

Application of Extension Evaluation Method in Development of Novel Eco-friendly Brake Materials

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ABSTRACT

Extenics is a new cross discipline to study rules and methods of solving contradictory problems in the real world. The basic concepts and theoretical frame of extenics are briefly introduced in this paper. Based on the merit of extenics, the extension evaluation method was applied to evaluate the brake materials according to a five-grade criterion established in this study. Considering the results computed by the original and simplified models, the similar conclusions were made: all four brake samples, marked A - D, were evaluated in the first grade based on the calculated dependence degrees, and sample B was judged as the best performing friction material with the highest dependence degree and the lowest wear rate. The preliminary results verify that it is feasible to apply the extension evaluation method for the development of friction materials, and the five-grade criteria established in this study can be applied for analyzing the results of the Friction Assessment and Screening Test (FAST) scientifically.

INTRODUCTION

The non-asbestos organic (NAO) brake friction material extensively used today is a multi-component polymer matrix composite with a complex formulation, which is generally developed through *trial and error* coupled with prior experience. There are many desirable

properties for the NAO friction materials, including safety (reliable and stable friction coefficient), durability (low wear rate), comfort (reducing the squealing, the judder and the groan), and environmental friendliness (using natural fibers [1-3]). The scientific and efficient methods for optimizing new brake materials have been increasingly a major concern. The gray relational analysis [4, 5] and fuzzy comprehensive evaluation [6, 7] were applied for evaluation the friction performance of brake materials in the past. On the basis of Extenics, a new cross-discipline theory, the extension evaluation method (EEM) is introduced. It allows to assess the friction performance of the newly developed brake materials, which was proved to be rather practical by analyzing the experimental results in two models.

BASIC CONCEPTS AND THEORY

Extenics is a new discipline first brought up by Professor Wen Cai in 1983, whose landmark article "Extension Set and Non-compatible Problems", proclaimed the birth of this new theory [8]. The object of Extenics is to study the rules and methods of solving contradictory (non-compromising and non-compatible) problems by employing formalized tool, i.e., qualitative analysis and quantitative analysis. Extension theory, extension methodology, and extension engineering constitute Extenics, originally called matter-element analysis [9, 10].

The theoretical pillars of extenics are matter-element theory and extension set theory, and its basic logical cell is matter-element [8-12]. Matter-element theory describes the extensibility of matters in a formalized model, matter-element model. Extension set and dependent function are introduced as the basis of this mathematical tool.

MATTER-ELEMENT

The ordered triple $R=(N,c,v)$ was used as the basic element to describe a certain matter, called matter-element, where N is the name of a matter (used for representing a matter), c is the characteristic, and v is the quantitative measure of N addressing the characteristic c . And N , c and v are the three key elements of a matter-element.

Yet, in real life, one matter can have several characteristics, which can be described as an n -dimensional matter-element:

$$R = \begin{pmatrix} N, & c_1, & v_1 \\ & c_2, & v_2 \\ & \dots & \dots \\ & c_n, & v_n \end{pmatrix} \quad (1)$$

EXTENSION SET

When set U is the field under discussion (the universe of discourse), if for any element u in U ($u \in U$), there is a corresponding real number $K(u) \in (-\infty, +\infty)$. This means that $K(u)$ is the characteristic value of element u from set U and ascribes u to a real number field I . Therefore,

$$\tilde{A} = \{(u, y) \mid u \in U, y = K(u)\}$$

is called an extension set in U , $y = K(u)$ is the dependent function of $\tilde{A}$, and $K(u)$ is the dependence degree of u about $\tilde{A}$. And

$$A = \{(u, y) \mid u \in U, y = K(u) \geq 0\},$$

$$\bar{A} = \{(u, y) \mid u \in U, y = K(u) \leq 0\},$$

$$J_0 = \{(u, y) \mid u \in U, y = K(u) = 0\}$$

are respectively called the positive field of $\tilde{A}$, the negative field of $\tilde{A}$, and zero boundary of $\tilde{A}$. Clearly, $u \in J_0$ implies $u \in A$ and $u \in \bar{A}$.

DEPENDENT FUNCTION

Dependent functions express the dependent degree that a given matter possesses one certain property. Dependent functions of the real numbers must be constructed to solve contradictory problems quantitatively.

Assuming that $x \in (-\infty, +\infty)$ is any point, and if there is an interval $X_0 = \langle a, b \rangle$ in the real number field, the distance on real axis between point x and interval X_0 is defined by equation (2):

$$\rho(x, X_0) = \left| x - \frac{a+b}{2} \right| - \frac{1}{2}(b-a) \quad (2)$$

Assuming that there is another interval $X = \langle c, d \rangle$, $X_0 \subset X$, and X_0 and X have no common ending point (this means $a \neq c$ or $b \neq d$), the position value of point x with regard to intervals X_0 and X is defined by equation (3):

$$D(x, X_0, X) = \begin{cases} \rho(x, X) - \rho(x, X_0), & x \notin X_0 \\ -|X_0| = a - b, & x \in X_0 \end{cases} \quad (3)$$

where

$$\rho(x, X) = \left| x - \frac{c+d}{2} \right| - \frac{1}{2}(d-c) \quad (4)$$

If the intervals X_0 and X have a common ending point (this means $a = c$ or $b = d$), then $D(x, X_0, X) \leq 0$.

Considering X_0 and X have no common ending point, the formula of a dependent function can be defined by equation (5). $K(x)$ is called a dependent function of x with regard to intervals X_0 and X .

$$K(x) = \frac{\rho(x, X_0)}{D(x, X_0, X)} \quad (5)$$

Then,

$$(1) \ x \in X_0, \text{ and } x \neq a, b \Leftrightarrow K(x) > 0;$$

$$(2) \ x = a \text{ or } b \Leftrightarrow K(x) = 0;$$

$$(3) \ x \notin X_0, \ x \in X, \text{ and } x \neq a, b, c, d \Leftrightarrow -1 < K(x) < 0;$$

$$(4) \ x = c \text{ or } d \Leftrightarrow K(x) = -1;$$

$$(5) \ x \notin X, \text{ and } x \neq c, d \Leftrightarrow K(x) < -1;$$

EXTENSION EVALUATION METHOD

The extension evaluation method (EEM) is a method applying extension methodology to the evaluation of a product's quality. The basic points of EEM are as follows:

(a) Dividing the quality level into several grades (for example, excellent, good, qualified, and unqualified).

(b) Building the sets of data according to each grade.

(c) Putting the measures of variables of the product into every set to compute the membership degree, respectively.

(d) Finding the best one by comparing the dependent degrees (DD). The greater DD is, the better is the quality grade of the product.

The extension evaluation method involves the following steps:

(1) Determining the classical and allowable fields

Matter-element R_{0j} ($j = 1, 2, \dots, m$) is used to grade materials in m quality grades, defined by equation (6):

$$R_{0j} = (N_{0j}, C, V_{0j}) = \begin{bmatrix} N_{0j}, & c_1, & V_{0j1} \\ & c_2, & V_{0j2} \\ & \dots & \dots \\ & c_n, & V_{0jn} \end{bmatrix} \quad (6)$$

$$= \begin{bmatrix} N_{0j}, & c_1, & \langle a_{0j1}, b_{0j1} \rangle \\ & c_2, & \langle a_{0j2}, b_{0j2} \rangle \\ & \dots & \dots \\ & c_n, & \langle a_{0jn}, b_{0jn} \rangle \end{bmatrix}$$

where N_{0j} = the j -th quality grade, $j = 1, 2, \dots, m$;

c_i = the i -th characteristic of quality grade N_{0j} ,

$i = 1, 2, \dots, n$;

V_{0ji} = the ranges of measures for quality grade N_{0j} with regard to characteristic c_i ;
respectively. $V_{0ji} = \langle a_{0ji}, b_{0ji} \rangle$ is the classical field.

R_{0j} describes all elements in the defined j -th quality grade.

Matter-element R_p describes all quality grades, defined by equation (7):

$$R_p = (P, C, V_p) = \begin{bmatrix} P, & c_1, & V_{p1} \\ & c_2, & V_{p2} \\ & \dots & \dots \\ & c_n, & V_{pn} \end{bmatrix} \quad (7)$$

$$= \begin{bmatrix} P, & c_1, & \langle a_{p1}, b_{p1} \rangle \\ & c_2, & \langle a_{p2}, b_{p2} \rangle \\ & \dots & \dots \\ & c_n, & \langle a_{pn}, b_{pn} \rangle \end{bmatrix}$$

where P = the total for quality grade;

c_i = the i -th characteristic of quality grade N_{0j} ,

$i = 1, 2, \dots, n$;

V_{pi} = the ranges of measures for P with regard to characteristic c_i , respectively. $V_{pi} = \langle a_{pi}, b_{pi} \rangle$, is the allowable field.

(2) Building the matter-element R to describe the product to be evaluated

Matter-element R describes a product to be evaluated, defined by equation (8):

$$R = (p, C, V) = \begin{bmatrix} p, & c_1, & v_1 \\ & c_2, & v_2 \\ & \dots & \dots \\ & c_n, & v_n \end{bmatrix} \quad (8)$$

where p = the product to be evaluate;

c_i = the i -th characteristic of quality grade N_{0j} ,

$i = 1, 2, \dots, n$;

v_i = the measure the product with regard to characteristic c_i , respectively.

(3) Determining the weight coefficients

Different weights $a_1, a_2, \dots, a_n$ are distributed to all judging conditions in term of magnitude.

Then:

$$\sum_{i=1, i \neq k}^n a_i = 1 \quad (9)$$

(4) First evaluation

First evaluation uses hard constraints to evaluate unqualified products:

(i) If $v_k \notin V_{0jk}$, then, product p is unqualified because it doesn't satisfy the important condition that must be satisfied;

(ii) If $v_k \in V_{0jk}$, then the product is qualified for grading, and the next step continues.

(5) Computing the membership degrees of the product p in every set of quality grade

$$K_j(v_i) = \frac{\rho(v_i, V_{0ji})}{D(v_i, V_{0ji}, V_{pi})} \quad (10)$$

(6) Calculating the dependence degree of product p to the j -th quality grade

$$K_j(p) = \sum_{i=1, i \neq k}^n a_i K_j(v_i) \quad (11)$$

(7) Evaluating the product p as the j_0 -th quality grade

$$K_{j_0}(p) = \max_{j_0 \in \{1, 2, \dots, m\}} K_j(p) \quad (12)$$

Furthermore, the applied method can analyze the correlation degree of one sample with regard to a different quality grade. The judgments are:

When $K_j(p) \geq 0$, $p \in N_{0j}$;

When $-1 \leq K_j(p) \leq 0$, $p \in P$ and $p \notin N_{0j}$;

When $K_j(p) \leq -1$, $p \notin P$.