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Novel fuzzy reliability analysis for heat transfer system based on interval ranking method

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A B S T R A C T

To improve the conservative estimate in traditional fuzzy reliability model, this paper proposes a new reliability analysis method for the fuzzy heat transfer system by using the novel interval ranking strategy. Fuzzy variables representing the subjective uncertainties in input parameters are transformed into a set of interval variables under different membership levels. By adopting the interval satisfaction degree to quantify the safety possibility and failure possibility, the proposed reliability model can efficiently utilize the uncertain information in the transition domain of limit state function, which is completely neglected in the traditional reliability model. Besides, as the basis of reliability analysis, a parameter perturbation method with small computational cost is presented for the fast prediction of uncertain temperature responses. By comparing results with traditional Monte Carlo simulation and fuzzy reliability model, two numerical examples evidence the feasibility and superiority of proposed method at fuzzy reliability analysis in practical engineering.

1. Introduction

Traditional heat transfer analysis has been conducted under the assumption that the material properties, external loads and boundary conditions are deterministic values. But in most engineering cases, various uncertainties representing system variability are unavoidable due to the aggressive environment factors, incomplete knowledge and inevitable measurement errors, which will lead to the uncertain temperature responses [1–3]. Among the many issues about uncertainty, the engineering reliability, which represents the ability of a system or component to perform its required functions under stated conditions for a specified period of time, has received extensive attention in recent years [4–6].

In the traditional reliability framework, the probabilistic models and methods can be considered as the most valuable strategies to deal with uncertain problems, where the input uncertainties are quantified as random variables or stochastic processes by using a great amount of sample statistical information [7–9]. But as pointed in Ref. [10], some important uncertain characteristics cannot be handled appropriately by probability theory, mainly because the concept of randomness is not necessarily the uncertainty source. The fuzzy set theory, emerged from the work of Zadeh [11], is another efficient category to model system uncertainty based on the subjective opinions. By using fuzzy logic and reasoning to construct the relation between input and output, the thermal performance of engineering phenomena was efficiently predicted [12,13]. In practice, fuzzy sets usually can be viewed as the generalization of non-probabilistic interval variables by introducing a membership function [14]. Thus, many fuzzy reliability models have been established on the basis of interval theory to deal with the engineering reliability problems. By combining the possibility theory with fuzzy interval technology, Cheng and Mon firstly presented the possibilitic considerations for evaluating the interval ranges of fuzzy reliability [15,16]. Cremona and Gao analyzed the fuzzy reliability based on new possibilistic safety index, which was defined as the shortest distance from the coordinate origin to the failure surface in the infinity norm [17]. However, it was only suitable to the fuzzy problems with symmetric Gaussian membership functions, and the non-Gaussian fuzzy variables need to be transformed in advance. In order to overcome this shortcoming, Guo et al. modified the fuzzy reliability model based on the interval theory, and made it more general to the various fuzzy systems with different types of membership functions [18]. By

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treating the membership levels of different fuzzy variables as independent random variables following the standard uniform distribution, the fuzzy reliability theory was further investigated from the probability perspective [19]. For the uncertain problems with random and fuzzy parameters existing simultaneously, some hybrid reliability models have been presented according to the merits of both two uncertainty quantification methods [20,21]. But it should be pointed out that in above fuzzy reliability models, only the information where the interval limit state function is strictly greater than zero is considered as safety domain. This operation makes the reliability analysis results conservative because of neglecting some useful information in the transition domain, where the interval limit state function stretches zero. Thus, in order to utilize available information more adequately and analyze valuable fuzzy reliability more accurately, it is necessary to develop more exactitude reliability model and method for fuzzy uncertain systems. Besides, current research on fuzzy reliability analysis is mainly concentrated in the structural mechanics, while its application in heat transfer system is promising but mostly unexplored [22].

In the uncertainty quantification methods, the interval theory has obtained rapid development due to its convenient modeling technology [23–25]. Assuming the interval parameters as the variables with uniform distribution in a certain range, a new interval ranking method has been developed to quantificationally compare two interval numbers [26], which makes it possible to accurately analyze the fuzzy reliability under any membership levels. Besides, as the precondition of reliability analysis, various fuzzy uncertainty propagation methods have been studied by many researchers [27–29]. In this paper, the interval reliability indices under different membership levels will be calculated based on interval ranking method, and the eventual fuzzy reliability indices will be derived by integral operation based on all the information in the entire uncertain space.

The paper is organized as follows. The fuzzy set theory and traditional reliability model are firstly reviewed in Section 2. Subsequently, a new interval ranking method based on satisfaction degree is introduced in Section 3, and a novel fuzzy reliability model combining all the uncertainty information is presented. To predict the uncertain temperature responses efficiently, Section 4 gives a first-order parameter perturbation method based on Taylor expansion and Neumann series. In Section 5, two numerical examples about a 1D heat conduction model and a 3D heat convection-diffusion model are provided to verify the feasibility of proposed method, and we conclude the paper with a brief discussion at last.

2. Traditional fuzzy reliability analysis

A fuzzy set X can be defined as

$$X = \{(x, \mu_X(x)) | x \in R, \mu_X(x) \in [0,1]\} \tag{1}$$

where $\mu_X(x)$ is called the membership function which expresses the degree a sample x belongs to the set R, and there always exists one sample $x \in R$ with $\mu_X(x) = 1$.

Many kinds of membership functions exist in fuzzy set theory, and various fuzzy variables can be defined based on the distribution type of membership function [30]. In this paper, we just take the triangular-type and Quasi-Gaussian-type for instance. If the membership function $\mu_X(x)$ is given as following form by three parameters, then X is called the triangular fuzzy variable, which can be denoted as a parameter triplet $X = (a, b, c)$

$$\mu_X(x) = \begin{cases} 0 & x \le a \\ \dfrac{x-a}{b-a} & a \le x \le b \\ \dfrac{c-x}{c-b} & b \le x \le c \\ 0 & x \ge c \end{cases} \tag{2}$$

Similarly, assume the membership function satisfies the Gaussian distribution in a bounded domain as follows, and then X will be called the Quasi-Gaussian fuzzy variable, which can be denoted as a parameter triplet $X = \langle x_0, \sigma, r \rangle$

$$\mu_X(x) = \begin{cases} \exp\left(-\dfrac{(x-x_0)^2}{2\sigma^2}\right) & \text{if } |x - x_0| < r\sigma \\ 0 & \text{if } |x - x_0| \ge r\sigma \end{cases} \tag{3}$$

The membership functions of above two kinds of fuzzy variables are shown in Fig. 1, from which we can see that the normal set $X_\lambda = \{x | x \in R, \mu_X(x) \ge \lambda\}$ for any membership level $\lambda \in [0,1]$ becomes a closed interval variable X_λ^I, and its lower bound $\underline{X}_\lambda$ and upper bound $\overline{X}_\lambda$ are given by

$$\begin{aligned} \underline{X}_\lambda &= lower\ X_\lambda^I = \min X_\lambda = \min\{x | x \in R, \mu_X(x) \ge \lambda\} \\ \overline{X}_\lambda &= upper\ X_\lambda^I = \max X_\lambda = \max\{x | x \in R, \mu_X(x) \ge \lambda\} \end{aligned} \tag{4}$$

In terms of the interval center representation, the λ-cut interval variable X_λ^I can be rewritten as

$$X_\lambda^I = [\underline{X}_\lambda, \overline{X}_\lambda] = X_\lambda^c + \Delta X_\lambda \cdot \delta \tag{5}$$

where $X_\lambda^c = (\overline{X}_\lambda + \underline{X}_\lambda/2)$ and $\Delta X_\lambda = (\overline{X}_\lambda - \underline{X}_\lambda/2)$ are called the midpoint and radius respectively, δ represents the standard interval variable $\delta = [-1, 1]$.

A set of fuzzy parameters $\mathbf{X} = \{X_1, X_2, ..., X_n\}$ are given to represent the uncertainties caused by the vaguely defined system characteristics, insufficient information and judgment subjectivity. Then the limit state function [7], which is adopted to represent the reliability state of uncertain system, can be expressed as following term with respect to the fuzzy parameters $\mathbf{X} = \{X_1, X_2, ..., X_n\}$

$$M = g(\mathbf{X}) = g(X_1, X_2, ..., X_n) \tag{6}$$

where the hypersurface $g(\mathbf{X}) = 0$ is named as the critical surface, and it divides the whole variable space into two parts: the failure domain $\Omega_f = \{\mathbf{X} | g(\mathbf{X}) < 0,\ \mathbf{X} \in R^n\}$ and the safety domain $\Omega_s = \{\mathbf{X} | g(\mathbf{X}) > 0,\ \mathbf{X} \in R^n\}$.

According to the level-cut strategy [29], the fuzzy limit state

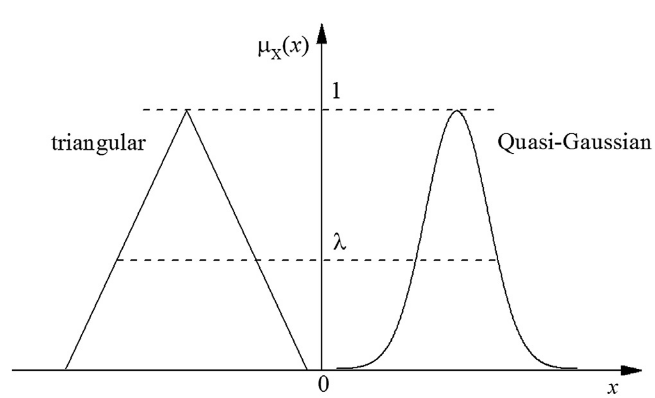

Fig. 1. Membership functions of triangular and Quasi-Gaussian fuzzy variables.