



# Time-variant random interval natural frequency analysis of structures

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## ABSTRACT

This paper presents a new robust method namely, unified interval Chebyshev-based random perturbation method, to tackle hybrid random interval structural natural frequency problem. In the proposed approach, random perturbation method is implemented to furnish the statistical features (i.e., mean and standard deviation) and Chebyshev surrogate model strategy is incorporated to formulate the statistical information of natural frequency with regards to the interval inputs. The comprehensive analysis framework combines the superiority of both methods in a way that computational cost is dramatically reduced. This presented method is thus capable of investigating the day-to-day based time-variant natural frequency of structures accurately and efficiently under concrete intrinsic creep effect with probabilistic and interval uncertain variables. The extreme bounds of the mean and standard deviation of natural frequency are captured through the embedded optimization strategy within the analysis procedure. Three particularly motivated numerical examples with progressive relationship in perspective of both structure type and uncertainty variables are demonstrated to justify the computational applicability, accuracy and efficiency of the proposed method.

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## 1. Introduction

Natural frequency, as one of the most important parameter in structural dynamic analysis and seismic design, is acquired through generalized eigenvalue analysis. Uncertainty and randomness that inherent in real engineering applications that related to geometric and material properties, boundary conditions as well as external environment will affect the mass and stiffness matrices, and subsequently change the natural frequencies of the structure. Proper modelling uncertainties thus become a crucial task in realistically engineering dynamic design. Stochastic uncertainty analysis is the most common one where all uncertain system parameters are modelled as random variables, fields or processes within the corresponding probability distribution function (PDF) [1–3]. However, stochastic analysis is restricted to the availability of sufficient and trustworthy probabilistic information in order to assess the distribution type and obtain the distribution function. Non-probabilistic approach, such as interval analysis, fuzzy approach, convex model, and info-gap analysis etc. [4–8], on the other hand, have become an alternative tool for situations where difficulties and insufficiency in data collection are encountered.

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To date, a large number of excellent researchers have implemented and revealed different strategies on stochastic natural frequency analysis [9–11]. Among which Monte Carlo simulation (MCS) method is the most versatile one for the analysis of random natural frequency problems [12,13]. The disadvantage of this method is the cost of computation. Many other outstanding approaches have also been reported in the literature such as the perturbation method [14–17], the random factor method [18], etc.

Interval natural frequency problem has attracted more and more attention in engineering applications when lack of enough statistical information but the bounds of the uncertain parameters can be distinguished. Rohn [19], one of the early researchers, derived the solution formulation for the symmetric interval matrix eigenvalue problem when error matrix had rank one. Gao [20] proposed an interval factor method to study the uncertain natural frequency and mode shape of truss structures with geometry and material interval uncertainties. Sofi et al. [21] developed an analysis scheme based on the sensitivity of interval variables by following the improved interval analysis via extra unitary interval [22] and avoids the combination procedure in Vertex method [23].

Despite the advancement of research works in the above mentioned two study areas in recent years, the combination of random and interval analyses in natural frequency study is lacking of enough attention. Wang et al. [24] applied perturbation method and random interval moment method [25] to study this problem. However, the interval perturbation is not very stable and could influence the accuracy depending on the problems. Furthermore, optimization approach is still necessary even with the expression for the bounds of mean and variance, and the adopted Triangular Inequality Theorem largely overestimate the exact bounds. Due to these issues and based on those who excelled in the hybrid uncertain analysis in static problems such as [25,26], this paper extended such solution algorithm in revealing the structural dynamic features.

More importantly, material properties can change over time, such as the Young's modulus of concrete due to the intrinsic creep effect. The time-variant feature will affect the stiffness matrix in dynamic analysis and in order to precisely assess the structural dynamic behaviour, day-to-day based calculation is necessary. Accurately and efficiently assessing a single framework of the uncertainty analysis is a non-trivial task, and it becomes even more challenging when time-variant material properties are taken into account for the hybrid random interval uncertainty analysis. Although traditional simulation method, theoretically, can easily combine the two uncertain frameworks together and simulate in a daily basis fashion, the computational efforts that it takes would be inapplicable and unaffordable for realistic engineering design. Surrogate model strategy [27] uses a set of observation points in the identified area of interest on the implicit performance function and constitutes an approximated explicitly formulated model. Consequently, computational cost can be reduced by using the explicit surrogate model and the study of time-variant feature of hybrid uncertain natural frequency becomes practically approachable.

Particularly, concrete-filled steel tubular (CFST) structures including columns, frames, arches etc. have been increasingly demonstrating the success in engineering applications. With the improving of concrete pouring techniques, this form of section is gaining popularity worldwide due to several advantages such as steel tube can serve as formwork onsite and reduce the amount of steel while still maintain satisfactory levels of stability and stiffness [28,29]. In this study, CFST structures are selected as the major interest in the numerical examples.

In this paper, a unified interval Chebyshev-based random perturbation scheme is presented to investigate natural frequency problems with both stochastic and interval uncertain input variables, especially for the case that time-variant material effect is involved. The upper and lower bounds of the statistical features of natural frequency are adequately estimated by applying optimization strategy on Chebyshev surrogate models. Both material and geometrical random and interval uncertain parameters commonly encountered in engineering applications are accommodated in this analysis framework.

The paper is organized as follow. In section 2, the proposed unified interval Chebyshev-based random perturbation method is structured by the presentation of first order perturbation method, the general Chebyshev surrogate model strategy and the step-by-step method implementation framework. Subsequently, three numerical examples are investigated by using the proposed approach, and compared with the dual sampling scheme in Section 3. Finally, some conclusions are drawn in Section 4.

## 2. Unified interval Chebyshev-based random perturbation method

### 2.1. Random perturbation method of hybrid uncertain natural frequency problem

Let  $\zeta^R \in Z(\mathfrak{N})$  where  $Z(\mathfrak{N})$  represent all possible random variables in a probability space  $(\Omega, \mathbf{A}, \mathbf{P})$ , and  $\mathfrak{N}$  denotes the set contains all real numbers. Also,  $\xi^I = [\underline{\xi}, \bar{\xi}] \Leftrightarrow \{\xi \in \mathfrak{N} | \underline{\xi} \leq \xi \leq \bar{\xi}\}$  is an interval variable of  $I(\mathfrak{N})$  which denotes the set of all closed real intervals, where  $\underline{\xi}$  and  $\bar{\xi}$  denote respectively the lower and upper bounds of  $\xi^I$ . The linear free vibration analysis of an n-DOF structure with random and interval uncertain variables lead to the hybrid eigenvalue problem:

$$\mathbf{K}^{RI} \Phi_k^{RI} = \lambda_k^{RI} \mathbf{M}^{RI} \Phi_k^{RI} \quad (1)$$

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