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A frequency and spatial domain decomposition method for operational strain modal analysis and its application

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ABSTRACT

Operational modal analysis (OMA), where only the responses are utilized, has been applied to various engineering problems more commonly due to its advantages in real life implementations. A frequency and spatial domain decomposition method for operational modal analysis making use of strain measurements is presented in this paper. With the proposed algorithm, accurate global characteristics of a structure can be obtained from only the measured strain responses. Singular value decomposition, power spectrum enhancement, and the least square fitting techniques are adopted to decouple and obtain the strain modes one by one. Strain modal analysis and acceleration modal analysis are conducted simultaneously to extract the modal parameters of a four-span bridge model with a pair of heavily coupled modes. The processes and the results are carefully compared with each other. Starting from the abnormal strain modes observed, the accidental change of a boundary condition of the bridge model is successfully detected, and also accurately located by the correlation calculation of strain mode shapes.

1. Introduction

Modal analysis is used to obtain global characteristics of a structure, such as modal frequencies and damping ratios. It has been widely applied to vibration troubleshooting, structural optimal design, model updating, and structural health monitoring in aerospace, mechanical and civil engineering. Based on the vibration testing technique, a large variety of algorithms for signal processing and data analysis are presented.

Conventionally, a modal test is conducted with some special excitation devices, such as shakers or impact hammers, which exert excitation forces on the test subjects. The excitation force and the resulting response are simultaneously recorded by various transducers and data acquisition systems. To obtain the modal parameters, frequency response functions or impulse response functions are generally estimated from the input and output time histories. Due to the requirement of a noise-free environment and the need for complex artificial excitation devices, such testing, usually, can only be performed in the laboratory. As a result, the modal analysis that makes use of both input and output data is named Experimental Modal Analysis (EMA) [1]. According to the number of input and output, many single-input/single-output (SISO), single-input/multiple-output (SIMO) and multiple-input/multiple-output (MIMO) modal identification algorithms in the time [2,3], frequency [4–6] and spatial domains [7,8] are developed.

From an EMA test, comparatively good results can be obtained. However, it is not feasible to perform an EMA test for large structures in the field testing. They may be too large to be easily excited by the artificial excitation devices. Moreover, such structures are always subjected to ambient or natural excitations under operational conditions, which cannot be measured. This situation brings out operational modal analysis (OMA), in which only the responses are utilized. After attracting attention in the early 1990 s, OMA has been applied to civil, aerospace and mechanical engineering more and more widely. It is believed that the real dynamic characteristics of structures can be better revealed under real operational conditions than under laboratory conditions. An OMA test can easily and quickly be conducted, since the troublesome installation of excitation equipment and simulation of boundary conditions are no longer needed. From the modal identification point of view, the natural excitation types such as wind, traffic and micro-tremor are of multi-input type naturally, and consequently the coupled or even repeated modes are able to be identified.

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Based on the calculation of the auto- and cross-correlation functions of the response time histories, which have similar properties to the impulse response functions, a natural excitation technique (NExT) [9] is proposed. According to the NExT technique, most of the time domain MIMO identification algorithms, such as polyreference complex exponential (PRCE) [10], extended Ibrahim time domain (EITD) [11], and eigenvalue realization algorithm (ERA) [3] can be used to extract modal parameters for operational modal analysis. Besides NExT, random decrement technique (RDT) [12,13]) has also been successfully applied to time domain operational modal analysis by estimating the random decrement functions instead of correlation functions. The auto-regression moving average vector (ARMAV) model [14] can also be employed for operational modal identification by computing the modal parameters from the coefficient matrices of the AR polynomials. Stochastic Subspace Identification (SSI) method [15,16] is thought to be one of the most effective identification algorithms in the time domain operational modal analysis. Many advanced mathematical tools, such as orthogonal projection, orthogonal-triangular (QR) decomposition, singular value decomposition (SVD) and least square technique are employed in the SSI algorithm. The covariance-driven type SSI requires the estimation of the covariance matrix at first, whereas the data-driven type SSI makes direct use of stochastic response data to identify modal parameters.

The major drawbacks of time domain identification algorithms are intensive computation and noise modes. It is usually a time-consuming process to extract modal parameters applying time domain algorithms, especially the algorithms that require nonlinear iteration. The noise modes are generated not only by measurement noise, but also by nonlinearity, leakage, computation and so on. The noise modes lead to difficulty in determining the model order and distinguishing the real modes from spurious modes.

In frequency domain, the peak-picking (PP) method is simple and rapid, however, it can only deal with well-separated modes and get approximate damping ratios by half-power band method. Based on the PP technique and singular value decomposition (SVD), Brinker et al. [17] developed a frequency domain decomposition (FDD) method, which has provided an ease of use and has been able to identify closely coupled or even repeated modes. An enhanced FDD (EFDD) [18] was developed later on to extract the damping ratio from the inverse fast Fourier transformation (IFFT) of singular value plot. The frequency and spatial domain decomposition (FSDD) method [19] was proposed in 2005, in which the modal frequencies and damping ratios are estimated from the enhanced power spectrum density (PSD) directly, without the necessity to perform IFFT. FSDD greatly improves the performance of FDD type algorithms, and has been widely applied in various engineering fields. In recent years, some transmissibility based operational modal analysis methods [20–23] with the theoretical advantage of independency from the characteristics of excitations have been developed. However, problems like being unable to identify repeated modes, existence of computational modes, and even lack of ability to estimate damping ratios are still big obstacles encountered in many applications of these kind of methods.

Conventional modal testing generally utilizes displacement responses or their derivatives with respect to time, i.e. velocity and acceleration, and all identification algorithms mentioned above are based on them. However, strain and stress are the parameters that have been related directly to the strength of materials and thus, can be used directly in integrity evaluation of structures. In recent years, strain sensor techniques have begun to develop more rapidly. Besides the commonly used metal-foil strain gauges, the optical fiber Bragg gratings (FBG) [24] and piezoelectric strain sensors [25] are gaining increasing attention in the engineering fields. The FBG sensors are small sized, lightweight, distance-independent, high precision, and can be used to measure very high strain. The piezoelectric strain sensors are reusable, have a high frequency range, and are compatible with the popular signal conditioners and data acquisition systems, making them extremely attractive.

Strain modal analysis was first proposed in the 1980 s [26–28]. Similar to the displacement/acceleration modes, strain modes can also reflect the inherent dynamic characteristics of a structure. Additionally, the strain modes are more sensitive to local damage [29], such as holes, grooves, and cracks. Many researchers have derived the analytical expressions of strain frequency response function (FRF), and have studied the relationship between displacement FRF and strain FRF [30]. Some classical modal identification algorithms for displacement/acceleration modal analysis, such as ERA and SSI, were applied to extract modal parameters from strain responses or strain FRF.

This paper presents a modal decomposition method in frequency and spatial domain specifically for strain measurements. Based on its displacement version, the algorithm is derived step by step for strain based modal analysis so as to use only output data without the need for excitation. Acceleration and strain modal analysis are both conducted to extract the modal parameters of a 4-span bridge model and the results are compared to verify the strain modal identification algorithm. An accidental change of the boundary condition of the 4-span bridge model is finally found by the observation and analysis of the strain modes.

2. Theoretical background

According to the modal superposition theorem, the displacement vector can be expressed by the modal coordinates and mode shapes [30].

$$\{u\} = \sum_{r=1}^{N} q_r \{\varphi_r\} \tag{1}$$

$\{u\}$ is the displacement vector. q_r is the rth modal coordinate, and $\{\varphi_r\}$ is the rth displacement mode vector. The strain is the partial derivative of the displacement. As an example, the normal strain in x direction may be described as:

$$\{\varepsilon_x\} = \frac{\partial\{u\}}{\partial x} = \frac{\partial}{\partial x}\left(\sum_{r=1}^{N} q_r\{\varphi_r\}\right) = \sum_{r=1}^{N} q_r\{\varphi_r^{\varepsilon}\} \tag{2}$$

where $\{\varphi_r^{\varepsilon}\} = \frac{\partial\{\varphi_r\}}{\partial x}$ represents the strain mode vector. In the steady state of the system, the modal coordinate, a function of frequency and time, can be expressed as:

$$q_r = \frac{\{\varphi_r\}^T\{F\}e^{j\omega t}}{k_r - \omega^2 m_r + j\omega c_r} \tag{3}$$

where k_r, m_r and c_r are the rth modal stiffness, mass and damping terms respectively. $\{F\}$ is the force vector. By substituting Eq. (3) into Eq. (2), the following expression is acquired:

$$\{\varepsilon_x\} = \sum_{r=1}^{N} q_r\{\varphi_r^{\varepsilon}\} = \sum_{r=1}^{N} \frac{\{\varphi_r^{\varepsilon}\}\{\varphi_r\}^T\{F\}e^{j\omega t}}{k_r - \omega^2 m_r + j\omega c_r} \tag{4}$$

From Eq. (4), the strain frequency response function (SFRF) can be obtained as:

$$[H_{\varepsilon}] = \sum_{r=1}^{N} \frac{\{\varphi_r^{\varepsilon}\}\{\varphi_r\}^T}{k_r - \omega^2 m_r + j\omega c_r} \tag{5}$$

Eq. (5) reveals that the SFRF matrix is unsymmetrical and does not obey the Maxwell's reciprocity theorem, which is totally different from the displacement FRF. It can also be expressed in the form of partial fractions of poles and residues: