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Model updating using correlation analysis of strain frequency response function

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ABSTRACT

A method is proposed to modify the structural parameters of a dynamic finite element (FE) model by using the correlation analysis for strain frequency response function (SFRF). Sensitivity analysis of correlation coefficients is used to establish the linear algebraic equations for model updating. In order to improve the accuracy of updated model, the regularization technique is used to solve the ill-posed problem in model updating procedure. Finally, a numerical study and a model updating experiment are performed to verify the feasibility and robustness of the proposed method. The results show that the updated SFRFs and experimental SFRFs agree well, especially in resonance regions. Meanwhile, the proposed method has good robustness to noise ability and remains good feasibility even the number of measurement locations reduced significantly.

1. Introduction

The structural dynamic strength analysis is not often taken into account in the engineering practice of structure design, thus many structural failure problems caused by excessive dynamic stress or vibration fatigue occurred in services. Therefore, attentions should be paid to the simulative evaluation of structural dynamic strength in structural design. The accuracy of simulative evaluation is affected by the accuracy of the dynamic finite element (FE) model. However, it is difficult to establish a sufficiently accurate dynamic FE model using FE modeling techniques. In order to improve the accuracy of dynamic FE model, model updating technique has been introduced and widely adopted to modify dynamic FE model using experimental data [1,2].

In the past decades, a large number of model updating methods were proposed. Almost all the dynamic parameters, such as modal frequencies, modal shapes, frequency response functions (FRFs) and dynamic response, were used in dynamic FE model updating. Modal parameters were the earliest to be used to update dynamic FE model. Mottershead et al. [3] adopted the eigenvalue sensitivity approach to update the FE models of welded joints. Steenackers and Guillaume [4] developed an updating method based on measured modal parameters, and took the uncertainty of measurement into account in their method. However, the incompleteness of measured modal parameters and modal analysis errors may significantly affect the accuracy of the updated model [2]. Compared with the model updating method based on modal parameter, the FRF-based model updating method has some advantages [5,6]: (1) the errors during the modal parameter identification can be avoided; (2) the incompleteness of measured data makes less impacts on the FRF-based model updating method; (3) the structure information included in FRF data is more than those in modal parameters. Most of the FRF-based model updating

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Nomenclature

FE	Finite element
SFRF	Strain frequency response function
FRF	Frequency response function
$\mathbf{H}_x$	Displacement frequency response function matrix
$\mathbf{H}_\varepsilon$	Strain frequency response function matrix
$\Re(\bullet)$	The real part of complex strain frequency response function
$\Im(\bullet)$	The imaginary part of complex strain frequency response function
$\mathbf{B}^e$	Strain-displacement mapping matrix
$\boldsymbol{\alpha}_s$	Shape correlation coefficient vector
$\boldsymbol{\alpha}_a$	Amplitude correlation coefficient vector
$\mathbf{H}_E^\varepsilon$	Experimental strain frequency response function matrix
$\mathbf{H}_A^\varepsilon$	Analytical strain frequency response function matrix
$\mathbf{S}$	Sensitivity matrix
p	Design parameter
$\mathbf{e}$	Residual vector
RDI_{ik}	Row linear dependency coefficient matrix
CDI_{ik}	Column linear dependency coefficient matrix
U	Unitary matrix
V	Unitary matrix

Superscript

H	Complex conjugate transpose operator of a matrix or a vector

methods modify the uncertain design parameters by minimizing the error norms between experimental and analytical FRFs [7,8].

The dynamic strength parameters, such as strain mode shapes, strain frequency response functions and dynamic strain responses, can reflect the local feature of structure well, thus these parameters are also used in dynamic FE model updating method. Ha et al. [9] developed a method of combining strain modal shapes and a closed-loop scheme to update FE model. Ip and Vickery [10] proposed a novel random walk approach using strain frequency response function (SFRF) to update the dynamic FE model, and described an investigation of analysis methods for predicting dynamic stresses in a structure. Esfandiari et al. [11] proposed a dynamic FE model updating method using incomplete SFRF, and used the least square method to solve the quasi-linear sensitivity equation in model updating.

SFRF, as a structural dynamic strength parameter, is used in dynamic FE model updating in the present work. By means of the correlation analysis between experimental and analytical SFRFs at the specific critical locations of a structure, a dynamic FE model updating method is proposed. A frequency selection strategy is also introduced to improve the computational efficiency and the stability of the proposed updating method. Based on sensitivity analysis of correlation coefficients between experimental and analytical SFRFs, the linear algebraic equations for model updating are established to modify the modeling errors. Meanwhile, the ill-pose problem in updating procedure is solved by regularization technique. Finally, the feasibility and robustness of the proposed method are demonstrated by numerical study and experimental validation respectively.

The rest of this current study is organized as follows: in Section 2, according to the derived SFRF expression, the correlation coefficients of experimental and analytical SFRFs are introduced. In Section 3, the dynamic FE model updating method using SFRFs is described. In order to check the feasibility and robustness of the updated method, a numerical study is adopted in Section 4. Section 5 presents an experimental example to demonstrate the efficiency of the proposed dynamic FE model updating method. Finally, some conclusions are drawn in Section 6.

2. SFRF and its correlation coefficients

2.1. Strain frequency response function

A continuous structure can be discretized into a multiple of freedom (MDOF) system using FE technique, the dynamic equation for a MDOF system is,

$$\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{K}\mathbf{x}(t)=\mathbf{f}(t) \tag{1}$$

where $\mathbf{M}$,$\mathbf{C}$,$\mathbf{K}$ are mass, viscous damping and stiffness matrices, respectively. $\mathbf{x}$ (t) and $\mathbf{f}$ (t) are displacement and force vectors, respectively.

Assuming the system is subjected to a harmonic excitation, the excitation and displacement response can be expressed as,

$$\mathbf{f}(t)=\mathbf{F}e^{j\omega t}$$
$$\mathbf{x}(t)=\mathbf{X}e^{j\omega t} \tag{2}$$