Research on Noise Diagnosis for Sweeping Vehicle Based on ANFIS

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Abstract. Aiming at the lack of method on noise diagnosis for sweeping vehicle, this paper proposes a vehicle noise diagnosis scheme based on adaptive fuzzy neural inference system (ANFIS). The paper explains the principle of ANFIS in the field of noise diagnosis, and performs a noise test on a sweeping vehicle. The spectrum analysis is utilized to obtain the data for ANFIS network training, inference and verification. Combined with ANFIS theory, the noise source distribution of the sweeping vehicle is inferred and verified. The results show that the noise source diagnosis method based on ANFIS is feasible and effective for the sweeping vehicle. Furthermore, the method can provide a reference for the similar situation where only parts of the noise sources are known.

1. Introduction

Not satisfied with traditional noise diagnosis methods, advanced methods on noise source identification based on signal analysis or array technology are emerging. Among them, wavelet analysis has been applied a lot, which extracts the signal of noise through wavelet transform and inverse transform [1]. Since the introduction of near-field acoustic holography by J.D. Maynard and E.G. Williams [2] in the 1980s, this method has been widely applied. A. T. Wall [3] et al. proposed a near-field acoustic holography method with multi-source statistical optimization. As a signal processing technology in the field of telecom, the beamforming method is mainly suitable for noise diagnosis in medium and high frequency. Meanwhile, the transfer path analysis (TPA) originated in the 1980s has gradually become one of the main methods for analyzing noise in recent years. P. Zhu [4] et al. proposed a TPA method for estimating the uncoupled transfer function of passive components based on tests without splitting the system.

ANFIS originated from the cross application of fuzzy logic theory and artificial neural network technology. The concept of fuzzy logic was first proposed by L.A.Zadeh [5] in 1965. In 1974, E.H. Mamdani [6] applied Zadeh's theory to practical engineering for the first time, and various intelligent technologies related to fuzzy logic came into being. The artificial neural network (ANN) is derived from the MP model proposed by W.S. McCulloch [7] and W. Pitts in 1943 and gradually becomes one...
of the core basic theories of artificial intelligence. There are two main types of feedforward neural networks: BP (backward propagation) neural network proposed by Rumelhart and McClelland [8] in 1986, which has the characteristics of signal forward propagation and error backward propagation; RBF (radial basis function) neural network proposed by D.S. Broomhead [9] in 1988 which was based on Powell's multivariate interpolation radial basis function. In order to integrate the advantages of fuzzy logic and neural networks, J.S.R. Jang [10] proposed an adaptive-network-based fuzzy inference system (ANFIS) in 1993. In the field of acoustics, Jian Liu [11] applies ANFIS to secondary source parameter optimization for active noise control. In the research of ANFIS optimization algorithm, J.P.S. Catalao [12] et al. combined wavelet transform with particle swarm optimization algorithm to forecast short-term electricity price.

This paper proposes a vehicle noise diagnosis method based on ANFIS. In order to verify the method, based on the distribution of the main noise source of the sweeping vehicle, the noise test is carried out. Combined with the spectrum analysis, ANFIS noise diagnosis method is utilized to infer the noise source in unknown frequency, and finally the source distribution and energy contribution order are obtained.

2. Basic theory

2.1. Process of noise diagnosis

The primary process of ANFIS in noise diagnosis is diagrammatized in Fig.1. Through the spectrum analysis of signals obtained from the noise test of the sweeping vehicle, the data used for training, inference and verification can be gained respectively. Then based on the inference results and spectrum analysis, the distribution of main noise sources of the sweeping vehicle is obtained.

![Figure 1. Primary Process of ANFIS.](image)

2.2. ANFIS for noise diagnosis

ANFIS consists of database and rule base. As for rule base, 2 forms of fuzzy rules are commonly utilized. Since the results of noise diagnosis require precise coordinates, the T-S inference rule as shown in Fig.2 is superior to the fuzzy rule when applied in this paper.

![Figure 2. T-S Inference Rule.](image)
For MIMO fuzzy system, the form of rule is:

\[
R^k: \text{IF } x_1 \text{ is } A_1^{k} \text{ and } \ldots \text{ and } x_i \text{ is } A_i^{k} \text{ THEN } X_i = \sum_{i=0}^{n_k} a_i^{k} x_i \text{ and } Y_i = \sum_{i=0}^{n_k} b_i^{k} x_i \text{ and } Z_i = \sum_{i=0}^{n_k} c_i^{k} x_i
\]  

(1)

Where \( n \) denotes the rule number with the maximum: \( i^k \); \( k \) is the input number, indicating the number of near-field points in noise test; \( i \) is the number of input sets, \( x \) is the input signal, and \( X, Y, Z \) are the output signals; \( w_n \) is the activation intensity of the \( n \)-th rule. The final output can be expressed as Eqs. 2.

\[
X = \sum_{n=1}^{N} w_n X_e / \sum_{n=1}^{N} w_e \quad Y = \sum_{n=1}^{N} w_n Y_e / \sum_{n=1}^{N} w_e \quad Z = \sum_{n=1}^{N} w_n Z_e / \sum_{n=1}^{N} w_e \quad (N = i^k)
\]  

(2)

The database contains premise parameters for input and consequent parameters for output. The former is embodied in the membership function (MF) of the fuzzy set, that is, \( A_{ik} \) in Eqs. (1). Generally, the range of the function is \([0, 1]\), and there are several commonly used MF type consisting of Gaussian MF, “bell” MF, trapezoidal MF and trigonometric MF. Gaussian membership function will be adopted, and its expression is:

\[
y = \exp\left(-\frac{(x-c)^2}{\sigma^2}\right)
\]  

(3)

Where \( c \) and \( \sigma \) determine the symmetry axis and shape of the function respectively. The consequent parameters are \( a_k, b_k \) and \( c_k \) in Eqs. (1).

For the fuzzy inference system constructed above for noise diagnosis, the ANFIS network shown in Fig.3 is established to train the unknown parameters. For sake of simplification, the MISO system on Z direction is utilized to illustrate Fig.3. The network consists of 5 layers, and the node functions of each layer share the same type. The nodes of first layer represent the input MFs used to define the magnitude of the value of the near-field microphones. The symbol of the nodes of second layer is \( \Pi \), which means that the input signals are multiplied in this layer, and the output is obtained by Eqs. (4).

\[
w_n = \mu_{A_1}^{n}(x_1) \times \mu_{A_2}^{n}(x_2) \times \ldots \times \mu_{A_i}^{n}(x_i)
\]  

(4)

Where \( w_n \) denotes the activation intensity of the \( n \)-th rule; \( \mu_{A_k}^{n} \) represents the input MF of the \( k \)-th microphone in the \( n \)-th rule. Where \( w_n \) denotes the activation intensity of the \( n \)-th rule; \( \mu_{A_k}^{n} \) represents the input MF of the \( k \)-th microphone in the \( n \)-th rule.
Each node of the third layer is labeled N, and its function is to calculate the ratio of the activation intensity of the fuzzy rule where the node is located, to the total activation intensity. This layer does not contain variable parameters, and the node output is calculated by Eqs. 5.

$$w_n = w_n / \sum_{n=1}^{N} w_n$$

(5)

The nodes in the fourth layer represent the T-S fuzzy rule output of each rule, and the output function of each node is:

$$O_n = w_n y_n = w_n \sum_{k=0}^{k_{max}} c_{nk} x_k$$

(6)

Where $c_{nk}$ denotes the output parameters of the fuzzy rule. The fifth layer is the accumulation layer. This layer has only one node, and its function is to sum all the output results obtained by the fourth layer.

The ANFIS network for noise diagnosis of the sweeping vehicle is constructed. The optimization algorithm of network training is a hybrid algorithm combining gradient descent and least squares. Finally, the trained network will be subjected to noise source inference to obtain the source of unknown frequency noise.

3. Testing and Calculation

In order to verify the feasibility of the method above, test and calculation were carried out for a sweeping vehicle. The basic parameters of the sweeping vehicle are shown in Table 1.

| No | Parameters                        | Value                  |
|----|-----------------------------------|------------------------|
| 1  | Length of the vehicle (mm)       | 8586                   |
| 2  | Width of the vehicle (mm)        | 2490                   |
| 3  | Height of the vehicle (mm)       | 2980                   |
| 4  | Wheelbase (mm)                   | 4800                   |
| 5  | Engine speed (rpm)               | 2300 (Primary); 2500 (Fan) |
| 6  | Rated Speed of Fan (rpm)         | 2350                   |

3.1. Testing and analyzing

For the engines, fan and the cleaning system of the vehicle can be operated independently to some extent, in order to obtain the noise characteristics of each component, the method of divisional operation can be adopted, and the test schematic diagram is as shown in Fig.4.

After that, select the 1/3 octave and power spectrum at the evaluation points under the operating conditions of rated work as shown in Fig.5. The frequencies of the signal measured at evaluation points with the value in the power spectrum greater than 68.87dB (within 20dB of the peak: 88.87dB) were concerned. As was shown in Fig.5, the main frequencies are 30Hz, 35Hz, 59.38Hz, 94.38Hz, 126.88Hz, 331.25Hz and 628.13Hz. By means of spectrum analysis combined with the basic parameters of the sweeping vehicle, we can determine the noise of the four frequencies 30Hz, 35Hz, 331.25Hz and 628.13Hz as shown in table 2.
1-9: Microphone 1-9  10: Three-axis accelerometer  11-13: Single-axis accelerometer 1-3

Figure 4. Noise Test Schematic Diagram.

![Noise Test Schematic Diagram](image)

Figure 5. Signals at Evaluation Points.

![Signals at Evaluation Points](image)

Table 2. Result of Spectrum Analysis.

| Frequency/Hz | 30  | 35  | 59.38 | 94.38 | 126.88 | 331.25 | 628.13 |
|-------------|-----|-----|-------|-------|--------|--------|--------|
| Source      | Fan Engine | Primary Engine | Unknown | Unknown | Unknown | Engine (F) | Cooler | Fan |

3.2. Theoretical calculation

The vehicle coordinate is established by taking the width as X direction, the length as Y direction, and the height as the Z direction. The coordinates of the center of the known noise source corresponding to Table 2 are measured as shown in Table 3.

The data corresponding to the 4 frequencies measured by 7 near-field microphones are combined with the coordinates to form the training data in three directions respectively. Therefore, a set of vectors with k+1 dimensions were formed to train the ANFIS network. In order to ensure the
unification of the input MF under different working conditions, the input part (first k dimensions) of the training vectors is normalized by the two-norm operator to limit the input between (0, 1), and the formula used here is:

$$a'_i = a_i / \sqrt{\sum_{m=1}^{3} a_m^2}$$  \hspace{1cm} (7)

Where $a_i$ and $a'_i$ denotes the training vectors before and after normalization respectively. The ANFIS network was trained using normalized vectors, and its training iteration error (direction Z) is shown in Fig.6 (left). The generalization performance (direction Z) of the trained network is shown in Fig.6 (right). It can be concluded that the optimization turned out to be effective.

![Figure 6. Optimization Performance.](image)

The near-field vectors of 59.38Hz, 94.38Hz and 126.88Hz under rated conditions were normalized according to Eqs. (7) to be the inference data as shown in Table 4. The unknown frequencies are inferred by the trained ANFIS model as the results shown in Table 5.

### Table 3. Coordinates of the Known Noise Source.

| Frequency   | 30Hz | 35Hz | 331.25Hz | 628.13Hz |
|-------------|------|------|----------|----------|
| X           | 1    | 1    | 2        | 1        |
| Y           | 3.5  | 2    | 3.5      | 6        |
| Z           | 2    | 1    | 4        | 3        |

$$a'_i = a_i / \sqrt{\sum_{m=1}^{3} a_m^2}$$  \hspace{1cm} (7)

### Table 4. Inference Data.

| No. | 1   | 2    | 3    | 4    | 5    | 6    | 7    |
|-----|-----|------|------|------|------|------|------|
| 59.38Hz | 0.53705 | 0.716781 | 0.31312 | 0.131176 | 0.101709 | 0.10355 | 0.247961 |
| 94.38Hz  | 0.96099 | 0.056659 | 0.262071 | 0.025223 | 0.032303 | 0.02988 | 0.045099 |
| 126Hz    | 0.9698  | 0.010701 | 0.23473 | 0.00104 | 0.004365 | 0.05968 | 0.026165 |

### Table 5. Results of Inference.

| X   | Y    | Z    |
|-----|------|------|
| 59.38Hz | 1.1303 | 2.3175 | 2.1819 |
| 94.38Hz  | 1.17  | 5.6717 | 1.4099 |
| 126Hz    | 0.9890 | 5.533 | 0.9903 |
3.3. Conclusion Verification

In order to verify the accuracy of the inference results in table 5, the corresponding eigenvectors with the same frequency peak in other operation conditions were selected to infer for verification. The root mean square of the difference from the according value in table 5 was taken as the error of verification to obtain Table 6, which shows that the inference results are relatively accurate.

| Frequency (Hz) | Error X | Error Y | Error Z |
|---------------|---------|---------|---------|
| 59.38         | 0.06529 | 0.29873 | 0.14027 |
| 94.38         | 0.11691 | 0.30866 | 0.34516 |
| 126           | 0.035216| 0.66317 | 0.15124 |

The inference result of coordinate value of the noise in 63Hz is reflected to the cavity inside the vehicle near the top of the fan engine. It is estimated that the cavity resonance inside the cabin is the noise source. In order to verify it, the spectrums at evaluation points under the conditions before (left) and after (right) the cabin is opened are compared in Fig. 7. It’s obvious that there is a significant peak near 60Hz when is cabin is closed, which disappeared after the cabin is opened, so that the conclusion that the 60Hz noise source belongs to the cavity resonance can be verified to some extent.

The inference results indicate that the fan is the source of the noise in 95Hz. The majority of fan noise is divided into two parts, one part is the aerodynamic noise with the frequency of 628.13Hz. The other part is radiated by vibration. Therefore, it is estimated that 95Hz noise is generated from the fan shell. In order to verify this conclusion, the spectrums measured by the three-axis accelerometer on the fan before (Left) and after (Right) the fan working are compared as shown in Fig. 8. It is obvious that, the vibration with a peak at 94.38Hz appears when the fan is working. Meanwhile, when the fan rotates, the peak is mainly reflected in the Z direction, that is, along the normal vector of the shell. Therefore, it can be ruled out that the vibration is transmitted by the fan engine through the belt. As a consequence, it is verified that the 94.38Hz noise source is the vibration of the fan shell to some extent.

According to table 5, the deduced point of 126.88Hz is located near the cleaning mechanism, therefore, 2 sets of spectrums of the microphone at the bottom of the cabin are compared under the situations with distinguished washing pump working conditions as shown in Fig. 9. It can be observed that the peak point of 129Hz exists only in the washing operation. Associated with the coordinate value obtained by inference, it can be determined that the noise source of 129Hz is the washing pump.
Combined spectrum analysis with the method based on ANFIS, the main noise source information of a sweeping vehicle can be obtained as shown in Table 7. Then according to Fig.5 and table 7, the energy ratio corresponding to each noise source at right evaluation point can be obtained, as shown in Table 8.

Table 7. Distribution of Noise Source.

| Frequency    | 30Hz | 35Hz | 59.38Hz | 94.38Hz | 126.88Hz | 331.25Hz | 628.13Hz |
|--------------|------|------|---------|---------|----------|----------|----------|
| Source       | Fan Engine | Primary Engine | Cavity Resonance | Fan Shell | Washing Pump | Engine (F) Cooler | Aerodynamic Noise of Fan |

Table 8. Energy Ratio of Noise Sources.

| Noise Source       | Engines | Engine (F) Cooler | Cavity Resonance | Washing Pump | Fan Shell |
|--------------------|---------|-------------------|------------------|--------------|-----------|
| Energy Ratio       | 9.685%  | 1.998%            | 21.3%            | 16.1878%     | 50.83%    |

It is obvious in table 8 that, in the rated working condition of the sweeping vehicle, the fan accounts for the largest proportion of energy of the total noise, followed by cavity resonance.

4. Conclusion
This paper first established an ANFIS network for noise diagnosis. Then analyzed the data obtained from the test on a sweeping vehicle to extracts the vectors related to the known sources as the training
data of ANFIS, and the vectors related to the unknown sources as the inference data. After that the parameters of the ANFIS network were trained in MATLAB by means of the hybrid algorithm to be utilized to deduce the noise sources. Subsequently, the results of the inference were verified by spectrum analysis to prove the feasibility of the method. Finally, an approach on vehicle noise diagnosis based on noise test, spectrum analysis and ANFIS was formed, which could provide a reference for noise diagnosis of the similar vehicles or the cases with partial sources known.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (no.51575201).

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