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Adaptive operational modal identification for slow linear time-varying structures based on frozen-in coefficient method and limited memory recursive principal component analysis

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ABSTRACT

To adaptively identify the transient modal parameters for linear weakly damped structures with slow time-varying characteristics under unmeasured stationary random ambient loads, this paper proposes a novel operational modal analysis (OMA) method based on the frozen-in coefficient method and limited memory recursive principal component analysis (LMRPCA). In the modal coordinate, the random vibration response signals of mechanical weakly damped structures can be decomposed into the inner product of modal shapes and modal responses, from which the natural frequencies and damping ratios can be well acquired by single-degree-of-freedom (SDOF) identification approach such as FFT. Hence, for the OMA method based on principal component analysis (PCA), it becomes very crucial to examine the relation between the transformational matrix and the modal shapes matrix, to find the association between the principal components (PCs) matrix and the modal responses matrix, and to turn the operational modal parameter identification problem into PCA of the stationary random vibration response signals of weakly damped mechanical structures. Based on the theory of "time-freezing", the method of frozen-in coefficient, and the assumption of "short time invariant" and "quasistationary", the non-stationary random response signals of the weakly damped and slow linear time-varying structures (LTV) can approximately be seen as the stationary random response time series of weakly damped and linear time invariant structures (LTI) in a short interval. Thus, the adaptive identification of time-varying operational modal parameters is turned into decompositing the PCs of stationary random vibration response signals subsection of weakly damped mechanical structures after choosing an appropriate limited memory window. Finally, a three-degree-of-freedom (DOF) structure with weakly damped and slow time-varying mass is presented to illustrate this method of identification. Results show that the LMRPCA algorithm, which is robustness to Gauss measurement noise disturbances, can well identify the transient modal parameters (transient natural frequencies & transient modal shapes) for weakly damped and slow LTV structures online only from non-stationary random response signals.

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1. Introduction

The vibration modal parameters (modal shapes, damping ratios and natural frequencies) are essential for model design and validation, as well as for the safety of a structure. Moreover, mode shapes give a mathematical description of vibration patterns, when the structure operates at the natural frequencies. Therefore, those parameters play important roles in structural modeling, dynamic modification, vibration control, structural health monitoring as well as damage detection in civil, mechanical and aerospace engineering [1,2].

Modal identification can be classified into four types: analytic solution, finite element analysis (FEA) method, experimental modal analysis (EMA) and operational modal analysis (OMA). The analytic solution is suitable for simple structures rather than complex structures. The FEA method mainly depends on the validity of modeling, the final result of which will be tremendously influenced by the treatment of boundary conditions. A good laboratory condition will become the highest priority since EMA requires accurate measurement of the input and output in order to obtain the frequency response functions (FRFs) for the estimation of modal parameter [3]. However, as an approach to extract modal parameters, OMA only involves measuring the response data of structures when the excitation is unknown or immeasurable. OMA usually assumes that the unknown or immeasurable ambient excitation is white noises or flat input spectrum stationary random signals, such as wind, traffic flow and the pulse of earth [4–7]. OMA has been widely applied in civil structures [8], bridges [9], and offshore platforms [10]. For a perfect white noise or a flat input spectrum, the operational deflection shapes are equal to the mode shapes [11]. In the practical engineering, because some ambient excitations are non-stationary or non-white noises, such as Davenport spectrum, Simiu spectrum, Hino spectrum, Kaimal spectrum, Harris spectrum and Karman spectrum for forward wind speed spectral [12,13], the extended natural excitation approach and the moving average model [14], Gabor [15], Cohen [16], empirical mode decomposition (EMD) [17] have been proposed for OMA with non-stationary ambient excitations, while Balance Realization (BR) [18,19] has been proposed for OMA with colorful noise inputs, such as the Kaimal forward wind speed spectrum. In order to simulate the ambient excitations for rotating machines, Wang et al. extracted operational natural frequencies and modal shapes based on the PCA method when input excitation is a multiple frequency sine superposition [20].

Some innovative OMA methods have been proposed and applied to practical engineering in recent years. Using the concept of modal coordinates, Wang et al. identified that there was a one-to-one relationship between vibration modal shapes of dynamic weakly damped mechanical structures and linear compound matrix, and a one-to-one relationship between modal responses and principal components [20,21]. Han et al. applied a PCA and orthogonal decomposition method on OMA, and demonstrated the orthogonality of principal modes [22,23] for dynamic weakly damped mechanical structures. Poncelet et al. introduced the blind source separation (BSS) and the independent component analysis (ICA) techniques [24,25]. Kerschen focused on the physical interpretation of independent component analysis in structural dynamics “For free and random vibrations of weakly damped structures, a one-to-one relationship between the vibration modes and the ICA modes is demonstrated using the concept of virtual source.” [26]. Bai et al. proposed a new method based on manifold learning termed locally linear embedding (LLE) [27]. Wang et al. presented the modal identification method based on a PCA algorithm in mechanical structures [21].

Academician Guangyuan pointed out [28] “In the field of mechanical analysis of time-varying (time-dependent) structures, at present, there are only several scattered research results, a new discipline of science is not yet formed. It is pointed out in this paper that the mechanics of time-varying structures should be divided into three parts: (1) rapidly varying structural mechanics (theory of vibration induced by the fast variation of the structure); (2) slowly varying structural mechanics (construction mechanics and time-frozen method of analysis); (3) extra slowly varying structural mechanics (Theory of time-dependent reliability analysis and theory of structural maintenance). ” In practical operating structures, the mechanical structures are often LTV, which are characterized by time-varying parameters (mass, stiffness & damping), such as vibration of continuous bridges under moving vehicles [29]. Hence, the study of LTV structures is of significant importance, both academically and practically. LTV structures can be described by variable coefficients (a function of time t) linear partial differential, ordinary differential or difference equations [30,31]. Even for a simple uniform extending cantilever beam (the length is a function of time t), its dynamic equation and boundary condition (a function of time t) are decided by partial differential equations with variable coefficient. Meanwhile, vibration mode function of LTV structures will also change with time [32]. Therefore, great difficulties exist in analyzing LTV structures unless they have been simplified. Since it is very challenging to solve the partial differential equation with variable coefficients, after the discretization of time and space for the equation, the finite difference methods (FDM) or the finite element methods (FEM) become a general solution. It is obvious that the commonly used frozen-in coefficient method is approximately available, only when the variable coefficient (as a function of time t) changes slowly with time [28]. Based on the frozen-in coefficient method, there are three main current research trends in slow LTV structures [33]. The first one is based on the time-frequency analysis of non-stationary random response signals [34,35] including wavelet transform (WT) [36], Hilbert-Huang transform (HHT) [33], subspace methods [37] and time varying autoregressive moving average (TVARMA) models [38]. The second one is based on the theory of “time-freezing” [39], assumption of “short time invariant” [40] and “quasistationary”, the non-stationary random response signals of the slow LTV structures can approximately be seen as the stationary random response time series of LTI structures in short time interval. The third one focuses on the online or recursive techniques [41–45]. Wu [46] summarized the basic theory involved in the modal parameter estimation of time-varying structures (including the introduction and discussion about the dynamic