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Research on the structure non-probabilistic reliability model based on rough set theory

Zhao Jia*

School of Information and Control Engineering, Xi'an University of Architecture and Technology, Shaanxi Xi' an 710055, (CHINA)

E-mail: zj52130@tom.com

ABSTRACT

There are all kinds of uncertain variables in the engineering structure analysis. The uncertain parameters of structures are expressed by rough variables easily. According to the non-probabilistic structural reliability analysis method, rough k-means, optimal model and interval analysis, a new methodology for structural reliability computation is presented. It fully considers the influence of uncertain variables. Examples of practical application are given.

KEYWORDS

Structure reliability index; Rough set theory; Rough variables; Non-probabilistic reliability.

INTRODUCTION

The structure reliability index indicates the capability for a structure to complete the defined functions within the regulated time and conditions and the corresponding probability is called as the reliability according to the definition of uniform standard of structure reliability index [1]. The regulated time indicates the designed use period, namely the time in which a structure or a component can work as expected without overhaul. The regulated conditions include "three normally", namely normal design, normal construction and normal use of defined functions, or called as safety, application and durability.

The traditional measurement computing method based on probability theory and mathematic statistics as the mathematical foundation is called as the probability reliability computing method [2], which is also called as reliability computing method. The frequent structure reliability computing methods include first-order second moment method, high-order moment method, optimization method, response surface method, Monte Carlo method and random finite element method.

Different engineering structures include many uncertain factors, e.g. structure physical property, geometric parameters and bearing load (e.g. wind load, wave load and seismic load). People can not know the value due to restricted conditions, so the influences caused by uncertain factors become more and more severe. The traditional uncertain information processing methods include fuzzy set theory, evidence theory and probability statistics theory.

Some references [3] show that the probability reliability computing method is very sensitive to the probability model parameter. A small error in probability data can lead to a big error in structure reliability computing, so the probability reliability theory faces huge challenge. This paper computes the structure reliability index by using the rough set theory, simulates structure uncertainty by using the rough set theory, describes the uncertainty parameters as rough variants, and measures reliability by using the maximum uncertainty permitted by the structure, so the obtained structure reliability indexes are accurate in variant representation and computing results.

BASIC THEORY ON ROUGH SET

The rough set theory [4] deals with inaccuracy, uncertain and incomplete data, can effectively analyze inaccurate, inconsistent, imperfect and incomplete information, and is a powerful tool for data reasoning. The rough set theory was first proposed by Pawlak, a Poland scientist, in 1982. The rough set includes the following strengths: only depend on the original data without any external information and prior information, e.g. probability distribution in statistics and membership in fuzzy set theory, so the description or processing of the problem uncertainty is relatively objective. Although other mathematical methods to deal with the inaccuracy and fuzzy problems will also compute the approximate values, e.g. fuzzy set and evidence theory, the rough set computes the approximate values by using the mathematic equation. The fuzzy set theory gets the approximate results by using the statistics method. The rough set method can be used to analyze the mass attribute and quantity attribute and reduce the redundant attributes. The reduction algorithm is simple. The decision rule set deduced by the rough set model gives the minimal knowledge representation, does not correct inconsistence, and divides the generated inconsistency rules into the certain rules and probable rules. The rough set can deduce results easy to understand, can find the anomaly in the data, eliminate the noise disturbance in knowledge discovery, facilitate parallel execution, and improve discovery efficiency. Compared to the fuzzy set method or neural network method, this rough set method can get the decision rules and reasoning process which is easy to prove and explain.

Definition 1 [5]: given that one knowledge representation system is

$S=(U,A,V,f), P\subseteq A, X\subseteq U, x\in U$,

down approximation, up approximation, negative interval, boundary interval and approximation precision of the set X on I are expressed as follows:

$$\underline{apr}_P(X)=\bigcup\{x\in U: I(x)\subseteq X\} \quad (1)$$

$$\overline{apr}_P(X)=\bigcup\{x\in U: I(x)\cap X\neq\Phi\} \quad (2)$$

$$neg_P(X)=\bigcup\{x\in U: I(x)\cap X=\Phi\} \quad (3)$$

$$bnd_P(X)=\overline{apr}_P(X)-\underline{apr}_P(X) \quad (4)$$

$$\alpha_P(X)=\frac{|\underline{apr}_P(X)|}{|\overline{apr}_P(X)|} \quad (5)$$

Based on the definition of the rough fuzzy set [6], for the fuzzy set FX, we can get:

$$\underline{apr}_P(FX)=\bigcup\{x\in U: \mu_{FX}(x)=1\} \quad (6)$$

$$\overline{apr}_P(FX)=\bigcup\{x\in U: \mu_{FX}(x)>0\} \quad (7)$$

Based on the definition of fuzzy set [7], we can get:

$$\ker(FX)=\underline{apr}_P(FX) \quad (8)$$

$\sup p(FX) = \overline{apr}_P(FX)$ (9)

Based on the definition of the rough membership function and precision-variable rough set model [8], for the random variant SX, we can get:

$\underline{apr}_P(SX) = \bigcup\{x \in U : \mu_{SX}(x) \geq \beta\}$ (10)

$\overline{apr}_P(SX) = \bigcup\{x \in U : \mu_{SX}(x) > 1-\beta\}$ (11)

When the structure reliability is analyzed, the membership function of fuzzy variants and probability of random variants need not be considered. Different uncertain variants are represented as uniform rough set variant, so it can facilitate computing.

STRUCTURE RELIABILITY ANALYSIS BASED ON ROUGH SET

Given that

$X = (X_1, X_2, \cdots, X_n)^T$ ($X_i = [a_i, b_i], i \in n$) indicates n rough variants affecting structure functions and X is the geometric size of the structure, physical dynamics parameter of material, and force on structure, we can call the random function

$G = g(X) = g(X_1, X_2, \cdots, X_n)$ (12)

As the function of the structure (or invalidity function), G is also a rough variant after computing and its mean and deviation is G^c and G^r, make

$Z = \frac{G^c}{G^r}$ (13)

$G = 0$ is the invalid surface of the structure and divides the rough domain U into the invalid rough domain and safe rough domain, namely $G > 0$ and $G < 0$. Based on the interval reliability analysis model [9], $Z > 1$ indicates that the structure is under stable state, $Z \leq -1$ indicates that the structure is under invalid state, $-1 < Z \leq 1$ indicates that the structure is under reliability state or invalid state, namely uncertain state. From the strict meaning, it belongs to invalid state.

Double rough variant function

Function

$G = X_1 - X_2 = 0$ (14)

X_1 and X_2 are the structure strength and stress rough variant. Based on the above analysis on rough variants, the rough variant is a constant and does not affect the structure reliability. The up rough variant is an interval. The mean and deviation of the rough variant is:

$X_i^{\,c} = \overline{X_i}^{\,c}$ (15)

$X_i^{\,r} = \overline{X_i}^{\,r}$ (16)

We can get
$$\begin{cases} Z = \dfrac{\overline{X_1}^{\,c} - \overline{X_2}^{\,c}}{\overline{X_1}^{\,r} + \overline{X_2}^{\,r}} & \overline{X_1}^{\,c} > \overline{X_2}^{\,c} \\ 0 & otherwise \end{cases} \quad (17)$$

Multiple rough variant function

Function

$$G = \sum_{i=1}^{m} a_i X_{1i} - \sum_{i=m+1}^{n} b_i X_{2i} = 0 \quad (18)$$

X_{1i} and X_{2i} are the rough variants independent of structure, we can get:

$$\begin{cases} Z = \dfrac{\sum_{i=1}^{m} a_i \overline{X_{1i}}^{\,c} - \sum_{i=m+1}^{n} b_i \overline{X_{2i}}^{\,c}}{\sum_{i=1}^{m} |a_i| \overline{X_{1i}}^{\,r} + \sum_{i=m+1}^{n} |b_i| \overline{X_{2i}}^{\,r}} & \sum_{i=1}^{m} a_i \overline{X_{1i}}^{\,c} - \sum_{i=m+1}^{n} b_i \overline{X_{2i}}^{\,c} > 0 \\ 0 & otherwise \end{cases} \quad (19)$$

Non-linear function of rough variants

For the general non-linear function, make:

$$\begin{cases} Z = \min(\|\ \delta\ \|_\infty) = \min(\max\{|\ \delta_1\ |, |\ \delta_2\ |, \cdots, |\ \delta_n\ |\}) \\ G = g(X) = g(X_1, X_2, \cdots, X_n) = 0 \end{cases} \quad (20)$$

δ_i is the standard up rough variant of the rough variant X_i. From the optimization model computed by the structure reliability index [10], we know that the structure is more remote from the invalidity domain and is under reliable state when Z is bigger. The rough variants are divided into different clusters via repeated iteration according to the rough k-means clustering algorithm [11] in minimum finding till the structure reliability index is obtained.

$$Z = \sqrt{\sum_{i=n} \delta_i^2} \quad (21)$$

$$= \sqrt{|\ \underline{X_1} - Z_1\ |^2 + |\ \underline{X_2} - Z_2\ |^2 + \cdots + |\ \underline{X_n} - Z_n\ |^2}$$

$C_i, i = k$ indicates k clusters in the rough variant set X and the cluster center is Z_i.

$$Z_i = \frac{1}{m} \sum_{j=m} C_{ij}$$

The rough k- means clustering algorithm is used to compute the structure reliability index via the following steps:

1) n rough variants of the structure compose the data set X. The decision attribute set and conditional attribute set are identified according to X and the attributes are reduced to construct the decision table.
2) Take the mean of K data samples from the data set X as the initial cluster center.
3) Compute distance from data in the data set to K cluster centers and compute the square sum.
4) Check if Z reaches the minimum. if Z does not reach the minimum, repeat the step 2) and 3).

EXAMPLE ANALYSIS

Example 1: linear function $G = R_1 + R_2 - 0.1S$, the decision information table 1 of the rough variants is described as follows:

TABLE 1: Attribute set decision information table of function

U	R_1	R_2	S
a	0.5	0.015	0.127
b	0.265	0.017	0.136
c	0.375	0.0162	0.180
$\vdots$	$\vdots$	$\vdots$	$\vdots$

$\underline{R_1} \in [0.5]$, $\overline{R_1} \in [0.275, 0.505]$, $\underline{R_2} \in [0.016]$, $\overline{R_2} \in [0.015, 0.018]$, $\underline{S} \in [0.1]$ and $\overline{S} \in [0.126, 0.182]$ are independent rough variants. After computing, the schematic 2 is shown as follows:

$$Z = \frac{0.5 + 0.016 - 0.1 \times 0.1}{[0.275, 0.505] + [0.015, 0.018] + 0.1 \times [0.126, 0.182]}$$

$$= [1, 1.433]$$

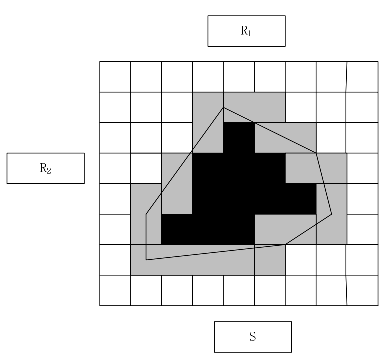

Figure 1: Rough variant and reliability index value schematic

Example 2: Considering that a non-linear limit state function $G = 567RS - 0.5H^2$, $\underline{R} \in [0.627]$, $\overline{R} \in [0.582, 0.672]$, $\underline{S} \in [2.18]$, $\overline{S} \in [2.071, 2.289]$, $\underline{H} \in [32.8]$ and $\overline{H} \in [31.16, 34.44]$ are independent rough variants:

$$\begin{cases} Z = \min(\|\delta\|_\infty) = \min(\max\{|R'|, |S'|, \cdots, |H'|\}) \\ \\ \qquad\qquad 567RS - 0.5H^2 = 0 \end{cases}$$

$$\overline{R} = 0.627 + 0.09R'$$
$$\overline{S} = 2.18 + 0.109S'$$
$$\overline{H} = 32.8 + 1.64H'$$

To substitute in the condition equation, shown as the figure 2, we can get:

$$Z = \sqrt{|\underline{R} - \overline{Z_R}|^2 + |\underline{S} - \overline{Z_S}|^2 + |\underline{H} - \overline{Z_H}|^2}$$
$$= \sqrt{|0.627 - 0.09|^2 + |2.18 - 0.109|^2 + |32.8 - 1.64|^2}$$

We can get:

$$Z = 1.56$$

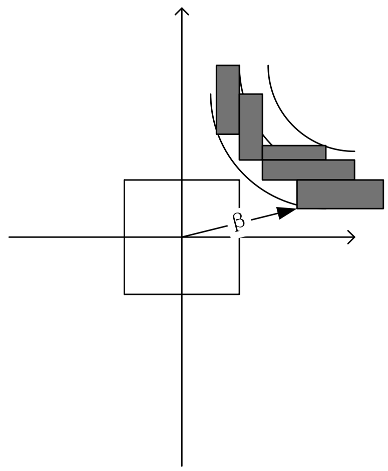

Figure 2: Structure reliability index of rough variant

CONCLUSIONS

A complicated structure includes many uncertain factors. How to accurately analyze the structure reliability by using a method is the key in engineering computing. The rough set theory can be used to analyze the fuzzy and random uncertainty factor, compute the value interval of the reliability index by using the up and down approximation set relation, and analyze the reliability index. The features of this method are described as follows: it is not necessary to distinguish if the parameters are fuzzy or random and identify the membership function of the related fuzzy variants or distribution function of random variants. The reasonable variant values can be obtained via the objective rough analysis. This method is different from the non-probabilistic interval reliability analysis method and does not compute the interval standardization of uncertain parameters. The objective rough analysis results are directly used for reliability analysis.

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