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A highly efficient and accurate stochastic seismic analysis approach for structures under tridirectional nonstationary multiple excitations

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ABSTRACT

This paper proposes an improved high precision direct integration method (I-HPDIM) and an absolute-response-oriented scheme of pseudo-excitation method (PEM) for nonstationary stochastic seismic analysis of large structures under tridirectional nonuniformly modulated spatial ground motions. The proposed approaches resolve the bottle-neck problem of conventional HPDIM and significantly improve computational efficiency of both PEM and HPDIM, making the proposed nonstationary stochastic analysis scheme more attractive for engineering purposes. Hence, it has been implemented in general finite element platforms, having powerful and versatile modelling and analysis capabilities, for stochastic seismic analysis of large and complex structures under tridirectional nonstationary spatial seismic motions.

1. Introduction

Spatially varying ground motions (SVGM) have a significant effect on the response of large structures [1], such as long span bridges, because of which commentaries and provisions on seismic analysis of spatially extended structures are specified in design standards [2,3]. In seismic analysis of large structures, it is particularly important to include tridirectionality and nonstationarity of SVGM [4,5]. To model ground motion nonstationarity, earthquakes are better to be modelled as nonuniformly modulated seismic excitations, because substantial high frequency components of ground acceleration, which emerge in the early stages of an earthquake, decay much faster than the low frequency components that the ground acceleration involves only low frequency components eventually. This nonstationary pattern of frequency components of an earthquake cannot be characterized by the usually used uniformly modulated evolutionary random process [1,4–9]. To the best knowledge of the authors, numerical analysis of structural responses to such nonuniformly modulated evolutionary random seismic excitations is very rare in the literature, let alone being included in stochastic seismic analysis of spatially extended structures under tridirectional SVGM.

Because earthquakes are in essence random and structural response history analysis usually leads to biased estimations of structural responses owning to uncertainty and intrinsic randomness of ground motions, random vibration based aseismic design of structures has been gradually accepted by the earthquake engineering community [2,8]. However, nonstationary stochastic seismic analysis is too complicated and difficult to be widely used in general engineering computations in spite of its recognized importance. In particular, for structures having many degrees-of-freedom (DoFs) and dozens of spatial supports, or the input nonuniformly modulated nonstationary ground motions being spatially correlated and tridirectional [10], their stochastic response formulas are rather complex and involve a great deal of multiple integration and summation operations, e.g., the Riemann–Stieltjes integration, requiring considerable computational effort [10].

To resolve the aforementioned large computational effort involved in the conventional nonstationary stochastic analysis, Lin et al. [11,12] proposed an accurate and efficient method, known as pseudo-excitation method (PEM), to transform both stationary and nonstationary stochastic analyses to deterministic dynamic response problems. PEM has excluded any computation associated with multiple integration and/or summation operations, making structural stochastic analysis very simple yet accurate and making PEM particularly attractive for engineering purposes. To be more specific, PEM is accurate because the cross-correlation terms

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between the participant structural modes and between the excitations are included in the results [11,12]. Also, PEM is computationally efficient and simple to be adopted, because stationary random analyses are transformed accurately into harmonic analyses, and nonstationary random analyses (for both uniformly modulated and nonuniformly modulated ground motions) are transformed exactly into deterministic transient analyses, which can be solved very easily using direct dynamic integration methods, such as the Duhamel integration, Newmark method, or Wilson-θ method [10–14].

However, these direct dynamic integration methods usually require rather small integration time steps that are dependent on the natural periods of structures to ensure sufficient computational precision and stable response results, thereby increasing the computational effort [11]. Alternatively, a high precision direct integration method (HPDIM), which can adopt larger time step, has been proposed by Zhong and Williams [15] in stationary/nonstationary random response analysis, reducing the computation time considerably [11].

Because of good computational efficiency of PEM and HPDIM, these two methods can be combined to make nonstationary structural stochastic vibration analyses, whether for uniformly or nonuniformly modulated evolutionary random excitations, much easier and much more efficient. However, the combined scheme is generally still very time consuming and costly, because the time step of HPDIM still has to be small enough to simulate recursively varying pseudo loadings properly, especially for nonuniformly modulated nonstationary pseudo loadings (the limitation of loading form assumption of HPDIM between two adjacent time steps, e.g., linear loading form, sinusoidal loading form). This becomes the bottle-neck problem in the application of HPDIM in nonstationary random response analysis [11].

To resolve the bottle-neck problem, the HPDIM parallel algorithm, in conjunction with PEM, has been used to solve the independent structural equations of motion subjected to deterministic pseudo loadings at each frequency step [13]. However, the parallel algorithm improves the efficiency of computation utilizing the parallel capability of computer hardware, rather than improving on the algorithms of HPDIM. To essentially resolve the bottle-neck problem in the application of HPDIM in solving structure equations of motion, this paper proposes an improved high precision direct integration method (I-HPDIM), in conjunction with the absolute-response-oriented scheme of PEM, to reduce significantly the number of transient analyses, without requiring small time step to maintain accurate approximation of forms of pseudo loadings between two adjacent time steps. The proposed I-HPDIM, combing with the absolute-response-oriented scheme of PEM [5], can greatly improve the computational efficiencies of both PEM [11] and conventional HPDIM [15], and it becomes more attractive for engineering purposes, particularly in the stochastic seismic analysis of some large yet complex structures under tridirectional nonstationary spatial seismic motions.

Following the above discussions, distinctions and improvements of the proposed stochastic analysis scheme in this paper with works by Lin et al. [7–14,16] and Zhong and Williams [15] are outlined, which include.

(1) I-HPDIM has been proposed to resolve the bottle-neck problem in application of conventional HPDIM by Zhong and Williams [15]. In comparison with HPDIM, I-HPDIM can significantly improve the efficiency of computation by reducing the number of transient analyses.
(2) The absolute-response-oriented scheme of PEM in solving equations of motion of structures under tridirectional nonstationary spatial excitations is proposed [5], where massive computations on static influence matrix and inverse of structure stiffness matrix are avoid, in comparison with the conventional scheme of applying PEM in determining stochastic response of structures under SVGM by Lin et al. [7–9,12,14].
(3) The proposed I-HPDIM and the absolute-response-oriented scheme of PEM are implemented on a general finite element (FE) platform that has powerful and versatile modelling and analysis capabilities. The implementation makes efficient and accurate I-HPDIM and PEM readily accessible for stochastic analysis of spatially extended structures with complex configurations, where efficient and accurate computational methods are always desired; whereas some self-developed codes, such as DDJ/W developed by Lin et al. [12], are difficult to be applied owing to their weak and limited modelling and analysis capabilities.
(4) Ground motion multidimensionality, effect of varying site conditions, and effect of site irregularities are considered and incorporated in the proposed stochastic seismic analysis methodology for large structures under SVGM, which were not considered in Lin's works [7–9,12].
(5) In modelling nonstationarity of SVGM, the uniformly modulated spatial ground motions have usually used in response history analysis or stochastic seismic analysis of large dimensional structures [7–9,12]. This paper adopts the nonuniformly modulated nonstationary spatial seismic motions, instead of uniformly modulated nonstationary spatial excitations, to represent more real and reasonable earthquake input.

Besides the time-domain type stochastic vibration approaches in this paper, i.e., PEM combined with HPDIM, some spectral approaches (highly efficient as well), such as wavelet-based approaches [17–19], are developed and applied in nonstationary stochastic vibration analysis. Spanos and Failla [17] developed a wavelet-based method to estimate the evolutionary power spectral density (PSD) of nonstationary stochastic processes, and the wavelet-based spectral approaches are recently used in the nonstationary stochastic seismic analysis of multi-span structures under spatially varying ground motions [18,19]. Comparing to the wavelet-based spectral approaches, the time-domain approaches of this paper can be more readily implemented on the general FE platform because of the transformed deterministic transient analyzes, which can be easily solved in any FE platform and can also be readily accessed and applied to engineering practices.

In Section 2, the absolute-response-oriented scheme of PEM combined with scheme of I-HPDIM is proposed and implemented in a general FE platform ANSYS, where a mathematical scheme for modelling tridirectional nonuniformly modulated SVGM, accounting for the incoherence, wave-path, varying site, and site irregularity effects, is derived. To demonstrate the proposed absolute-response-oriented scheme of PEM and I-HPDIM, seismic pounding analysis of a high-pier railway bridge under tridirectional nonuniformly modulated SVGM is conducted in Section 3. Conclusions are drawn in Section 4.

2. Theoretical basis

2.1. Absolute-response-oriented PEM scheme for structures to tridirectional nonstationary SVGM

2.1.1. Equations of motion of structure under pseudo-excitations by PEM

For long-span structures (with m supports and $6n$ DoFs) under tridirectional nonstationary multiple ground motions, the discrete