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MISFIRE FAULT DIAGNOSIS OF GASOLINE ENGINES USING THE COSINE MEASURE OF SINGLE-VALUED NEUTROSOPHIC SETS

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Abstract – Single-valued neutrosophic set (SVNS) is very suitable for expressing indeterminate and inconsistent information in fault diagnosis problems, and then its cosine measure is a useful mathematical tool for handling the decision making, pattern recognition, and fault diagnosis problems. However, due to the lack of engineering applications of SVNSs in fault diagnoses, the paper develops a cosine measure-based fault diagnosis method and applies it to the misfire fault diagnosis of gasoline engines with SVNS information. Through the cosine measure between each fault pattern and a real-testing sample, according to the largest cosine measure value, we can determine that the testing sample should belong to the fault pattern. Finally, we provide nine real-testing samples to illustrate the misfire fault diagnoses of gasoline engines. All diagnosis results are in accordance with actual fault types. The results demonstrate the effectiveness and rationality of the proposed diagnosis method.

Keywords **–** *Cosine measure, single-valued neutrosophic set, misfire fault diagnosis, gasoline engine.*

1 Introduction

Neutrosophic set proposed by Smarandache [1] is a powerful tool to deal with incomplete, indeterminate and inconsistent information in real world. It is a generalization of the theory of fuzzy sets, vague sets, intuitionistic fuzzy sets and interval-valued intuitionistic fuzzy sets, then the neutrosophic set is characterized by a truth-membership degree, an indeterminacy-membership degree and a falsity-membership degree independently, which are within the real standard or nonstandard unit interval $]^{-}0, 1^{+}[$. Therefore, if their range is restrained within the real standard unit interval [0, 1], the neutrosophic set is easily applied to engineering problems. For this purpose, Wang et al. [2] introduced the concept of a single-valued neutrosophic set (SVNS) as a subclass of the neutrosophic set.

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In a fault diagnosis problem, various symptoms usually imply a lot of incomplete, uncertainty and inconsistent information for a fault, which characterizes a relation between symptoms and a fault. Thus we work with the uncertainties and inconsistencies to lead us to proper fault diagnosis. Hence, SVNSs are very suitable for expressing incomplete, indeterminate and inconsistent information comprehensively in fault diagnosis problems. However, similarity measure is an important mathematical tool in fault diagnoses. Recently, Ye [3] proposed cotangent similarity measures between SVNSs based on cotangent function and successfully applied them to the fault diagnosis of steam turbine under a single-valued neutrosophic environment. Because misfire fault problems of gasoline engines are usually produced in operating process [4], they can affect the operating power and working performance of gasoline engines and increase fuel consumption. To find out misfire fault problems in gasoline engines, extension set theory and neutrosophic numbers have been applied respectively to the misfire fault diagnosis of gasoline engines [4, 5]. However, till now SVNSs have been not applied to fault diagnoses of gasoline engines. To extend existing fault diagnosis methods, the main purposes of this paper are to propose a fault diagnosis method based on the cosine measure of SVNSs and to apply it to the misfire fault diagnosis of gasoline engines with single-valued neutrosophic information.

The remainder of this paper is organized as follows. Section 2 briefly describes some basic concepts and cosine measure of SVNSs. Section 3 establishes a fault diagnosis method using the cosine measure of SVNSs and applies it to the misfire fault diagnosis of gasoline engines under a single-valued neutrosophic environment to demonstrate the effectiveness and nationality of the developed method. Section 4 contains conclusions and future research direction.

2 Some Concepts and Cosine Measure of SVNSs

Smarandache [1] firstly proposed the concept of the neutrosophic set from a philosophical viewpoint. Then, it is difficult to apply the neutrosophic set to engineering applications. Consequently, Wang et al. [2] introduced the definition of a SVNS, which is a subclass of the neutrosophic set.

Definition 2.1. [2]. Let X be a universal of discourse. A SVNS N in X is characterized by a truth-membership function $t_N(x)$, an indeterminacy-membership function $i_N(x)$ and a falsity-membership function $f_N(x)$. Then, a SVNS N can be denoted by the following form:

$$N = \{\langle x, t_N(x), i_N(x), f_N(x)\rangle \mid x \in X\},$$

where $t_N(x)$, $i_N(x)$, $f_N(x) \in [0, 1]$ for each point x in X. Obviously, the sum of $t_N(x)$, $i_N(x)$ and $f_N(x)$ is $0 \le t_N(x) + i_N(x) + f_N(x) \le 3$.

Let $N = \{\langle x, t_N(x), i_N(x), f_N(x)\rangle \mid x \in X\}$ and $M = \{\langle x, t_M(x), i_M(x), f_M(x)\rangle \mid x \in X\}$ be two SVNSs. Then there are the following relations [2]:

(1) Complement: $N^c = \{\langle x, f_N(x), 1 - i_N(x), t_N(x)\rangle \mid x \in X\}$;

(2) Inclusion: $N \subseteq M$ if and only if $t_N(x) \le t_M(x)$, $i_N(x) \ge i_M(x)$ and $f_N(x) \ge f_M(x)$ for any x in X;
(3) Equality: $N = M$ if and only if $N \subseteq M$ and $M \subseteq N$.

Based on cosine function, Ye [6] proposed an improved cosine measure between SVNSs and gave the following definition.

Definition 2.2. [6] Let two SVNSs N and M in the universe of discourse $X = \{x_1, x_2, \ldots, x_n\}$ be $N = \{\langle x_j, t_N(x_j), i_N(x_j), f_N(x_j)\rangle \mid x_j \in X\}$ and $M = \{\langle x_j, t_M(x_j), i_M(x_j), f_M(x_j)\rangle \mid x_j \in X\}$. Then, a cosine measure between SVNSs N and M is defined as

$$C(N,M) = \frac{1}{n}\sum_{j=1}^{n}\cos\left\{\frac{\pi}{6}\left(\left|t_N(x_j)-t_M(x_j)\right|+\left|i_N(x_j)-i_M(x_j)\right|+\left|f_N(x_j)-f_M(x_j)\right|\right)\right\}, \quad (1)$$

The cosine measure $C(N, M)$ satisfies the following properties (1)-(4) [6]:

(1) $0 \le C(N, M) \le 1$;
(2) $C(N, M) = 1$ if and only if $N = M$;
(3) $C(N, M) = C(M, N)$;
(4) If P is a SVNS in X and $N \subseteq M \subseteq P$, then $C(N, P) \le C(N, M)$ and $C(N, P) \le C(M, P)$.

Considering the importance of elements in the universe of discourse, one needs to give the weight w_j of the element x_j ($j = 1, 2,\ldots, n$) with $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$. Then, the weighted cosine measure between SVNSs N and M can be introduced as follows [6]:

$$W(N,M) = \sum_{j=1}^{n} w_j \cos\left\{\frac{\pi}{6}\left(\left|t_N(x_j)-t_M(x_j)\right|+\left|i_N(x_j)-i_M(x_j)\right|+\left|f_N(x_j)-f_M(x_j)\right|\right)\right\}, \quad (2)$$

3 Application of the Cosine Measure in Misfire Fault Diagnosis of Gasoline Engines

3.1 Fault Diagnosis Method Based on the Cosine Measure

In general, a set of m fault patterns (fault knowledge) $P = \{P_1, P_2, \ldots, P_m\}$ and a set of n characteristics (attributes) $A = \{A_1, A_2, \ldots, A_n\}$ should be established in a fault diagnosis problem. Then the fault information of each fault pattern P_k ($k = 1, 2, \ldots, m$) with respect to characteristics of A_j ($j = 1, 2, \ldots, n$) can be expressed by a set of single-valued neutrosophic values (SVNVs) $P_k = \{p_{k1}, p_{k2}, \ldots, p_{kn}\}$, where $p_{kj} = <t_{kj}, i_{kj}, f_{kj}>$ is a SVNV, which is a basic component in the SVNS P_k, for $0 \le t_{kj} + i_{kj} + f_{kj} \le 3$ ($k = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$). Then, the information of a testing sample is expressed by a set of SVNVs $S_t = \{s_{t1}, s_{t2}, \ldots, s_{tn}\}$, where $s_{tj} = <t_{tj}, i_{tj}, f_{tj}>$ is a SVNV in the SVNS S_t for $0 \le t_{tj} + i_{tj} + f_{tj} \le 3$ ($t = 1, 2, \ldots, q$; $j = 1, 2, \ldots, n$).

Then, the cosine measure between a testing sample S_t and each fault pattern P_k ($k =1,2,\ldots, m$) can be calculated by the following formula:

$$W(S_t, P_k) = \sum_{j=1}^{n} w_j \cos\left\{\frac{\pi}{6}\left(\left|t_{tj} - t_{kj}\right| + \left|i_{tj} - i_{kj}\right| + \left|f_{tj} - f_{kj}\right|\right)\right\}. \tag{3}$$

According to the largest measure value of $W(S_t, P_k)$, we can determine that the testing sample S_t should belong to the fault pattern P_k.

3.2 Application in the Misfire Fault Diagnosis of Gasoline Engines

In this subsection, we apply the fault diagnosis method based on the cosine measure to the misfire fault diagnosis of gasoline engines to show the effectiveness and rationality of the proposed diagnosis method.

Misfire fault problems are usually produced in operating process of gasoline engines [4, 5]. Thus, they can reduce the operating power and working performance of gasoline engines and increase fuel consumption so that they aggravate the pollution of exhaust emission when the burning quality of mixture gases descends in the combustion chamber of gasoline engines. To keep better working performance of gasoline engines, we have to find out and eliminate the affected factors of low burning quality in gasoline engines. Then, the main components of HC, NO_x, CO, CO_2, O_2, water vapor etc included in the exhaust emission of gasoline engines can affect the burning quality of mixture gases in the engines. Under different burning conditions in the engines, the exhaust emission content can be changed in some variable ranges corresponding to the change of operating status or the occurrences of various mechanical and electronic faults in the engines. We have discovered the relation between the misfire fault and the content of the components in the exhaust emission of gasoline engines [4]. Hence, we can judge the operating status of the engines by analyzing the change of exhaust emission content.

Let us investigate the misfire fault diagnosis problem of the gasoline engine EQ6102 [4, 5]. In general, the misfire faults of the engine can be classified into three fault types: no misfire (normal work), slight misfire and severe misfire to indicate the operating status of the engine. The slight misfire indicates the decline in the performance of ignition capacitance or the ignition delay, or the spark plug misfire in one of six cylinders; while the severe misfire indicates the spark plug misfire in two of six cylinders. According to real-testing data [4, 5], we can obtain three kinds of fault patterns: no misfire (P_1), slight misfire (P_2), severe misfire (P_3), which are denoted by a set $P = \{P_1, P_2, P_3\}$, with respect to five characteristics (HC, NO_x, CO, CO_2, O_2) denoted by a set $A = \{A_1, A_2, A_3, A_4, A_5\}$, as shown in Table 1.

In Table 1, $\varphi_{HC}\times10^{-2}$, φ_{CO2}, $\varphi_{NOx}\times10$, $\varphi_{CO}\times10^{-1}$ and φ_{O2} in the characteristic set $A = \{A_1, A_2, A_3, A_4, A_5\}$ indicate the exhaust emission concentration of the five components HC, CO_2, NO_x, CO and O_2 expressed by volume percentage [4, 5], and then the characteristic values of A_j (j = 1, 2, 3, 4, 5) are expressed as SVNVs in Table 1.

To illustrate the effectiveness of the misfire fault diagnosis of the engine, we introduce the nine sets of real-testing samples for the engine EQ6102 from [4, 5], and then the characteristic values in the real-testing samples are expressed by SVNVs, which are shown in Table 2.

Table 1. Fault knowledge expressed bySVNVs for the engine EQ6102 [5]

	A_1 ($\varphi_{\mathrm{HC}}\times10^{-2}$)	A_2 (φ_{CO2})	A_3 ($\varphi_{\mathrm{NOx}}\times10$)	A_4 ($\varphi_{\mathrm{CO}}\times10^{-1}$)	A_5 (φ_{O2})
P_1 (Normal work)	<0.03, 0.05, 0.92>	<0.51, 0.42, 0.07>	<0.03, 0.05, 0.92>	<0.3, 0.2, 0.5>	<0.062, 0.028, 0.91>
P_2 (Slight misfire)	<0.01, 0.036, 0.954>	<0.428, 0.41, 0.16>	<0.04, 0.08, 0.88>	<0.29, 0.21, 0.5>	<0.04, 0.07, 0.89>
P_3 (Severe misfire)	<0.2, 0.3, 0.5>	<0.3, 0.4, 0.3>	<0.1, 0.2, 0.7>	<0.1, 0.2, 0.7>	<0.07, 0.08, 0.85>

Table 2. Real-testing samples of exhaust emission

	A_1 ($\varphi_{\mathrm{HC}}\times10^{-2}$)	A_2 (φ_{CO2})	A_3 ($\varphi_{\mathrm{NOx}}\times10$)	A_4 ($\varphi_{\mathrm{CO}}\times10^{-1}$)	A_5 (φ_{O2})	Actual fault type
S_1	<0.0455, 0, 0.9545>	<0.047, 0, 0.953>	<0.033, 0, 0.967>	<0.48, 0, 0.52>	<0.0527, 0, 0.9473>	P_2
S_2	<0.0572, 0, 0.9428>	<0.075, 0, 0.925>	<0.062, 0, 0.938>	<0.42, 0, 0.58>	<0.0751, 0, 0.9249>	P_1
S_3	<0.0261, 0, 0.9739>	<0.065, 0, 0.935>	<0.086, 0, 0.914>	(0.453, 0, 0.547>	<0.0431, 0, 0.9569>	P_2
S_4	<0.0312, 0, 0.9688>	<0.062, 0, 0.938>	<0.051, 0, 0.949>	<0.287, 0, 0.713>	<0.1064, 0, 0.8936>	P_2
S_5	<0.3761, 0, 0.6239>	<0.045, 0, 0.955>	<0.139, 0, 0.861>	<0.179, 0, 0.821>	<0.1025, 0, 0.8975>	P_3
S_6	<0.422, 0, 0.578>	<0.052, 0, 0.948>	<0.188, 0, 0.812>	<0.194, 0, 0.806>	<0.0931, 0, 0.9069)	P_3
S_7	<0.0189, 0, 0.9811>	<0.081, 0, 0.919>	<0.091, 0, 0.909>	<0.459, 0, 0.541>	<0.0377, 0, 0.9623>	P_2
S_8	<0.0555, 0, 0.9445>	<0.086, 0, 0.914>	<0.057, 0, 0.943>	<0.39, 0, 0.61>	<0.0736, 0, 0.9264>	P_1
S_9	<0.0551, 0, 0.9449>	<0.085, 0, 0.915>	<0.05, 0, 0.95>	<0.386, 0, 0.614>	<0.0789, 0, 0.9211>	P_1

Table 3. Fault diagnosis results of the nine real-testing samples

	P_1	P_2	P_3	Diagnosis result	Actual fault type
S_1	0.9552	**0.9616**	0.9364	P_2	P_2
S_2	**0.9618**	0.9617	0.9358	P_1	P_1
S_3	0.9616	**0.9618**	0.9421	P_2	P_2
S_4	0.9611	**0.9616**	0.9490	P_2	P_2
S_5	0.9402	0.9512	**0.9560**	P_3	P_3
S_6	0.9482	0.9493	**0.9560**	P_3	P_3
S_7	0.9615	**0.9617**	0.9232	P_2	P_2
S_8	**0.9618**	0.9586	0.9170	P_1	P_1
S_9	**0.9618**	0.9602	0.9187	P_1	P_1

Then, the importance of the five characteristics (five components) is considered by the weight vector $\boldsymbol{W} = (w_1, w_2, w_3, w_4, w_5) = (0.05, 0.35, 0.3, 0.2, 0.1)$ [4]. By using Eq. (3), the diagnosis results are shown in Table 3. From Table 3, all the fault diagnosis results are in accordance with all the actual fault types.

Therefore, the proposed fault diagnosis method for the gasoline engine is effective. Compared with the fault diagnosis method for the gasoline engine in [4, 5], the fault diagnosis method proposed in this paper is simpler and easier than the fault diagnosis method by using extension set theory [4], and then the fault diagnosis method with SVNSs in this paper contains more information (including truth information, indeterminacy information and falsity information) than the fault diagnosis method using the neutrosophic numbers [5] which consist of the determinate part and indeterminate part.

4 Conclusions

This paper proposed a fault diagnosis method based on the cosine measure of SVNSs and applied it to the misfire fault diagnosis of gasoline engines under a single-valued neutrosophic environment. The fault diagnosis results of the gasoline engine demonstrated the effectiveness and rationality of the proposed fault diagnosis method. The diagnosis method proposed in this paper is an extension of existing fault diagnosis methods and provides a new way for fault diagnoses of gasoline engines. In the future, the developed diagnosis method will be extended to other fault diagnoses, such as vibration faults of turbines, aircraft engines and gearboxes.

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