n \tilde{\varepsilon}^2(k)}{\sum_{k=1}^n s^2(k)} \quad (10)$$

Where $\tilde{\theta}$ is the optimal parameter vector.

- c) If Ω^2 is high enough and increasing model order doesn't help increasing the value of Ω^2 , select the model with the smallest order.

To minimize the prediction error between the real outputs and the modeled outputs and obtain the optimized forward outputs simulated, and further obtain the impulse response function matrix from the system parameters (a_i, b_j) calculated, we applied genetic algorithm estimation (GAE) method [8] into the calculation procedure of solving the values of (a_i, b_j) from the forward system model finalized through training the needed data rapidly.

For GA based error estimation, there are normally the five steps need to execute, which are 1) Reproduction; 2) Crossover; 3) Mutation; 4) New blood; 5) Elite. However, we have to define the entropy $H(a_n, b_m)$ shown in Eq. (11) to minimize the prediction error through fast GA training method.

$$\tilde{\theta}[a_n, b_m]_{opt} = H(a_n, b_m) \quad (11)$$

Where the entropy $H(a_n, b_m)$ is decomposed into two factors $H(a_n)$ and $H(b_m)$ shown in Eq. (12 and 13).

$$H(a_n) = - \sum_{i=1}^n P(a_n) \log P(a_n) \tag{12}$$

$$H(b_m) = - \sum_{i=1}^n P(b_m) \log P(b_m) \tag{13}$$

Finally, we can obtain the IRF matrix G_f^s (shown as Eq. (14)) needed.

$$G_f^s = \begin{bmatrix} g(0) & 0 & 0 & \Lambda & 0 \\ g(1) & g(0) & 0 & \Lambda & 0 \\ M & M & O & O & M \\ g(n-2) & g(n-3) & O & O & 0 \\ g(n-1) & g(n-2) & \Lambda & g(1) & g(0) \end{bmatrix} \tag{14}$$

2.3 Inverse Model Operator

In order to reconstruct impact force, the force signal from impact can be predicted based on the inverse model operator using the sensor data of the structure response. Then, through applying the structure system model defined and the impulse response expression (Eq. 5) described in Subsection 2.2, the inverse IR model for force reconstruction can be found and the corresponding force signal due to impact can be also calculated by this inverse procedure.

Based on the assumption of zero initial conditions, the inverse IR model can be established as follows,

$$u(k) = \sum_{i=0}^k \hat{g}(i) s(k+r-i) \quad k = 1, 2, \dots \tag{15}$$

Where the inverse impulse response function matrices are defined by,

$$\hat{g}(0) = (CA^{r-1}B)^T \quad \hat{g}(i) = \hat{C}\hat{A}^{i-1}\hat{B} \quad i = 1, 2, \dots \tag{16}$$

Finally, an impact force which is applied to a structure at the location (x,y) can be reconstructed through Equation (17) that is the matrix convolution expression of Equation (15).

$$U_{(x,y)} = \hat{G}_f^s S_i \tag{17}$$

2.4 Estimation of Impact Locations

To determine multi-position points of impacts and decrease the estimation time for both impact locations and reconstructions, an initial estimation method was adopted by the energy distribution method we defined to search and identify the sensors closest to the impact points, which is rapid and accurate to locate the impacted regions without the susceptibility from any measurement noise. While, this allows for one or multiple regions of the sensor array to be formed and isolated, and next distribute to update the accuracy locations of impact forces.

2.4.1 Extraction of Sensor Regions

By comparing the energies in the initial time windows of sensor data, the close sensor array were determined and the corresponding energies from the sensor signals can be calculated as,

$$E = \sum_{i=0}^{N-1} s_{exp}^2(i) \tag{18}$$

Where E is the energy of the each sensor interested. N is the number of data points included in the initial time window. This method provides a reliable way to isolate an impacted region made up of sensor array.

2.4.2 Locating Impact Coordinates

To updating the accurate locations of impact forces act on a structure, there exist an effective search parameter index – Time of Flight (ToF), which is an important feature parameter that represent the stress waves propagate in a structure.

Within an identified impact zone which is composed of four neighboring sensors, an unknown impact position can be obtained to minimize the area of the triangle (as Figure 1) and calculate the x and y coordinates of the triangle centroid, which is expressed in Equations (19-21).

$$L_i = C_p(\theta_i) \times \Delta T_i \quad i = 1, 2, 3 \tag{19}$$

Where L_i is the distance between unknown impact position and a sensor S_i , where we chosen three different sensors S_1, S_2, S_3 located in the interested zone, as illustrated in Fig. 1. $C_p(\theta_i)$ is the phase velocity of stress waves with the deflection angle of the propagating path from the impact to sensor S_i , where three different angles (namely $\theta_1, \theta_2, \theta_3$) for wave propagation directions were assumed. And then, ΔT_i is the Time of Flight for sensor S_i .

$$X_{imp} = \frac{1}{n} \left(\sum_{i=1}^n x_{s_i} \right) \quad n = 3 \tag{20}$$

$$Y_{imp} = \frac{1}{n} \left(\sum_{i=1}^n y_{s_i} \right) \quad n = 3 \tag{21}$$

Where x_{s_i} and y_{s_i} are the x and y coordinates for the $V_i(i = 1, 2, 3)$ vertices, respectively. The entire procedure, presented graphically in Fig. 1, can be implemented for any configuration of three sensors.

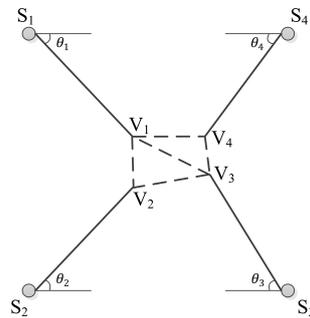


Figure 1 : Demonstration of impact positioning procedure through updating triangulation

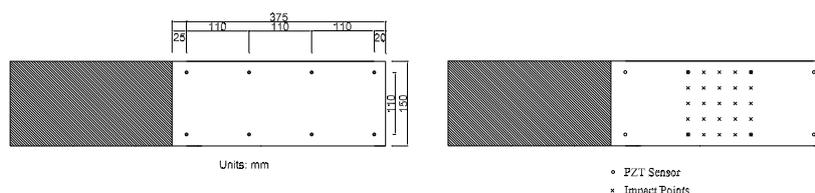
3. EXPERIMENTAL TESTS SETUP

With the theoretical development and computer implementation of the EII technique, it is necessary to setup the experiment tests for some specific practical application.

3.1 Experimental Specimen and Setup

The experimental specimen (Figure 2) was a CFRP plate with 660 by 150 by 5 mm³ sizes without any stiffener, and its layups were adopted as $[0^\circ, 90^\circ]_w/[0^\circ/90^\circ]_s/[0^\circ, 90^\circ]_w$. Meanwhile, the sensor spacing was chosen as 110 by 110 mm², as shown in Figure 2A.

An distributed piezoelectric sensor network and associated wiring were mounted on the backward surface of the CFRP panel structure, which was convenient to impact on the forward surface of the CFRP panel by an instrumented hammer and the small balls. In order to ensure good surface conduction at sensor locations, the surface of the CFRP panel was sanded and a small amount of conductive epoxy were applied.



A) Geometry of the CFRP plate and its sensor locations B) Demonstration for formation of IRF network

Figure 2 : Geometry of the CFRP plate and its sensor locations and the formation of IRF network

Next, the CFRP panel was impacted by a hand-held, instrumented hammer manufactured by PCB Piezotronics. Both the impact force signal data from the hammer and the sensor output data of the structural response were recorded using a computer data acquisition system (DAQ-cards) manufactured by National Instruments. Because that we designed the impact cases which were low-velocity impact experiments, thus we took the samples at 25kHz, and all data were in the range of ± 15 V.

We utilized the specimen to verify the adaptive forward system model established and evaluate the location estimation, and evaluate the applicability of the EII technique for the various types of impactors and under external noise condition.

Meanwhile, the CFRP panel was fixed on the one side and the other side was free, which was built as a cantilever structure shown in Figure 3.

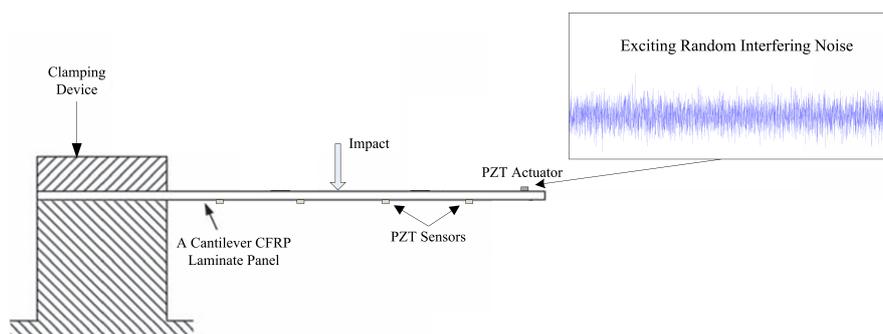


Figure 3 : Boundary conditions for the experimental configuration

3.2 Impact Tests

In order to obtain the IRFs, the impact experimental tests were performed over the specimen. For forming the network nodes of the IRFs, impact force signals and sensor signals of the structural response were recorded from the tests of the impact points on the specimen (the schematic demonstration is shown as Figure 2B), where the experimental impact points were made at evenly spaced locations, and random force magnitude was applied at each location. Once the network made up of the IRF nodes was obtained, impact experimental tests could be made on random locations.

Meantime, the verification experiments were performed through using the various small balls to verify the impact force reconstruction methodology. Because that the weights, materials and velocities of the balls determined the amplitudes and frequency contents of the force impulses, thus the wave shapes of the structural responses were dependent on the balls. We employed three different balls as impactors, which were rubber, plastic and steel balls that presented soft, medium and hard materials.

4. RESULTS

The results are illustrated to validate the efficiency of the EII technique for impact source identification. Then, the issues about the evaluation of impact locations estimations, the effect of external noise on force reconstruction and the effects of the differential impact objects on force reconstruction will be discussed in detail as follows.

4.1 Evaluation of Impact Locations Estimation

To evaluate the impact locations estimations, the estimated location error was defined in Equations (22-24), which is expressed as the distance from the calculated impact location to the actual impact location, whereas the x-direction is the length direction of the CFRP plate.

$$\Delta x = x_{cal} - x_{act} \quad (22)$$

$$\Delta y = y_{cal} - y_{act} \quad (23)$$

$$\mathbb{L}_e = \sqrt{\Delta x^2 + \Delta y^2} \quad (24)$$

Through a set of verification tests for several impact points forced on the specimen, generally the average location errors were mostly in the range of 15% of the corresponding sensor spacing mounted, which is shown in Figure 4.

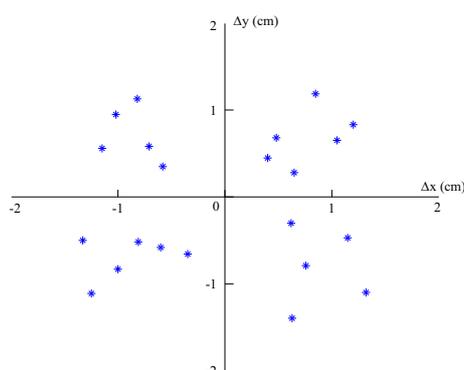


Figure 4 : Estimated location errors for the random impact points

4.2 Force Reconstructions under External Noise Effect

To verify the capability of the EII technique against external noise effect, we added random interfering noise conditions into our experimental tests. Then through processing using the EII technique, we compared the different results of force reconstructions (shown in Fig. 5), which include that the results of reconstructions under denoising, a result of reconstruction with noise of SNR of 20 and a result of reconstruction with noise of SNR of 10. Finally, we calculated the average error of force reconstructions with noise contamination a little more than that of denoising, which is approximately more 5% errors.

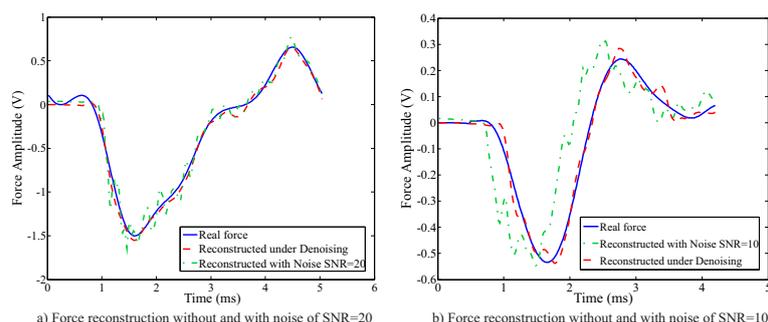


Figure 5 : Comparison of force reconstructions with noise contamination and under denoising

4.3 Force Reconstructions for Various Types of Impact Objects

Additional experiments were performed to verify the force reconstruction methodology for various impactors. First, an IRF matrix network was obtained from a series of impact tests using an impact hammer. The hammer tip was made of plastic and the mass of impactor was 0.161kg. Using the IRF matrix network obtained from the hammer, force reconstructions were performed for various impact tests with the differential small balls.

The results of force reconstructions with different material balls are shown in Figure 6. With the given IRF matrix network, the reconstruction results matched well with the actual force signals recorded in terms of both maximum amplitude and time duration. And the ratio of the sum error is evenly 15% of the magnitude value of the actual force.

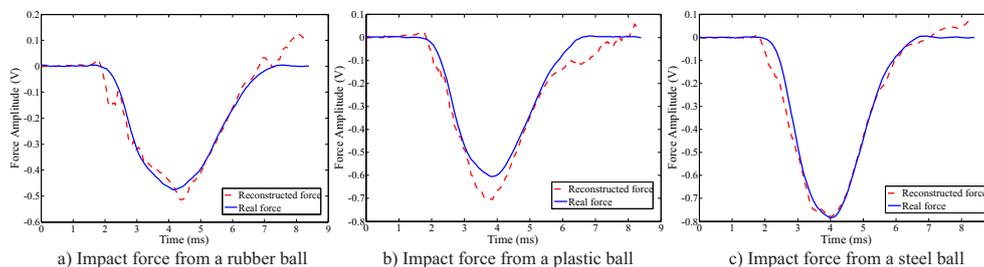


Figure 6 : Force reconstructions for the impact balls with different materials and masses

5. CONCLUSION

This paper presents a systematic integrated impact identification scheme. By using the smart distributed sensors network defined, an advanced real-time ensemble impact identification technique was proposed to estimate the impact locations and force histories including the information of the force magnitudes. In the automatic identification procedure, a precise forward system model for a given structure incorporated with the piezoelectric sensors can be established rapidly using the EII technique. However, using the dynamic state-space model from the EII technique, the impact forces can be reconstructed from a small number of impulse response functions from the optimal system parameters (a_i , b_j) calculated using GA estimation during forward system modeling, where eliminates the need of numerous impact training tests for impulse response functions on the structure. Meanwhile, the initial impact locations can be estimated from an energy distribution method and the accurate location coordinates of impact forces can be also updated by using the time of flight (ToF) based triangular sensor network positioning method proposed. This smart real-time ensemble impact identification technique showed satisfactory success on predicting impact locations and force histories for different impact loads, and was verified its capability of impact monitoring and identification.

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