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Structural damage identification using interval modeling technique based on Neuro-Fuzzy system

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Abstract

This paper presents a structural damage identification method using Interval Modeling Technique based on Neuro-Fuzzy System. The proposed approach begins by filtering the sensor's output time series with wavelet real-time filtering algorithm. Adaptive Neuro-Fuzzy Inference System (ANFIS) is then used to model the structure and predict the displacement response. The Internal Modeling Technique accepts prediction results as the input and gives uncertainty coordinates as the output. Information Fusion is subsequently accomplished and then the damage can be identified after damage index is constructed. The proposed approach is demonstrated by application to an unmanned helicopter model. The result shows that, with the excitation and displacement signals, the proposed method can identify both the time and the location when the structural damage occurs unexpectedly.

Keywords: wavelet real-time filtering algorithm; interval modeling technique; adaptive Neuro-Fuzzy inference system; uncertainty coordinates; information fusion

1. Introduction

Structural damage identification (SDI) has received much attention in the field of aerospace engineering. Numerous techniques have been introduced for the damage detection of aircraft structures, among which the vibration based approaches have been widely exploited. These methods are based on the fact that any structure can be considered as a dynamic system with stiffness, mass and damping. Once some damages occur in the structure, the structural parameters will change, and the time-history response and modal parameters of the structural system will also shift. Thus, the change of the structural modal parameters or any other features extracted from the responses can be taken as the indications of early damage occurrence in the structural system.

A difficulty in the process of damage monitoring, localization and status identification is handling various uncertainties. Methods for identifying structural damage based on low-frequency vibration response can be used to handle uncertainty caused by noise interference and measurement error. This has successfully been done with wavelet transform method [1-3], adaptive neuro-fuzzy system [4-6] and interval modeling technique [7-9]. Furthermore, the incorporation of the three methods generates a better effect for identifying structural damage.

This paper presents a structural damage identification method using interval modeling technique based on neuro-fuzzy system. When time series is estimated and predicted, modeling uncertainties are smaller if processed by adaptive neural fuzzy inference system (ANFIS) than by ANN. However, ANFIS may not be able to cope with non-stationary data, if preprocessing of the input and/or output data is not performed, which can be effectively addressed by using wavelet transform algorithm. Fitting of structural vibration response can be realized by wavelet transform based ANFIS method, which as a single output system yet cannot directly identify damage of multi-sensor structures. This issue can be supplemented by introducing interval modeling technique through information fusion.

Interval modeling technique, a kind of parameter uncertainty quantitative method suitable for sampling control system, has been used for aircraft real-time structural damage identification [9]. The application of ANFIS and wavelet transform as system feature extractors to structural damage detection and localization under different excitations has been widely researched. But the previous studies have not involved the combination of interval modeling technique as damage feature extractor and ANFIS as structural modeling tool, which can substantially improve damage identification capacity and has been proved in this paper.

2. Interval Modeling Technique and ANFIS

Interval modeling technique was proposed to solve structural certification problem under various uncertainty conditions. For system uncertainties in the parameter vector, interval modeling technique extracts system feature and expresses parameter variation as dominant uncertainty coordinates. Parameter vector processed by interval modeling technique can be represented as

$$p(t_i) = p_0 + \sum_{j=1}^{k} \alpha_j(t_i) q_j \tag{1}$$

where $\alpha_j(t_i)$ is the *jth* element of the coordinate vector and p_0 is the average of all the parameter vectors. The structural damage can also be regarded as a kind of abnormal uncertainty and be identified after the construction of damage index exploits the special distribution of uncertainty coordinate vector.

ANFIS, the combination of fuzzy logic and neural network, performs better than single neural network or single fuzzy system in system modeling. There are two structures using neural network to realize fuzzy system: fuzzy neural networks based on the Mamdani model and on Takagi-Sugeno [10] model. ANFIS, adopting the latter, refers to fuzzy inference system based on adaptive networks.

ANFIS processing wavelet filtered structural response is used in this paper to accomplish structural modeling and to finally achieve

$$\hat{x}(k) = f_{ANFIS}(x(k-1), x(k-2), f(k-1)) \quad (k = 3, \ldots, K) \tag{2}$$

Wavelet transform method is developed for its adjustable time-frequency window to replace Fourier transform. The essence of wavelet transform is to express signals as the composition of signal projection in different wavelet base functions, thus conducting time series data filtering.

Damage location can be determined by computing "location factor"

$$SP_k^j((i+1)T) = \frac{(p_j^{S_d})^T (p^k{}_{(i+1)T})}{\|p_j^{S_d}\|_2 \bullet \|p^k{}_{(i+1)T}\|_2} \tag{3}$$

where $\|p_j^{S_d}\|_2$ and $\|p^k{}_{(i+5)T}\|_2$ are Euclidean lengths of vectors $p_j^{S_d}$ and $p^k{}_{(i+5)T}$. The above SP_k^j is between -1 and 1. If the "location factor" approaches to 1, then the damage to be determined is in the same position as the corresponding "base damage" S_d.

The integration of wavelet transform, ANFIS and interval modeling technique is depicted in Fig. 1.

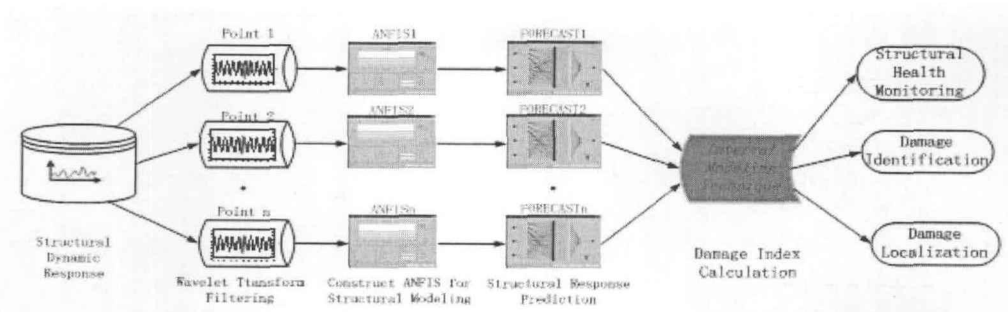

Fig. 1. Schematic diagram of interval modeling technique based on ANFIS

3. Example and Results

3.1. Modeling

The fuselage structure of BUAA FH-1 coaxial unmanned helicopter is used for example analysis, whose size and shape are shown in figure 2. Young's modulus, density and Poisson's ratio of the fuselage material are 207GPa, 7780kg/m3 and 0.3 respectively. Rayleigh damping model is employed to depict the structural damping, whose α and β are 3 and 0.0001 separately. Six degrees of freedom constraint are added to the joint of the fuselage and the landing gear. f_1 and f_2 are the same in Fig. 2, and are used to simulate the cycle loading the blade acts on the fuselage, which is $100\sin(80\pi \cdot t)+100\cos(160\pi \cdot t)N$ .The displacements are output in the tagged 14 points.

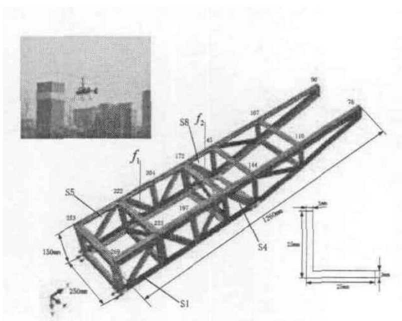

Fig. 2. Finite element model of FH-1 unmanned helicopter fuselage structure [11]

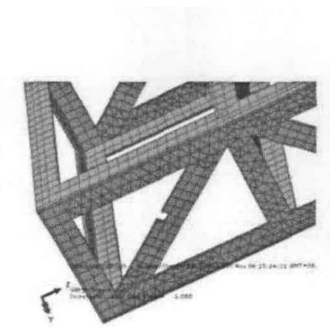

Fig. 3. Model of damage S1-2e5

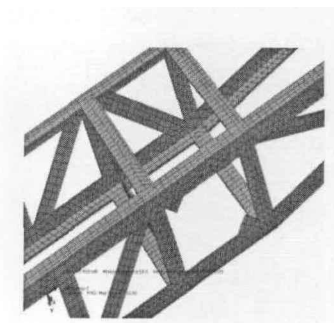

Fig. 4. Model of damage S4-100.

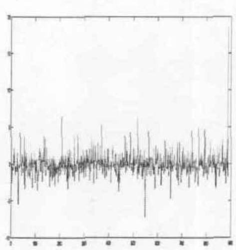

Fig. 5. Damage example 1

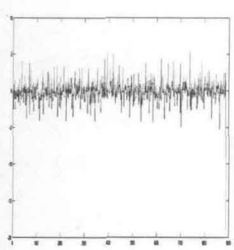

Fig. 6. Example 2

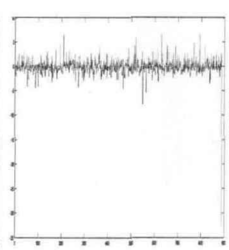

Fig. 7. Example 3

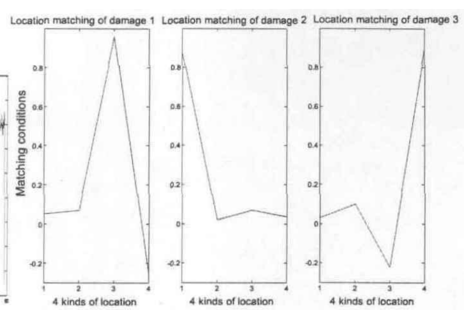

Fig. 8. Damage location identification

This paper studies 4 positions and 16 types of damage. Positions of damage occurring in the four diagonal braces are respectively $S1$, $S2$, $S3$ and $S4$. 16 types of damage, representing degree of damage, are respectively $S1\text{-}2e5$, $S1\text{-}15$, $S1\text{-}50$, $S1\text{-}100$, $S4\text{-}4$, $S4\text{-}12$, $S4\text{-}50$, $S4\text{-}100$, $S5\text{-}3$, $S5\text{-}12$, $S5\text{-}50$, $S5\text{-}100$, $S8\text{-}3$, $S8\text{-}12$, $S8\text{-}50$ and $S8\text{-}100$. Damages $S1\text{-}2e5$ and $S4\text{-}100$ are depicted in Figs. 3 and 4.

3.2. Identification of unknown damage time and location

Now the identification effect the proposed method generates on time and type of suddenly-occurred damage is observed. In the process of simulation, three damages (among the 16 types of damage) with unknown time and type are applied to the fuselage. In the total 11 seconds of the simulation process, the value change of damage index M is monitored in real-time and its variation is shown in Figs. 5-7.

The structural damages are identified in the simulation time of 10.01s, and all the three damages occur at time 10s. The damages occurring at time 10s are identified at time 10.01s.

The following is to identify the damage locations. "Location factors" of the three kinds of damage are computed and showed in Fig. 8. From the matching degree in Fig. 8, the results can be seen apparently that damage type 1 belongs to the third kind of position; damage 2 the first kind of position; damage 3 the fourth kind of position.

4. Conclusions

Based on the research of system modeling techniques and uncertainty quantification methods, an aircraft structural damage detection and localization method mustering real-time filtering algorithm, adaptive neural fuzzy inference system and interval modeling technique is studied, and then is demonstrated by the simulation analysis of an unmanned helicopter model. The results show the feasibility of this method in identifying aircraft structural damage.

This paper uses redundancy sampling frequency method to process sensor output time series for real-time filtering. Sampling frequency of 10 kHz imposes high performance requirements on the data acquisition system. The identification effect is relatively obvious if simulation analysis is under low noise level, whilst un-conspicuous if under high noise level. The damage status can't be effectively identified at present, and it needs further study.

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