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# Development in vibration-based structural damage detection technique

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**Abstract**

This paper presents a general summary and review of state-of-the-art and development of vibration-based structural damage detection. Various structural damage detection methods based on structural dynamic characteristic parameters are summarised and evaluated. The principle of intelligent damage diagnosis and its application prospects in structural damage detection are introduced, and the development trends of structural damage detection are also put forward.


*Keywords:* Damage detection; Structural vibration; Intelligent diagnosis

## 1. Introduction

At present, using non-destructive examination (NDE) method to detect damage status of engineering structures has become a hotspot and difficult issue. Recently, NDE technique is widely applied in industries, such as astronautics aviation, space vehicle, power plant equipment, architecture, metallurgy and mechanical manufacture, etc. Generally, structural damage detection can be classified as local-damage detection [1] and global-damage detection. Local-damage detection techniques refer to non-destructive testing (NDT) as CT scanning and ultrasonic, etc., because it is mainly used to detect local damage in structures, and it can determine damage existence and its location. Local damage detection methods utilise only data obtained from the damaged structure. Baseline data and theoretical models of the undamaged structure are not used. These are the main advantages of local damage detection. For small and regular structures, such as pressure vessels, local damage detection is very effective. However, for the large and complicated structures in invisible or closed environments, it is very difficult to detect damage using local damage detection method. The engineers have to make on-site structural damage detection. Therefore, local damage detection methodology can only be used to detect some special components of a structure. In order to detect damage throughout the whole structure, especially some large, complicated structures, a methodology called global vibration-based structural damage detection [2,3] has been proposed. Its basic principle can be explained as follows. For any

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structure, it can be taken as a dynamics system with stiffness, mass and damping. Once some damages emerge in the structure, the structural parameters will change, and the frequency-response function and modal parameters of the structural system will also change. Thus, the change of the structural modal parameters can be taken as the signal of early damage occurrence in the structural system [4–9]. Recently, researches on vibration-bases structural damage detection have become a hot area because it can solve this particular problem, i.e., to insure reliable operation of multitudinous important engineering structures by online and continuous damage detection using vibration-bases method. The aim of this paper also attempts to give an all-around summarisation on recent progress and development of this hot area. Because the vibration-bases structural damage detection is involved in theories and techniques among interaction of multiple disciplines, such as structural dynamics, artificial intelligence, signal processing and measure technology, maybe, review on this hot area should give all-sided introduction on new developments as many as possible, but detail description on every special methodology may be unwanted. Although vibration-based structural damage detection is a newly emergent research topic, its development can still be divided into traditional- and modern-type. The traditional-type refers to detection method for structural damage only utilising itself mechanics characteristics of structures, such as natural frequencies, modal damping, modal strain energy or modal shapes, etc. However, this kind of method generally requires experimental modal analysis or transfer function measure, and this is very not convenient for online detection of structures in service because these experimental measures often need multifarious instrument or manual operation. Therefore, one's interest in this method is being letdown for recent decade. It seems to be reasonable to define the above-mentioned method as "traditional-type". It has three obvious disadvantages: (1) it has more dependence on experiments, especially the measurement of mode shape and damping. Thus, it is time-consuming and expensive, and these factors will not be adaptive to online damage detection for servicing structures; (2) when using traditional-type method to detect the location of structural damage, it is difficult to establish a universal methodology for various structures, and is more dependant on the properties of individual structures to be detected; and (3) the traditional-type method is generally not sensitive to initial tiny damage in structures.

The modern-type refers to detection method for structural damage based on online measured response signal of structures in service. Because realisation of this method is simple and also feasible to build continuous and automatic structural damage detection for structures in service, researches on this area have become the most important hot area for recent decade. Many new technology and results based on interaction of multiple-discipline have welled up. It also seems to be reasonable to define the vibration-response-bases method as "modern-type". Its advantages can be summarised as: (1) it is less dependant on experiments. It only needs to measure vibration responses at few points in the servicing structure to be detected. Thus, structural shutdown or production halt is not needed, so the cost is lower and it is easy to actualise online. (2) it can easily establish some universal methodology to detect the location and severity of damage in any structures. This methodology will not depend on the peculiar shape of the structures to be detected. (3) using the modern-type method smaller structural damage can be detected by constructing and extracting better characteristic information from structural dynamic response signals.

Among the modern-type methods for structural damage detection, the representative ones include Wavelet analysis, Genetic algorithm (GA) and Artificial Neural Network (NN), etc. Of course, there are still several problems to be investigated and solved in the modern-type method, such as: (1) this method has to rely on the environment excitation to the structures to be detected; (2) the measured signals are possibly contaminated by noise so that information from tiny damage in structures may be covered by the noise; and (3) the selection and construction of the feature index of structural damage are very flexible and variable.

Generally, the structural damage detection can be divided into five levels: (1) identification of damage existence in a structure; (2) localisation of damage; (3) identification of the damage type; (4) quantification of damage severity; and (5) prediction of the remaining service life of the structure [10]. The basic problems for structural damage detection are how to ascertain emergence, location and severity of structural damage using the given measured structural dynamic responses. In order to detect structural damage from structural dynamic response signals, the first problem is to select damage feature index to be constructed. The physical variable used to identify damage may be a global one, but the physical variable used to determine damage location is better to be a local one, and it should meet the following two requirements: (1) the variable must be sensitive to structural local-damage. (2) The variable must be monotone function of the location coordinate

[11]. Generally, determination of structural damage location is equivalent to determining a region, where the structural stiffness and loading capacity decreases using a measurable quantity. The key factor of vibration-based damage detection is to establish the calculation model and to estimate the vibration parameter to be measured. Especially, the selection and sensitivity of the structural damage feature index will affect the final results and accuracy of structural damage detection [12].

The significance of vibration-bases structural damage detection behaves at the forecasting structural damage or destruction in advance. This means that to identify initial damage (generally, small damage) of structures in service is more important. However, the influence on structural response caused by structural small damage always is very puny, and it is very difficult directly to identify small damage from structural response signals. Therefore, it is necessary to construct and extract more sensitive damage feature index to small damage from structural dynamic responses using multifarious advanced methods by combination of artificial intelligence and signal processing. This should be most important hot area on vibration-bases structural damage detection. In addition, the identification under operational conditions, identification under environmental excitation, output-only identification, the uncertainty analysis with identification, time domain approach for on-line identification and statistical approach for health monitoring, etc., are also very important hot area on vibration-bases structural damage detection, and many different types of techniques have been developed to solve these problems including complete or incomplete measurements, new macro-parameters for identification, solution algorithms, optimisation techniques, etc.

## 2. Traditional-type vibration-based structural damage detection method

The traditional-type vibration-based structural damage detection method is mainly based on the natural vibration characteristics of the structures. For example, the natural frequency or mode shapes. The damage location and severity can be determined through finding difference of structural dynamic characteristics between the intact and damaged structures [13]. The traditional-type damage detection (TTDD) method is equivalent to the determination of structural character in given structural locations. Hence, it is the practical application and development of structural dynamic modification method, which is an inverse problem in structural vibration. Since any change of structural mass or stiffness matrix caused by structural mass or stiffness loss in the given part of the structure will be reflected in the measured natural frequency and mode shape, when the measured data of the natural frequency or mode shape are different from those of the intact system, it indicates the damage emergence in the structural system [14]. Some typical TTDD methods can be briefly summarised as follows:

### *2.1. TTDD method based on the change of natural frequency*

In a practical structure, the natural frequency is easy to measure and is independent of the measured position. Generally, the measurement accuracy of natural frequency is higher than that of mode shape or modal damping. In many researches, structural natural frequency has been used to indicate structural damage. Lee and Chung [15] present a method of determining the structural damage size and location using natural frequencies. In this method, first, the approximate crack location is obtained using Armon's Rank-ordering method and the first four natural frequencies are used. Secondly, based on the result of the crack position range, an appropriate FEM model is adopted and the crack size is determined by the FEM. Finally, the actual crack location can be identified by Gudmundson's equation using the determined crack size and the aforementioned natural frequencies. Kim et al. [16] have also proposed a methodology to non-destructively locate and estimate the size of damage in structures using a few natural frequencies. A damage-localisation algorithm to locate damage from changes in natural frequencies and a damage-sizing algorithm to estimate crack-size from natural frequency perturbation are formulated. The advantage of using the change of structural natural frequency to detect damage is its convenient measurement and high accuracy. However, the measurement of natural frequency cannot provide enough information for structural damage detection. Furthermore, the natural frequency is often not sensitive enough to initial damage in structures. Usually, this method can only ascertain existence of the large damage, but may not be able to give the damage location because the structural damage in different location may cause the same frequency change.

### 2.2. TTDD method based on the change of structural vibration mode

Examples of existing sensitivity analysis method for damage detection of practical structures based on natural frequency and mode shape show that the sensitivity of the stiffness losing at different element to different natural frequency and mode is different. It is necessary to measure structural vibration modes for most of the TTDD methods. Generally speaking, structural damage existence can be detected through the natural frequency change, while ascertaining the location of structural damage needs information of vibration modes. Yang et al. [17] present a method of damage detection using the invariance property of element modal strain energy. This method is to assign element modal strain energy to two parts, and defines two damage detection indicators. One is compression modal strain energy change ratio (CMSECR); the other is flexural modal strain energy change ratio (FMSECR). The present modal strain energy is obtained by incomplete mode shape and structural stiffness matrix. Structural health monitoring is thus accomplished via monitoring the elemental CMSECR and FMSECR. Khoo et al. [18] present modal analysis techniques for locating damage in a wooden wall structure by evaluating damage-sensitive parameters such as resonant pole shifts and mode shapes, and damaged region is identified by visual comparison of the deformation mode shapes before and after damage. The modal residue and stiffness changes are also quantified for a better representation of the damage location.

However, the measurement error of vibration mode is distinctly larger than that of the natural frequency. Besides, the measured vibration modes are often not complete, so that vibration mode expansion becomes necessary; as a result, it is quite possible that the measurement errors mix with the errors caused by the vibration mode expansion. Although that the measurement accuracy of structural vibration mode is lower than that of the natural frequency, the vibration mode contains more damage information. For example, using the mode shape curvature method can ascertain structural damage location according to the change of mode shape curvature. Similarly, using the graphic change of mode shape can confirm the structural damage location.

### 2.3. TTDD method based on the change of structural flexibility or stiffness

The principle of structural damage detection based on the change of flexibility matrix can be explained as follows. When the structural vibration modes satisfy the normalisation condition, the flexibility matrix is a function of the mode shape and the reciprocal of natural frequency. Thus, the effect of high-frequency components in flexibility matrix will rapidly decrease with the increase of natural frequency. Therefore, one can get the flexibility matrix with enough accuracy by only measuring several low-order modes and frequencies. According to the difference matrix of the flexibility matrixes before and after structural damage, the largest element value in each column can be found, and then the structural damage location can be ascertained by examining the largest element value in each column. Aoki and Byon [19] pay attention to deducing localised flexibility properties from the experimentally determined global flexibility matrix, and present the underlying theory that can be viewed as a generalised flexibility formulation in three different generalised coordinates, namely, localised or substructural displacement-basis, elemental deformation-basis and element strain-basis. Yan and Golinval [20] also present a damage diagnosis technique based on changes in dynamically measured flexibility and stiffness of structures. The covariance-driven subspace identification technique is applied to identify structural modal parameters, and these are then used to assemble the flexibility matrix of dimensions corresponding to the measured degrees of freedom. The corresponding stiffness matrix is obtained by a pseudo-inversion of the flexibility matrix. Damage localisation is achieved by a combined assessment of changes in these two measured matrices in moving from the reference state to the damaged state. Since the location of damage is given directly by the position of sensors, no geometrical measurements and finite-element models are needed.

Generally, when some damage appears in a structure, stiffness matrix can offer more information than the mass matrix. Using the change of stiffness matrix to detect damage is because the stiffness changes remarkably when big damage appears in a structure. However, if the damage is very small, this method cannot work well.

### 2.4. TTDD method based on transfer function (frequency-response function)

Park and Park [21] think only using measured frequency-response functions without requiring exact analytic model can detect structural damage. However, when applying the method to a real structure, it requires lots of experiments. Therefore, they have proposed a method to reduce the experimental load by detecting damage within a substructure. Furukawa et al. [22] present a structural damage detection method using uncertain frequency-response functions. Structural damage is detected according to the changes in FRFs from the original intact state. The measurements are always contaminated by noise, and sufficient data are often difficult to obtain; these factors make it is difficult to detect damage with a finite number of data. In order to surmount this difficulty, they introduce hypothesis tests based on the bootstrap method to statistically prevent detection errors due to measurement noise. The proposed method iteratively zooms into the damaged elements by excluding the elements, which have been assessed as undamaged from the damage candidates, step by step.

Since the change of transfer function caused by structural damage is uniquely determined by the damage type and location, one need only measure one column data in transfer matrix to detect damage instead of measuring the whole transfer matrix, which is a burdensome work. Other developing methods based on frequency-response function include the frequency-response related coefficients method [23], curvature method [24] and so on. The advantages of these methods are no need for mathematics model, vibration mode measurement and experiential knowledge. Therefore, this method can be used in online monitoring. The disadvantage for this method is that the accuracy of structural damage detection is prone to be influenced by the amount and position of measurement point.

### 2.5. TTDD method based on statistic information

In system analysis, damage can be regarded as an additive excitation on the system. It can cause the change of output signal from the system. When one tries to search the additive excitation using the measured output signals, the noise problem in output signal must be taken into account, especially that the signal change caused by small damage may be covered by noise. Hence, detection method for initial damage based on statistic information is proposed. In using statistic mode, the detection for structural damage is based on the probability of damage emergence.

Iwasaki et al. [25] present a methodology of damage detection by judging the statistical difference between data of the intact state and the damaged state. The method requires data of the undamaged state, but does not require complicated modeling or data for training. Damage is detected from the change of strain data using statistical tools such as the response surface and $F$-statistics. As a result, the method successfully diagnoses the damage without the need to use modeling or data of the damaged state. Fugate et al. [26] focuses on applying statistical process control methods referred to as ‘control charts’ to vibration-based damage detection. First, an autoregressive (AR) model is fit to the measured acceleration-time histories from an undamaged structure. Residual errors, which quantify the difference between the prediction from the AR model and the actual measured time history at each time interval, are used as the damage-sensitive features. Next, the X-bar and S control charts are employed to monitor the mean and variance of the selected features. Control limits for the control charts are constructed based on the features obtained from the initial intact structure. The residual errors computed from the previous AR model and subsequent new data are then monitored relative to the control limits. A statistically significant number of error terms outside the control limits indicate a system transit from a healthy state to a damaged state. Lopez-Diez et al. [27] analyse the applicability of the statistical energy analysis (SEA) for detecting incipient damage in a typical spacecraft structure, and point out that, because incipient damage affects mainly on the highest modes, rather than on the lowest ones, the coupling loss factor between sub-elements can be used to detect and localise the damage.

### 2.6. TTDD method based on power flow

Using the transfer and reflection of the power flow in a damaged structure, one can analyse the characteristics of vibration power flow and the relationship between the power flow and structural damage location as well as severity. It becomes feasible to detect structural damage by analyzing the change laws of the power stream. Li et al. [28] investigate a transverse open damage by means of vibrational power flow based on structure-borne sound, vibrational wave analysis of infinite beam structures. In their study, the damage is modeled as a joint of a local spring with a constant value that is deduced from the relationship between the strain energy and stress intensity factor in fracture mechanics, then the input power flow and transmitted power flow of perfect and damaged beams are computed. The results show that the vibrational power flow of damaged beam is highly related to the degree and location of damage. Mahapatra and Gopalakrishnan [29] has developed a spectral finite-element model (SFEM) to study the effect of wave scattering and power flow through multiple delaminations and strip inclusions in composite beams with general ply stacking sequence. The model uses three-dimensional (3D) beam wave-guides to represent the dynamics of the base- and the sub-laminates or strip inclusions with distributed friction at the inter-laminar region. A compact matrix methodology based on finite-element discretisation in wave-number space ($k$-space) and fast Fourier transform (FFT) to obtain frequency domain as well as time domain response is developed. This model has exact shape function and dynamic stiffness matrices, and dynamically consistent load vector, which can be used to analyse broadband-coupled wave propagation in composite beam wave-guide. Effect of length- and depth-wise multiple delaminations and strip inclusion on the scattered power flow is studied. The analysis may find its suitability and superiority to capture the dynamics of delaminated composite structure over a broad frequency band in vibrating environment and in structural health monitoring applications using diagnostic waves.

With the development of science and technology, various new material, such as composite material, ceramic material and non-crystalloid alloy are continually emerging. One should try to find new NDE instrument and methodologies to meet the needs of NDE with high accuracy and sensitivity for these new materials. Therefore, many new technologies, such as the optical fiber sensing techniques based on optical wave-guide theory [30], stress-wave technology based on elastic-wave theory [31], high-frequency mechanical impedance technology [32], etc., have been developed rapidly.

## 3. Modern-type vibration-based structural damage detection method

Modern-type vibration-based structural damage detection, also called intelligent damage diagnosis, is a sort of method using online measured structural vibration responses to detect damage. These methods mainly take modern signal-processing technique and artificial intelligence as analysis tools. With well universality and less dependence on structural shape, they are also called intelligent damage diagnosis methods. The structural dynamic response measured by online and non-destructive technology may indicate the change of structural dynamic parameters at the structural damaged status. Vibration-based structural damage detection is a vital field both in theoretical research and engineering application. Many scholars have carried out a great deal of researches to perform damage detection for large and complex structures. The representative methods among them are wavelet analysis, NN, GAs, etc.

### *3.1. Wavelet analysis method*

Wavelet analysis is very suitable to analyse non-stationary signal, so it can be used as a feasible method for processing signal in damage detection to construct the needed feature index of structural damage. Wavelet analysis has got various applications in structural damage detection, for example, singular signal detection, signal-to-noise separation, frequency-band analysis and so on. The spectrum graph obtained using wavelet transform can indicate the damage existence directly. Rajasekaran and Varghese [33] proposed a wavelet-based approach for structural damage detection in beams, plate and delamination detection of composite plates. The main concept used is the breaking down of the dynamic signal of a structural response into a series of local basis function called wavelets, so as to detect the special characteristics of the structure using scaling and transformation property of wavelets. Lu and Hsu [34] present a study based on the wavelet transform for structural damage detection. Through comparing the discrete wavelet transforms of two sets of vibration signals from the undamaged and damaged structures in the space domain, not only the presence of defects can be detected, but also their number and location as well. To simulate the defects of the structure, they attached several point masses and springs on the string. Numerical results show that even a minor localised defect can induce significant changes in the wavelet coefficients of the vibration signals. Law et al. [35] have derived analytically the sensitivity of wavelet packet transform (WPT) component energy with respect to local change in the system parameters based on the dynamic response sensitivity. The proposed method show both analytically and numerically to be not sensitive to measurement noise. The method can differentiate damages at close proximity to each other with good resolution using a very short duration of measured data from only two sensors. Yan and Yam [36] present the method for online detection of initial damage in a composite laminated plate based on energy variation of structural dynamic responses decomposed using wavelet analysis. This study shows that the constructed structural damage index is basically monotonously changeable with the severity of crack damage in the plates, and is also very sensitive to small damage. A typical relationship between the severity and damage index is shown in Fig. 1.

The method similar to wavelet analysis is empirical modes decomposition (EMD) and Hilbert–Huang method. Xu and Chen [37] present an experimental investigation on the applicability of the empirical mode decomposition (EMD) for identifying structural damage caused by a sudden change of structural stiffness. The EMD is applied to measured time histories to identify damage occurring time instant and damage location for various test cases. The comparison of identified results with measured ones show that damage occurring time instants could be accurately detected in terms of damage spikes extracted directly from the measurement data by EMD. The damage location could be determined by the spatial distribution of the spikes along the building. Yang et al. [38] have proposed two methods to extract the information of damage as much as possible from measured data containing damage events of the structure. The first method, based on the EMD, is intended to extract damage spikes due to a sudden change of structural stiffness from the measured data thereby detecting the damage occurring time instants and damage locations. The second method, based on EMD and Hilbert transform is capable of detecting the damage occurring time instants, and determining the natural frequencies and damping ratios of the structure before and after damage.

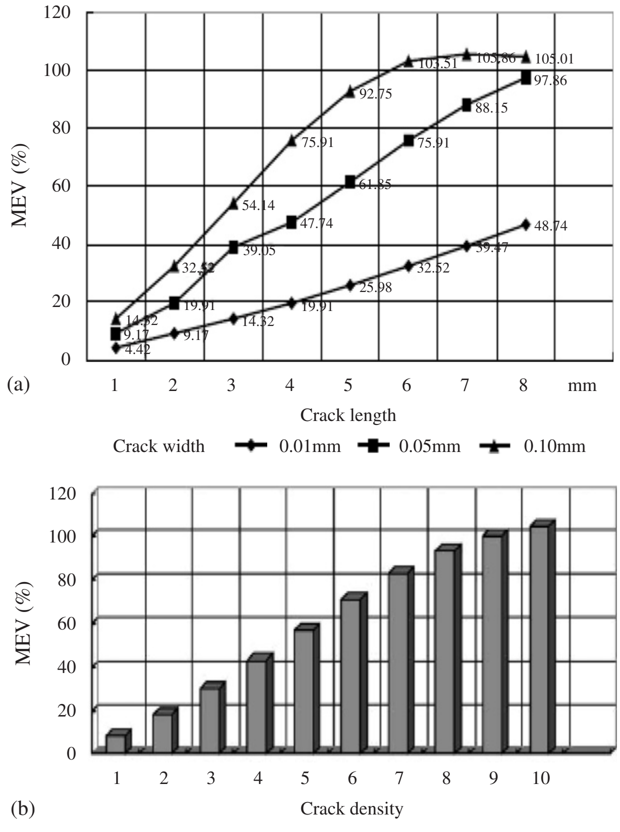


Fig. 1. Damage severity vs. the constructed damage feature index [36].

### 3.2. Neural network method

The BP NN has been widely used in structural analysis because of its strong non-linear mapping ability. It is usually constructed by three layers, an input layer, a hidden layer and an output layer. Structural damage detection based on NN includes the following steps: to determine the network structure; to select the network parameters; to normalise the learning samples; to give initial weight value and to detect structural damage. Based on this idea, the constructed NN will be first trained according to the following step. The known feature information (NN input) and the corresponding status (NN output) of structural damage are taken as train samples to train the constructed NN. These damage information as train sample can be obtained by experiments or numerical simulations for a structure to be detected. When the NN has been well trained, one can input the experimentally measured real structural damage feature index into the trained NN, and the output of the trained NN will be able to give the location and severity of the structural damage. Kao and Hung [39] present a NN-based approach for detecting structural damage. The proposed approach involves two steps. The first step, system identification, the neural system identification networks (NSINs) is used to identify the undamaged and damaged statuses of a structural system. The second step, structural damage detection, the aforementioned trained NSINs is used to generate free vibration responses with the same initial condition or impulsive force. Comparing the periods and amplitudes of the free vibration responses of the damaged and undamaged statuses allows the extent of changes to be assessed. Chen et al. [40] studied the diagnose of faults in engineering structures in the situations where the excitation signals are unavailable or inaccessible, and response-only data are utilised to train NNs. The NN classifiers clearly deliver the diagnostic indications of the faults introduced into the structural systems, which suggests that the transmissibility function is a sensible response-only data source for structural fault diagnosis. Qu et al. [41] deals with structural damage detection by using BPNN. Features extracted from FRFs by applying independent component analysis (ICA) are used as input data to NN. The Latin hypercube sampling (LHS) is adopted for efficient generation of the patterns for training the NN.

NN and GA techniques are very important hot areas on vibration-bases structural damage detection because the location and variety of structural damage can be identified using these techniques, and many results on this area have been obtained. Recently, Yuen and Lam [42] proposed an approach for damage detection based on the pattern matching approach utilising dynamic data. Artificial NNs are employed as tools for matching the "damage patterns" for the purpose of detecting damage locations and estimating their severity. Since research results on structural damage detection using NN and GA techniques are very profuse, and the detail discussions can be found from publications shown as the references.

If we combine the predominance of wavelet signal analysis with the identification function of NN, it is easy to form a more universal online structural damage detection method. The precondition to realise this intention is only to obtain the dynamic response data of damaged structure by online measurement and some known information to train the NN. Su and Ye [43] present an intelligent signal processing and pattern recognition (ISPPR) approach using the wavelet transform and artificial NN algorithms, and this is actualised in a signal processing package (SPP). The ISPPR technique comprehensively functions as signal filtration, data compression, characteristic extraction, information mapping and pattern recognition, capable of extracting essential yet concise features from acquired raw wave signals and further assisting in structural health evaluation. Yam et al. [44] have studied crack damage detection for a honeycomb sandwich plate using the energy spectrum of dynamic response decomposed by wavelet transform and the artificial NN. In their study, the constructed feature index of structural damage is

$$V_d = \{v_1, v_2, \cdots, v_{2^{k-1}}\}^T = \left\{1 - \frac{U^d_{k,1}}{U^0_{k,1}}, 1 - \frac{U^d_{k,2}}{U^0_{k,2}}, \cdots, 1 - \frac{U^d_{k,2^{k-1}}}{U^0_{k,2^{k-1}}}\right\}^T,$$

where the $U^0_{k,j}$ and $U^d_{k,j}$ are the generalised energy of the $j$th order sub-signals of the intact and damaged structures, respectively. These sub-signals are obtained by wavelet decomposition using WPA. The used structural model is shown in Fig. 2. Enough damage samples are obtained using numerical simulation to the damaged structure. These samples are inputted to the NN shown in Fig. 3 for training. Then, an intelligent NN is obtained, which can identify damage of the given structure. Finally, the vibration response data of the

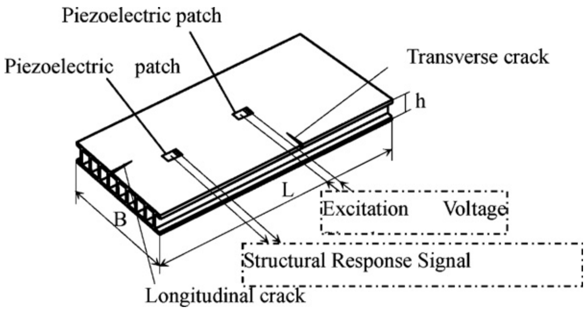


Fig. 2. A honeycomb sandwich plate with crack damage [44].

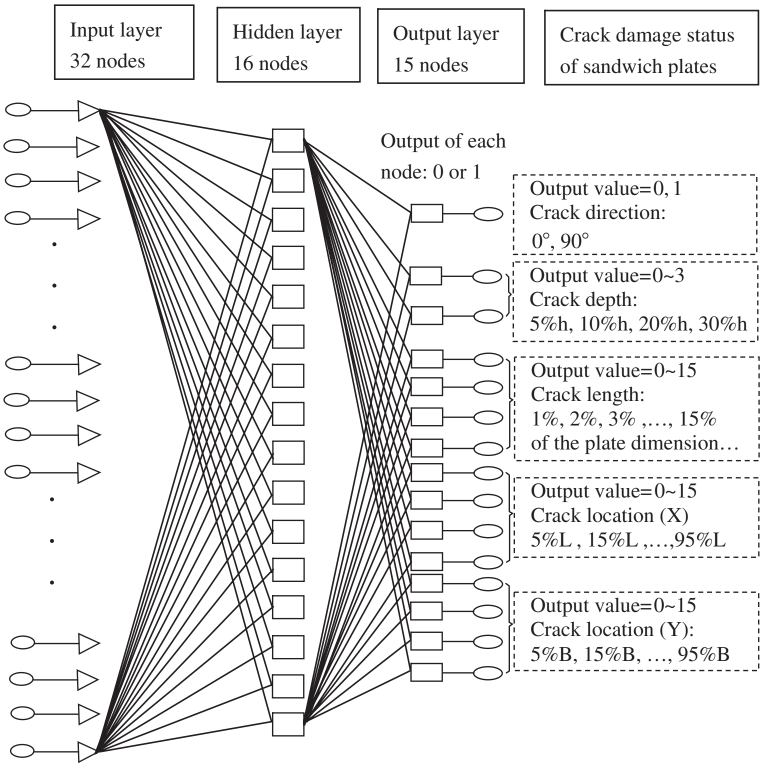


Fig. 3. BP neural network for identification of multiple crack parameters [44].

damaged structure are experimentally measured and the corresponding damage feature indexes are calculated. When these indexes are inputted to the trained NN to identify the structural damage, the given outputs from the NN are listed in Table 1. The results show that taking the energy spectrum of the decomposed wavelet signals of dynamic responses as the inputs of the NN can simplify the NN design for structural damage detection and it possesses a high sensitivity to small damage. The results also show that the NN designed in this study can accurately detect multiple damage parameters or give some significant reference range of the damage parameters.

### *3.3. GA method*

GA is a powerful universal tool to solve optimisation problem, and it is independent of the details of the research object. In structural damage detection, it is suitable to use GA to ascertain the damage locations. The

Table 1
Real outputs of the trained ANN and the theoretic outputs corresponding to practical damage for the three plate specimens

| Crack status and output bit | | EP1 | | | EP2 | | | EP3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | RO | AO | TO | RO | AO | TO | RO | AO | TO |
| Direct. angle[a] | 1 | 1.24 | 1 | 1 | 1.22 | 1 | 1 | −0.15 | 0 | 0 |
| Crack depth | 2 | −0.28 | 1 | 1 | 1.06 | 1 | 1 | 1.06 | 1 | 1 |
| | 3 | 1.14 | 0 | 0 | −0.25 | 0 | 0 | −0.12 | 0 | 0 |
| Crack length | 4 | −0.20 | 0 | 0 | 0.16 | 0 | 0 | 1.06 | 1 | 1 |
| | 5 | 0.24 | 0 | 0 | 1.26 | 1 | 1 | −0.17 | 0 | 0 |
| | 6 | 1.18 | 1 | 1 | 1.14 | 1 | 1 | 0.14 | 0 | 0 |
| | 7 | 1.33 | [b] | 1 | 0.19 | 0 | 0 | 0.89 | 1 | 1 |
| Location in $x$-direction | 8 | 0.90 | 0 | 0 | 0.26 | 0 | 0 | −0.16 | 0 | 0 |
| | 9 | 0.49 | [b] | 0 | 0.23 | 0 | 0 | 0.12 | 0 | 0 |
| | 10 | 0.76 | 1 | 1 | 1.20 | 1 | 1 | 1.12 | 1 | 1 |
| | 11 | 1.21 | 0 | 0 | 0.24 | 0 | 0 | 0.17 | 0 | 0 |
| Location in $y$-direction | 12 | 1.19 | 0 | 0 | 0.10 | 0 | 0 | 1.10 | 1 | 1 |
| | 13 | −0.22 | 0 | 0 | 0.29 | [b] | 0 | 0.14 | 0 | 0 |
| | 14 | 0.59 | [b] | 1 | 0.78 | 1 | 1 | 1.16 | 1 | 1 |
| | 15 | 0.54 | [b] | 0 | 1.10 | 1 | 1 | −0.10 | 0 | 0 |

EP1–EP3: number of experimental plates; RO: real outputs of the trained ANN; AO: approximate values according to a maximum allowable error of 25%; TO: theoretic outputs.

[a]Direct. angle denote along what direction the crack has ruptured. Generally, the geometrical description for a crack in structures includes the crack length, width, depth and direction. If a Cartesian coordinate system is established on the structure with cracks, the crack direction can be expressed by an angle relative to the $x$- or $y$-axis. For a small crack, one is more interested in its length and direction angle than its width and depth.

[b]Maybe 0 or 1 (unable to be determined).

encoding operation of GA ensures that it can fully use the information in every set of solutions in iteration. Meanwhile, GA has high calculation efficiency in parallel data processing, and it can search for agminate solutions simultaneously. Thus, it is possible to obtain the global optimum solution. Moslem and Nafaspour [45] present a two-stage procedure; they utilise incomplete measurements to detect the location and extent of structural damage. In the first stage, candidate damaged elements are identified using the residual force method. Based on a priori knowledge from the first stage, the damage extent is determined from candidate elements using a proposed optimisation scheme based on the method of simulated evolution. Chou and Ghaboussi [46] have proposed a method of structural damage detection by using GA. Static measurements of displacements at few degrees of freedom (DOFs) are used to identify the changes of characteristic properties of structural members, such as Young's modulus and cross-sectional area, which are indicated by the difference of measured and computed structural responses. In order to avoid structural analyses in fitness evaluation, the displacements at unmeasured DOFs are also determined by GA. Unlike the traditional mathematical methods, which guide the direction of hill climbing by the derivatives of objective functions, GA searches the problem domain by the objective function itself at multiple points. The proposed method is able to detect the approximate location of the damage, even when practical considerations limit the number of on-site measurements to only a few. Raich and Liszkai [47] have discussed a robust structural damage detection method that can handle noisy frequency-response function information. The inherent unstructured nature of damage detection problems is exploited by applying an implicit redundant representation (IRR) GA. The unbraced frame structure results obtained show that the IRR GA is less sensitive to noise than a SGA. Recently, we have completed a study on damage detection for a model of an airfoil case (shown in Fig. 4) using the Niche GA. Results show that, even though this model has a rather complex structure, its damage location and degree can be easily detected simultaneously using the Niche GA combined with CMSE [48]. The results also indicate that the Niche GA possesses high efficiency in searching structural damage location.

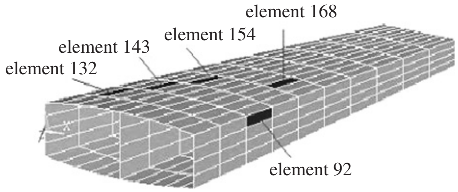


Fig. 4. A composite airfoil case model and the given damage status.

In addition to the above-mentioned typical methodologies in structural damage detection, there are some other developed methods so far. For example, static load redistribution [49], static noisy data [50], support vector machine [51], fuzzy optimum system hierarchy analysis selection [52], combined parameters [53], iterative general-order perturbation [54], probability density [55], virtual passive controllers [56], etc. All these methodologies have revealed the feasibility and some special advantages in structural damage detection based on structural dynamics. In a word, the vibration-based structural damage detection will be one of the most active topics in structural dynamics for a long-term future.

## 4. Development trend of structural damage detection technology

The vibration-bases structural damage detection is a high technique with widely applied foreground, and also it is involved in interaction development among multi-disciplines. Since many key techniques and basic theories in vibration-base structural damage detection still needs to be studied and developed up to its practical application, the development trend and highlight in future will be very multiplex and profuse. Maybe, one cannot accurately foresee future developments, i.e., the research actuality in vibration-bases structural damage detection may not be entirely accordant with the future highlights. However, following topics in structural damage detection should be emphatically researched in future:

(1) Structural damage mechanism and dynamics modeling of damaged structure. Because in practice the collectable sample data of structural damage is always insufficient and limited, and it is also costly and time-consuming to obtain structural damage samples by a large number of experiments, obtaining multitudinous structural damage samples has to depend on numeric simulations by establishing dynamics model of the damaged structure. In fact, how to involve structural damage mechanism into structural dynamic model will be a premise of basic research.
(2) Construction and extraction of feature index for small structural damage from structural vibration response. To construct and extract the feature index of small structural damage from structural vibration responses are the key issue for successful damage detection. Since there are various feature indexes, the research of this topic is very significant.
(3) Development of structural damage detection technology based on multidisciplinary intercrossing. With the development of information science, artificial intelligence, intelligent structure and advanced dynamic analysis technology, new structural damage detection technology will continually appear. This will provide infinite vitality for the development of this scientific field.
(4) Optimisation of the position and number of measurement sensors. Selecting optimal number and position of measurement sensors to obtain plentiful information of the structure to be detected is a very important factor. This will also involve electronic technique, optimisation theory and structural dynamics of damaged structure. Although this topic has been noticed since the beginning of developing structural damage detection, the research of sensor optimisation is still far from the end.
(5) Non-linear factors in structural damage detection. It is well known that the non-linear factor in structural dynamics has a great influence on structural dynamic characteristics. Many theoretical problems are not yet well solved. The structural damage detection based on structural dynamics must be involved in non-linear problems. Therefore, the research on this topic will be long-term and arduous.

The structural damage detection technology based on multidisciplinary intercrossing will be a more advanced research. Besides the knowledge of the advanced complex structures, it is also related to many other disciplinary knowledge, such as mechanical, architecture, material and vibration theory, etc. Only combining structural vibration theory with signal processing, mode identification, artificial intelligence, control theory and material science, etc., can it be possible to enhance the accuracy of vibration-based structural damage detection. Structural damage detection is a complex problem, although many methods of using structural vibration response and system dynamic parameter to detect damage have been developed, there are still a lot of difficulties in the practical application of these methods because of the complexity of structural damage and the uncertainty of various influencing factors. We suggest that the above-mentioned first three research topics should be taken as the research emphases in structural damage detection.

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