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Fault diagnoses of steam turbine using the exponential similarity measure of neutrosophic numbers

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Abstract

Since the neutrosophic number consists of its determinate part *d* and its indeterminate part *eI* denoted by $N = d + eI$, it is very suitable for dealing with real problems with indeterminacy. Therefore, this paper proposes the exponential similarity measure of neutrosophic numbers and a fault diagnosis method of steam turbine by using the exponential similarity measure of neutrosophic numbers. By the similarity measure between the fault diagnosis patterns and a testing sample with neutrosophic numbers and its relation indices, we can determine the fault type and indicate fault trends. Then, the vibration fault diagnosis results of steam turbine demonstrate the effectiveness and rationality of the proposed diagnosis method. The proposed diagnosis method not only gives the main fault types of steam turbine but also provides useful information for multi-fault analyses and future fault trends. The developed diagnosis method is effective and reasonable in the fault diagnosis of steam turbine under an indeterminate environment.

Keywords**:** Neutrosophic number; Exponential Similarity measure; Steam turbine; Fault diagnosis

1. Introduction

For the complex structure of steam turbine-generator sets, if there is a fault of the equipment, it will produce a chain reaction and cause the fault of other parts or equipments, and then will seriously impact the reliability of power generation. Therefore, one is convinced of the importance of fault diagnoses. The vibration fault of huge steam turbine-generator sets is usually a typical fault type. The fault diagnosis of the steam turbine realized by the frequency features is a simple and effective method. In many real situations, the testing data of the frequency features extracted from the vibration signals of steam turbine cannot provide deterministic values because the fault testing data obtained by experts are usually imprecise, uncertain and indeterminate due to a lack of data, time pressure, measurement errors, or the experts' limited attention and knowledge. In some situations, the fault testing data usually contain the determinate information and the indeterminate information. Therefore, some researchers have developed the fault diagnosis methods of steam turbine based on the similarity measures of vague sets [1, 2, 3] and the cross entropy of vague sets [4] under an imprecise and uncertain environment. However, these diagnosis methods cannot deal with fault diagnosis problems with indeterminacy, which exist in real world, because the vague set cannot

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include indeterminate and inconsistent information [5].

To deal with incomplete and indeterminate information in real world, Smarandache [6] firstly proposed the concept of a neutrosophic number, which is a subclass of neutrosophy. The neutrosophic number can be represented as $N = d + eI$, which consists of its determinate part d and its indeterminate part eI. In the worst scenario, N only contains its indeterminate part without its determinate part d, i.e. $N = eI$. In the best scenario, there is only its determinate part d without its indeterminate part eI, i.e. $N = d$. Obviously, it is very suitable for the expression of problems with determinate and indeterminate information. Therefore, the neutrosophic numbers can effectively represent the fault data with incomplete and indeterminate information. Recently, Ye [7] firstly provided a neutrosophic number tool for group decision-making problems with indeterminate information under a neutrosophic number environment and developed a de-neutrosophication method and a possibility degree ranking method for neutrosophic numbers from the probability viewpoint as a methodological support for group decision-making problems. Kang et al. [8] proposed the cosine similarity measure of neutrosophic numbers for misfire fault diagnosis of gasoline engines. Although the neutrosophic numbers have been defined in neutrosophic probability since 1996 [6], till now, little progress has been make for handling indeterminate problems by neutrosophic numbers in scientific and engineering areas. Furthermore, existing fault diagnosis methods for steam turbine cannot deal with fault problems with indeterminacy. In order to break through the predicament in engineering applications of neutrosophic numbers, this paper proposes an exponential similarity measure between neutrosophic numbers and a fault diagnosis method based on the exponential similarity measure for handling the fault diagnosis problems of steam turbine under a neutrosophic number environment.

The remainder of this paper is organized as follows. Section 2 briefly describes some basic concepts of neutrosophic numbers. Section 3 presents the exponential similarity measure of neutrosophic numbers and investigates its properties. In Section 4, based on the exponential similarity measure of neutrosophic numbers, we establish a fault diagnosis method for the vibration fault diagnosis of steam turbine under an indeterminate environment and demonstrate the effectiveness and nationality of the proposed diagnosis method. Section 5 contains conclusions and future research.

2. Neutrosophic numbers and their basic operational relations

A neutrosophic number proposed by Smarandache [6] consists of the determinate part and the indeterminate part, which is denoted by $N = d + eI$, where d and e are real numbers, and I is indeterminacy, such that $I^2 = I$, $0 \times I = 0$ and I/I = undefined.

For example, assume that there is a neutrosophic number $N = 6 + 2I$. If $I \in [0, 0.4]$, it is equivalent to $N \in [6, 6.8]$ for sure $N \geq 6$, this means that the determinate part of N is 6, while the indeterminate part of N is $2I$ for $I \in [0, 0.4]$, which means the possibility for the number "N" to be within the interval [6, 6.8].

Let $N_1 = d_1 + e_1I$ and $N_2 = d_2 + e_2I$ be two neutrosophic numbers for $d_1, e_1, d_2, e_2 \in R$ (R is all real numbers). Smarandache [6, 9, 10] introduced the operational relations of neutrosophic numbers as follows:

(1) $N_1 + N_2 = d_1 + d_2 + (e_1 + e_2)I$;

(2) $N_1 - N_2 = d_1 - d_2 + (e_1 - e_2)I$;;

(3) $N_1 \times N_2 = d_1d_2 + (d_1d_2 + e_1d_2 + e_1e_2)I$;

(4) $N_1^2 = (d_1 + e_1I)^2 = d_1^2 + (2d_1e_1 + e_1^2)I$;

(5) $\dfrac{N_1}{N_2} = \dfrac{d_1 + e_1 I}{d_2 + e_2 I} = \dfrac{d_1}{d_2} + \dfrac{d_2 e_1 - d_1 e_2}{d_2(d_2 + e_2)} \cdot I$ for $d_2 \neq 0$ and $d_2 \neq -e_2$;

(6)
$$\sqrt{N_1} = \sqrt{d_1 + e_1 I} = \begin{cases} \sqrt{d_1} - (\sqrt{d_1} + \sqrt{d_1 + e_1})I \\ \sqrt{d_1} - (\sqrt{d_1} - \sqrt{d_1 + e_1})I \\ -\sqrt{d_1} + (\sqrt{d_1} + \sqrt{d_1 + e_1})I \\ -\sqrt{d_1} + (\sqrt{d_1} - \sqrt{d_1 + e_1})I \end{cases}.$$

Let $N_1 = d_1 + e_1I$ and $N_2 = d_2 + e_2I$ be two neutrosophic numbers. If $d_1, e_1, d_2, e_2 \geq 0$, $N_1 = d_1 + e_1I$ and $N_2 = d_2 + e_2I$ are called positive neutrosophic numbers. Then the relations between two positive neutrosophic numbers N_1 and N_2 are defined as follows:

(1) $N_1 \subseteq N_2$ if and only if $d_1 + \inf(e_1I) \leq d_2 + \inf(e_2I)$ and $d_1 + \sup(e_1I) \leq d_2 + \sup(e_2I)$;

(2) $N_1 = N_2$ if and only if $d_1 + \inf(e_1I) = d_2 + \inf(e_2I)$ and $d_1 + \sup(e_1I) = d_2 + \sup(e_2I)$.

3. Exponential similarity measure between neutrosophic numbers

In this section, we propose the similarity measure between neutrosophic numbers based on exponential function.

Based on an exponential function e^{-x}, we can give the definition of the exponential similarity measure between neutrosophic numbers.

Definition 1. Let $A = \{N_{A1}, N_{A2}, \ldots, N_{An}\}$ and $B = \{N_{B1}, N_{B2}, \ldots, N_{Bn}\}$ be two sets of neutrosophic numbers, where $N_{Aj} = d_{Aj} + e_{Aj}I$ and $N_{Bj} = d_{Bj} + e_{Bj}I$ ($j = 1, 2, \ldots, n$) for $d_{Aj}, e_{Aj}, d_{Bj}, e_{Bj} \geq 0$. Then, the exponential similarity measure between A and B is defined as

$$E(A,B) = \frac{1}{n}\sum_{j=1}^{n} e^{-\left(\left|d_{Aj} + \inf(e_{Aj}I) - d_{Bj} - \inf(e_{Bj}I)\right| + \left|d_{Aj} + \sup(e_{Aj}I) - d_{Bj} - \sup(e_{Bj}I)\right|\right)}. \tag{1}$$

Then, the exponential similarity measure satisfies the following proposition.

Proposition 1. The defined exponential similarity measure $E(A, B)$ satisfies the following properties:

(1) $0 < E(A, B) \leq 1$;

(2) $E(A, B) = 1$ if and only if $A = B$;

(3) $E(A, B) = E(B, A)$;

(4) If $A \subseteq B \subseteq C$ for a neutrosophic number C , then $E(A, C) \leq E(A, B)$ and $E(A, C) \leq E(B, C)$.

Proof:

(1) It is obvious that the property is true.

(2) If $A = B$, then there are $N_{Aj} = d_{Aj} + e_{Aj}I = N_{Bj} = d_{Bj} + e_{Bj}I$ ($j = 1, 2, \ldots, n$) for $d_{Aj}, e_{Aj}, d_{Bj}, e_{Bj} \geq 0$ and $d_{Aj} = d_{Bj}$ and $e_{Aj} = e_{Bj}$, *i.e.* $d_{Aj} + \inf(e_{Aj}I) = d_{Bj} + \inf(e_{Bj}I)$ and $d_{Aj} + \sup(e_{Aj}I) = d_{Bj} + \sup(e_{Bj}I)$. Hence there is $E(A, B) = 1$.

If $E(A, B) = 1$, there is $d_{Aj} + \inf(e_{Aj}I) = d_{Bj} + \inf(e_{Bj}I)$ and $d_{Aj} + \sup(e_{Aj}I) = d_{Bj} + \sup(e_{Bj}I)$ since $e^0 = 1$, i.e. $d_{Aj} = d_{Bj}$ and $e_{Aj} = e_{Bj}$ for $j = 1, 2, \ldots, n$. Obviously, there is $A = B$.

(3) It is obvious that the property is true.

(4) If $A \subseteq B \subseteq C$, then this implies $d_{Aj} + \inf(e_{Aj}I) \subseteq d_{Bj} + \inf(e_{Bj}I)$ and $d_{Aj} + \sup(e_{Aj}I) \subseteq d_{Bj} + \sup(e_{Bj}I)$. Hence, there are the following inequations:

$$\left|d_{Aj}+\inf(e_{Aj}I)-d_{Bj}-\inf(e_{Bj}I)\right|\le\left|d_{Aj}+\inf(e_{Aj}I)-d_{Cj}-\inf(e_{Cj}I)\right|,$$

$$\left|d_{Aj}+\sup(e_{Aj}I)-d_{Bj}-\sup f(e_{Bj}I)\right|\le\left|d_{Aj}+\sup(e_{Aj}I)-d_{Cj}-\sup(e_{Cj}I)\right|,$$

$$\left|d_{Bj}+\inf(e_{Bj}I)-d_{Cj}-\inf(e_{Cj}I)\right|\le\left|d_{Aj}+\inf(e_{Aj}I)-d_{Cj}-\inf(e_{Cj}I)\right|,$$

$$\left|d_{Bj}+\sup(e_{Bj}I)-d_{Cj}-\sup(e_{Cj}I)\right|\le\left|d_{Aj}+\sup(e_{Aj}I)-d_{Cj}-\sup(e_{Cj}I)\right|.$$

Thus, there are $E(A, C) \le E(A, B)$ and $E(A, C) \le E(B, C)$ since the exponential function e^{-x} is a decreasing function for $x \in [0, \infty)$.

Therefore, the proofs of these properties are completed. □

In practical applications, the elements in the set of neutrosophic numbers are considered as different weights. Assume that the weight vector of the elements is $\boldsymbol{W} = (w_1, w_2, \ldots, w_n)^T$, $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$. Thus, we can introduce the following weighted exponential similarity measure between A and B:

$$E_w(A,B)=\sum_{j=1}^{n} w_j e^{-\left(\left|d_{Aj}+\inf(e_{Aj}I)-d_{Bj}-\inf(e_{Bj}I)\right|+\left|d_{Aj}+\sup(e_{Aj}I)-d_{Bj}-\sup(e_{Bj}I)\right|\right)}. \quad (2)$$

Obviously, the weighted similarity measure also satisfies the above properties (1)-(4) in Proposition 1.

4. **Vibration fault diagnosis of steam turbine using the exponential similarity measure**

In this section, a fault diagnosis method for the vibration fault diagnosis of steam turbine is proposed based on the exponential similarity measure of neutrosophic numbers.

4.1 Fault diagnosis method based on the exponential similarity measure between neutrosophic numbers

For a fault diagnosis problem with indeterminacy, neutrosophic numbers are most suitable for the expression of the indeterminate problem. Assume that a set of m fault patterns (fault knowledge) is $P = \{P_1, P_2, \ldots, P_m\}$ and a set of n characteristics (attributes) is $A = \{A_1, A_2, \ldots, A_n\}$. Then the information of a fault pattern P_k ($k = 1, 2, \ldots, m$) with respect to a characteristic A_i ($i = 1, 2, \ldots, n$) is represented by a neutrosophic number $P_k = \{d_{k1} + e_{k1}I, d_{k2} + e_{k2}I, \ldots, d_{kn} + e_{kn}I\}$ ($k = 1, 2, \ldots, m$), where $d_{kj}, e_{kj} \ge 0$ ($k = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$). Then, a testing sample is represented by a neutrosophic number $P_t = \{d_{t1} + e_{t1}I, d_{t2} + e_{t2}I, \ldots, d_{tn} + e_{tn}I\}$, where $d_{tj}, e_{tj} \ge 0$ ($j = 1, 2, \ldots, n$).

The exponential measure value v_k ($k = 1, 2, \ldots, m$) can be obtained by the following exponential similarity measure between P_t and P_k:

$$v_k=E_w(P_k,P_t)=\sum_{j=1}^{n} w_j e^{-\left(\left|d_{kj}+\inf(e_{kj}I)-d_{tj}-\inf(e_{tj}I)\right|+\left|d_{kj}+\sup(e_{kj}I)-d_{tj}-\sup(e_{tj}I)\right|\right)}. \quad (3)$$

For convenient diagnosis, the measure values of v_k ($k = 1, 2, \ldots, m$) are normalized into the values of relation indices within the interval [–1, 1] by

$$r_k=\frac{2v_k-v_{\min}-v_{\max}}{v_{\max}-v_{\min}}, \quad (4)$$

where $v_{\max} = \max_{1 \le k \le m}\{v_k\}$, $v_{\min} = \min_{1 \le k \le m}\{v_k\}$ and $r_k \in [-1, 1]$ for $k = 1, 2, \ldots, m$.

Then, we can rank the relation indices in a decreasing order, determine the fault type, and indicate possible fault trends for the tested equipment. If the maximum value of the relation indices is $r_k = 1$, then we can determine that the testing sample P_t should belong to the fault pattern P_k.

4.2. **Vibration fault diagnosis of steam turbine**

Here, we introduce the vibration fault diagnosis of steam turbine by use of the proposed fault diagnosis method based on the exponential similarity measure of neutrosophic numbers to demonstrate the effectiveness of the proposed method.

In the fault diagnosis problem of steam turbine [4], we consider a set of ten fault patterns P = {P_1(Unbalance), P_2(Pneumatic force couple), P_3(Offset center), P_4(Oil-membrane oscillation), P_5(Radial impact friction of rotor), P_6(Symbiosis looseness), P_7(Damage of antithrust bearing), P_8(Surge), P_9(Looseness of bearing block), P_{10}(Non-uniform bearing stiffness)} as the fault knowledge and a set of nine frequency ranges for different frequency spectrum A = {A_1(0.01-0.39f), A_2(0.4-0.49f), A_3(0.5f), A_4(0.51-0.99f), A_5(f), A_6(2f), A_7(3-5f), A_8(Odd times of f), A_9(High frequency > 5f)} as a characteristic set (attribute set) under operating frequency f. Then, the information of the fault knowledge P_k (k = 1, 2, …, 10) with respect to the frequency range (attribute) A_i (i = 1, 2, …, 9) can be introduced from [4], which are shown in Table 1. Then, assume that the weight of each characteristic A_i is w_i = 1/9 for i = 1, 2, …, 9. Each basic element (vague value [t_{kj}, 1-f_{kj}]) in a vague set P_k (k = 1, 2, …, 10; j = 1, 2, …, 9) in Table 1 can be also considered as an interval value, then we can transform it into a neutrosophic number when indeterminacy I is within the interval [0, 0.02], as shown in Table 2.

Table 1 Fault knowledge with vague values [4]

P_k (Fault knowledge)	Frequency range (f: operating frequency)								
	A_1 (0.01-0.39f)	A_2 (0.4-0.49f)	A_3 (0.5f)	A_4 (0.51-0.99f)	A_5 (f)	A_6 (2f)	A_7 (3-5f)	A_8 (Odd times of f)	A_9 (High frequency >5f)
P_1 (Unbalance)	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.85, 1.00]	[0.04, 0.06]	[0.04, 0.07]	[0.00, 0.00]	[0.00, 0.00]
F_2 (Pneumatic force couple)	[0.00, 0.00]	[0.28, 0.31]	[0.09, 0.12]	[0.55, 0.70]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.08, 0.13]
P_3 (Offset center)	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.30, 0.58]	[0.40, 0.62]	[0.08, 0.13]	[0.00, 0.00]	[0.00, 0.00]
P_4 (Oil-membrane oscillation)	[0.09, 0.11]	[0.78, 0.82]	[0.00, 0.00]	[0.08, 0.11]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
P_5 (Radial impact friction of rotor)	[0.09, 0.12]	[0.09, 0.11]	[0.08, 0.12]	[0.09, 0.12]	[0.18, 0.21]	[0.08, 0.13]	[0.08, 0.13]	[0.08, 0.12]	[0.08, 0.12]
P_6 (Symbiosis	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.18, 0.22]	[0.12, 0.17]	[0.37, 0.45]	[0.00, 0.00]	[0.22, 0.28]

looseness)									
P_7 (Damage of antithrust bearing)	[0.00, 0.00]	[0.00, 0.00]	[0.08, 0.12]	[0.86, 0.93]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
P_8 (Surge)	[0.00, 0.00]	[0.27, 0.32]	[0.08, 0.12]	[0.54, 0.62]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
P_9 (Looseness of bearing block)	[0.85, 0.93]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.08, 0.12]	[0.00, 0.00]
P_{10} (Non-uniform bearing stiffness)	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.77, 0.83]	[0.19, 0.23]	[0.00, 0.00]	[0.00, 0.00]

Table 2 Fault knowledge with neutrosophic numbers

P_k (Fault knowledge)	Frequency range (f: operating frequency)								
	A_1 (0.01-0.39f)	A_2 (0.4-0.49f)	A_3 (0.5f)	A_4 (0.51-0.99f)	A_5 (f)	A_6 (2f)	A_7 (3-5f)	A_8 (Odd times of f)	A_9 (High frequency >5f)
P_1 (Unbalance)	0	0	0	0	0.85+7.5I	0.04+2I	0.04+1.5I	0	0
P_2 (Pneumatic force couple)	0	0.28+1.5I	0.09+1.5I	0.55+7.5I	0	0	0	0	0.08+2.5I
P_3 (Offset center)	0	0	0	0	0.30+14I	0.40+11I	0.08+2.5I	0	0
P_4 (Oil-membrane oscillation)	0.09+I	0.78+2I	0	0.08+1.5I	0	0	0	0	0
P_5 (Radial impact friction of rotor)	0.09+1.5I	0.09+I	0.08+2I	0.09+1.5I	0.18+1.5I	0.08+2.5I	0.08, 2.5I	0.08+2I	0.08+2I
P_6 (Symbiosis looseness)	0	0	0	0	0.18+2I	0.12+2.5I	0.37+4I	0	0.22+3I
P_7 (Damage of antithrust bearing)	0	0	0.08+2I	0.86+3.5I	0	0	0	0	0
P_8 (Surge)	0	0.27+2.5I	0.08+2I	0.54+4I	0	0	0	0	0
P_9	0.85+	0	0	0	0	0	0	0.08+	0

(Looseness of bearing block)	$4I$							$2I$	
P_{10} (Non-uniform bearing stiffness)	0	0	0	0	0	0.77+ $3I$	0.19+ $2I$	0	0

In the vibration fault diagnosis of steam turbine, two real-testing samples are introduced from [4] as the form of neutrosophic numbers: P_{t1} = {0, 0, 0.1, 0.9,0, 0, 0, 0, 0} and P_{t2} = {0.39, 0.07, 0, 0.06, 0, 0.13, 0, 0, 0.35}.

For the fault diagnoses of the testing samples P_{t1} and P_{t2}, the exponential similarity measures and relation indices between P_k (k = 1, 2, …, 10) and P_{ti} (i = 1, 2) are calculated by Eqs. (3) and (4), as shown in Table 3.

Table 3 Results of the relation indices and fault diagnoses

P_{ti}	Relation indices (r_k)										Fault diagnosis result
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	
P_{t1}	–0.5970	0.1972	–0.9014	–0.5174	–0.7707	–1.0000	1.0000	0.3037	–0.5729	–0.6780	P_7
P_{t2}	–0.4736	0.4815	–1.0000	–0.4583	0.7359	0.7144	–0.5086	–0.6737	1.0000	–0.4397	P_9

For the first real-testing sample P_{t1}, we can see from Table 3 that the fault type of the turbine is P_7 due to maximum relation index (1.0000), which indicates that the vibration fault of the turbine is firstly resulted from the damage of antithrust bearing. Then, the fault types of surge (P_8) and pneumatic force couple (P_2) have possibility because the relation indices of the fault types P_8 and P_2 are positive. While the fault types of P_1, P_3, P_4, P_5, P_6, P_9, and P_{10} have very low possibility due to the negative relation indices. By actual checking, we discover that one of antithrust bearings is damage. Therefore, it causes the violent vibration of the turbine. Hereby, the ranking order of all faults is $P_7 \to P_8 \to P_2 \to P_4 \to P_9 \to P_1 \to P_{10} \to P_5 \to P_3 \to P_6$.

For the second real-testing sample P_{t2}, we can see from Tale 3 that the vibration fault of the turbine is firstly resulted from the looseness of bearing block (P_9), next the radial impact friction of rotor (P_5) and the symbiosis looseness (P_6) have high possibility because their relation indices are more than 0.5, then pneumatic force couple (P_2) has possibility because the relation index of the fault type P_2 is positive. Clearly, the fault types of P_1, P_3, P_4, P_7, P_8 and P_{10} have very low possibility due to the negative relation indices. By actual checking, we discover the friction between the rotor and cylinder body in the turbine, and then the vibration values of four ground bolts of the bearing between the turbine and the gearbox are very different. We also discover that the gap between the nuts and the bearing block is oversize. Thus, the looseness of the bearing block causes the violent vibration of the turbine, which is in accordance with the actual fault. Hereby, the ranking order of all faults is $P_9 \to P_5 \to P_6 \to P_2 \to P_{10} \to P_4 \to P_1 \to P_7 \to P_8 \to P_3$.

Obviously, the results of all fault diagnoses are the same as the actual faults of steam turbine. The fault diagnosis results of the turbine show that the proposed method not only indicates the main fault types of the turbine, but also provides useful information for multi-fault analyses and future fault trends. The proposed methods in this paper are effective and reasonable in the fault diagnoses.

5. Conclusion

This paper proposed the exponential similarity measure between neutrosophic numbers and its fault diagnosis method for the vibration fault diagnosis of steam turbine under a neutrosophic number environment. The fault diagnosis results demonstrated the effectiveness and rationality of the proposed method. The proposed diagnosis method can not only determine the main fault type of steam turbine but also predict future fault trends according to the relation indices. The proposed diagnosis method can handle fault diagnosis problems with indeterminacy and is simpler and easier than existing diagnosis methods, while the existing diagnosis methods cannot deal with fault diagnosis problems with indeterminacy. The diagnosis method proposed in this paper extends existing diagnosis methods and provides a new way for fault diagnoses under an indeterminate environment. In the future, the developed diagnosis method will be extended to other fault diagnoses, such as vibration faults of aircraft engines and gearboxes.

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Table 1 Fault knowledge with vague values [4]

P_k (Fault knowledge)	Frequency range (f: operating frequency)								
	A_1 (0.01-0.39f)	A_2 (0.4-0.49f)	A_3 (0.5f)	A_4 (0.51-0.99f)	A_5 (f)	A_6 (2f)	A_7 (3-5f)	A_8 (Odd times of f)	A_9 (High frequency >5f)
P_1 (Unbalance)	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.85, 1.00]	[0.04, 0.06]	[0.04, 0.07]	[0.00, 0.00]	[0.00, 0.00]
F_2 (Pneumatic force couple)	[0.00, 0.00]	[0.28, 0.31]	[0.09, 0.12]	[0.55, 0.70]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.08, 0.13]
P_3 (Offset center)	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.30, 0.58]	[0.40, 0.62]	[0.08, 0.13]	[0.00, 0.00]	[0.00, 0.00]
P_4 (Oil-membrane oscillation)	[0.09, 0.11]	[0.78, 0.82]	[0.00, 0.00]	[0.08, 0.11]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
P_5 (Radial impact friction of rotor)	[0.09, 0.12]	[0.09, 0.11]	[0.08, 0.12]	[0.09, 0.12]	[0.18, 0.21]	[0.08, 0.13]	[0.08, 0.13]	[0.08, 0.12]	[0.08, 0.12]
P_6 (Symbiosis looseness)	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.18, 0.22]	[0.12, 0.17]	[0.37, 0.45]	[0.00, 0.00]	[0.22, 0.28]
P_7 (Damage of antithrust bearing)	[0.00, 0.00]	[0.00, 0.00]	[0.08, 0.12]	[0.86, 0.93]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
P_8 (Surge)	[0.00, 0.00]	[0.27, 0.32]	[0.08, 0.12]	[0.54, 0.62]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]
P_9 (Looseness of bearing block)	[0.85, 0.93]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.08, 0.12]	[0.00, 0.00]
P_{10} (Non-uniform bearing stiffness)	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.00, 0.00]	[0.77, 0.83]	[0.19, 0.23]	[0.00, 0.00]	[0.00, 0.00]

Table 2 Fault knowledge with neutrosophic numbers

P_k (Fault knowledge)	Frequency range (f: operating frequency)								
	A_1 (0.01-0.39f)	A_2 (0.4-0.49f)	A_3 (0.5f)	A_4 (0.51-0.99f)	A_5 (f)	A_6 (2f)	A_7 (3-5f)	A_8 (Odd times of f)	A_9 (High frequency >5f)
P_1 (Unbalance)	0	0	0	0	0.85+7.5I	0.04+2I	0.04+1.5I	0	0
P_2 (Pneumatic force couple)	0	0.28+1.5I	0.09+1.5I	0.55+7.5I	0	0	0	0	0.08+2.5I
P_3 (Offset center)	0	0	0	0	0.30+14I	0.40+11I	0.08+2.5I	0	0
P_4 (Oil-membrane oscillation)	0.09+I	0.78+2I	0	0.08+1.5I	0	0	0	0	0
P_5 (Radial impact friction of rotor)	0.09+1.5I	0.09+I	0.08+2I	0.09+1.5I	0.18+1.5I	0.08+2.5I	0.08, 2.5I	0.08+2I	0.08+2I
P_6 (Symbiosis looseness)	0	0	0	0	0.18+2I	0.12+2.5I	0.37+4I	0	0.22+3I
P_7 (Damage of antithrust bearing)	0	0	0.08+2I	0.86+3.5I	0	0	0	0	0
P_8 (Surge)	0	0.27+2.5I	0.08+2I	0.54+4I	0	0	0	0	0
P_9 (Looseness of bearing block)	0.85+4I	0	0	0	0	0	0	0.08+2I	0
P_{10} (Non-uniform bearing stiffness)	0	0	0	0	0	0.77+3I	0.19+2I	0	0

Table 3 Results of the relation indices and fault diagnoses

P_{ti}	Relation indices (r_k)										Fault diagnosis result
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	
P_{t1}	–0.5970	0.1972	–0.9014	–0.5174	–0.7707	–1.0000	1.0000	0.3037	–0.5729	–0.6780	P_7
P_{t2}	–0.4736	0.4815	–1.0000	–0.4583	0.7359	0.7144	–0.5086	–0.6737	1.0000	–0.4397	P_9