Journal of the Institute of Industrial Applications Engineers Vol.6, No.1, pp.1–8, (2018.1.25)
DOI: 10.12792/JIIAE.6.1 Online edition: ISSN 2187-8811 Print edition: ISSN 2188-1758

Paper

Analysis of waveform spectrum of compact fan motor applying MT system

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(Received July 5, 2017, revised December 8, 2017)

Abstract: The demand for compact fan motor increases for cooling use in the electronic equipment by weight saving of IT apparatus, spacing-saving now. The quality check of compact fan motor in production field is being conducted by sensory test of inspector. This sensory test requires a lot of experience to accurately examine the subtle difference the fan's noise and vibration, and dispersion occurs in judgment depending on physical condition of inspector and environmental change. Development of a measuring device for quantitatively examine the sound and vibration level and quality of a small fan motor is required in order to improve the problems in these inspection processes. In this research, we focused on improvement of discrimination inspection accuracy of abnormality / normality by extraction of feature value of waveform data and evaluation of effectiveness. As a result, by applying the MT system, it was found that appropriate discrimination test can be performed with the acoustic / vibration waveform of compact fan motor.

Keywords: Feature value, Pattern recognition, Mahalanobis distance (MD), Effectiveness analysis, MT method

1. Introduction

Demand for compact fan motors for cooling the inside of electronic devices is increasing now due to weight reduction and space saving of IT equipment. In the quality inspection process at the site, quality inspection of compact fan motor is carried out by sensory inspection of inspector. This sensory test requires a lot of experience in order to accurately diagnose the subtle difference in sound of fan and difference in vibration, and variation in pass / fail judgment occurs due to changes in physical condition and environment of inspector.

In order to solve the problems in these inspection processes, development of a measuring device capable of quantitatively diagnosing the acoustic / vibration level and quality of a compact fan motor is required.

In a previous study, it has been reported on frequency analysis of the acoustic waveform of a compact fan motor and investigating characteristics appearing in normal and abnormal fans. However, we cannot find appropriate feature values from measured values and analytical results obtained by sound and vibration.

In this research, we focused on improvement of discrimination inspection accuracy of abnormality / normality by extraction of feature value of waveform data and evaluation of effectiveness.

2. Research purpose

In many cases, because of noise level of fan depends on the noise level of the whole motor, it is important to reduce the noise. Also, if the fan approaches and interferes with the fan cover on the stationary side, remarkable resonance sound may be generated.

The fan noise includes a rotational sound component (f_z) which is the product of the number of rotations (f) and the number of blades (z) and a turbulent sound component generated by turbulence of the wind flow. Recently, a method of changing the rotation speed by an inverter is used. In this case, with respect to ventilation noise, the rotational sound component (f_z) may generate superior noise at a certain rotational frequency.

This outstanding noise is called pure tone and is evaluated as a noisy sound. From studies of conventional fan noise, numerous studies on noise reduction have been made on rotational sound and turbulent sound from flow analysis on the number of blades and optimization of blade shape. [10]

In precedent research, there was a case of verifying the usefulness by introducing MT system which is one of pattern recognition methods, and understands a thing effective to some extent. In the case of using pattern recognition method, processing for extracting feature value from measurement data is performed. If an invalid feature amount is included in the abnormality detection, sensitivity and reliability of recognition decrease.

Therefore, it is important to set feature values considered valid for discrimination without excess or deficiency. Statistical values such as average value and peak value of the waveform were used as feature value in precedent research. However, in order to improve the accuracy of discrimination, many feature values and number of samples were required. If it is possible to extract feature values effective

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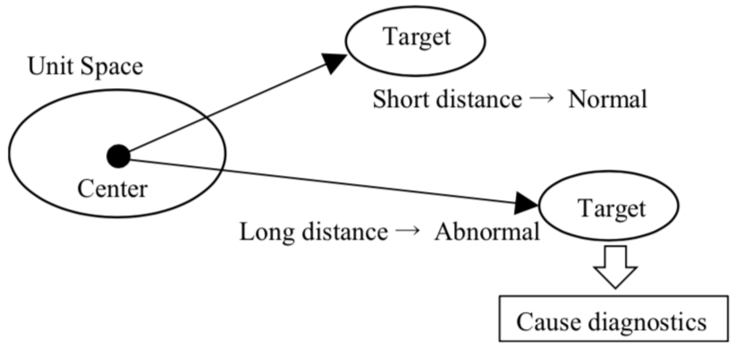

Figure 1: Conceptual drawing of the MT method

for abnormality detection from number of few samples, discrimination can be performed with high efficiency.

In this research, we applied a feature extraction technique of MT system which is a pattern recognition method, and studied to extract effective feature value for abnormality detection and to obtain stable discrimination result. [9]

3. Principle

3.1 Pattern recognition Pattern recognition technology is a technology to replace information processing such as human judgment and prediction with computer. In other words, it is a process of evaluating how much an unknown input pattern resembles a pre-input standard pattern by numerical values and determining which category it belongs to. In this research, MT (Mahalanobis · Taguchi) system was adopted as a pattern recognition technology. MT system is an information processing system which constitutes a data group of a reference pattern as a unit space and can judge whether target data belongs to a unit space or not. [9]

3.2 The MT Method The MT Method is a method for gaining cognizance of whether the target data (otherwise referred to as unknown data) belongs to the same standard, homogeneous, group. The MT Method defines a homogeneous population as the Unit Space. And it finds the distance between the center of the Unit Space and the target data in the form of Mahalanobis Distance (MD). [6]

As shown in Fig. 1, it is recognized that, if the MD turns out to be short, the pattern is close to the Unit Space, and that, if the MD turns out to be long, the pattern is distant. When the Unit Space is a normal population, if the MD is short, there is a strong possibility that the target data is normal.

The MT Method stands on a simple concept and is very easy to use; among the components of the MT System, the MT Method has the greatest number of practical applications. MD itself was proposed by Indian mathematician P.C. Mahalanobis, and is the result of converting multivariate information in which multiple variables are intertwined complicatedly into distance information. [4] [5]

3.2.1 Formulation of MD Mahalanobis' Distance is called MD. It is a kind of distance for multivariable space. Correlation effect is included in this distance. [6] [7]

a) Normalize data
MD calculation is possible without normalization. But after normalization, covariance in the next step is correlation coefficient. So evaluation of correlation effect is easy.

b) Make convariance matrix

$$\text{Convariance matrix} = \begin{pmatrix} 1 & B \\ B & 1 \end{pmatrix}$$

c) Make inverse matrix of covariance matrix

$$\begin{pmatrix} a & b \\ b & a \end{pmatrix} = \begin{pmatrix} 1 & B \\ B & 1 \end{pmatrix}^{-1} or$$

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} a & b \\ b & a \end{pmatrix}\begin{pmatrix} 1 & B \\ B & 1 \end{pmatrix}$$

d) Calculation of the square of MD

$$MD_i^2 = \begin{pmatrix} x_{1i} & x_{2i} \end{pmatrix}\begin{pmatrix} a & b \\ b & a \end{pmatrix}\begin{pmatrix} x_{1i} \\ x_{2i} \end{pmatrix}$$

$$MD^2 = XAX \text{ (if A is inverse matrix and X is data)}$$

3.2.2 MD derivation and certification The concept of MD is a value obtained by consolidating the deviation from the relationship between the distance and the correlation from the average of the object of interest in consideration of the correlation of the plurality of variables. [7]

MD in the relation of the target data of two items is given by following expression.

$$MD = \sqrt{\frac{u_1^2 - 2ru_1u_2 + u_2^2}{1 - r^2}} \quad (1)$$

$$u_1 = \frac{x_1 - m_1}{\sigma_1} \quad (2)$$

$$u_2 = \frac{x_2 - m_2}{\sigma_2} \quad (3)$$

x_1, x_2 : Target data
m : Average
σ : Standard deviation
r : Correlation coefficient

Equation(1)-(3) means to investigate how many times the distance from the average corresponds to the standard deviation which is an index of the variation of all data.

The MD calculation formula obtained by expanding $\sqrt{}$ in Expression (1) to a plurality of items is as follows.

$(u_1 \cdots u_k)$ on the right side is a value normalized by using the average and standard deviation of subscript item data.

$$MD = D^2 = (u_1 \cdots u_k) \begin{bmatrix} 1 & \cdots & r_{1k} \\ \vdots & \ddots & \vdots \\ r_{k1} & \cdots & 1 \end{bmatrix}^{-1} \begin{bmatrix} u_1 \\ \vdots \\ u_k \end{bmatrix} \quad (4)$$

$$u_k = \frac{x_k - m_k}{\sigma_k} \quad (5)$$

m_k : Average of data group
σ_k : Standard deviation of data$group$

$\begin{bmatrix} 1 & \cdots & r_{1k} \\ \vdots & \ddots & \vdots \\ r_{k1} & \cdots & 1 \end{bmatrix}^{-1}$: inverse matrix of the correlation matrix.

When the equation (4) is verified in the case of $k = 2$,

$$MD = D^2 = (u_1\ u_2) \begin{pmatrix} 1 & r \\ r & 1 \end{pmatrix}^{-1} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix}$$

The inverse matrix equation of the 2×2 matrix is,

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix}^{-1} = \frac{1}{a \cdot d - b \cdot c} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}^{-1}$$

$$\begin{pmatrix} 1 & r \\ r & 1 \end{pmatrix}^{-1} = \frac{1}{1 - r^2} \begin{pmatrix} 1 & -r \\ -r & 1 \end{pmatrix}^{-1}$$

Therefore, the following expression is obtained,

$$\begin{aligned} \therefore D^2 &= (u_1\ u_2) \frac{1}{1 - r^2} \begin{pmatrix} 1 & -r \\ -r & 1 \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \\ &= \frac{1}{1 - r^2} (u_1 - ru_2 - ru_1 + u_2) \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \\ &= \frac{u_1^2 - 2ru_1u_2 + u_2^2}{1 - r^2} \end{aligned}$$

It proved to satisfy the expression in $\sqrt{}$ equation (1).

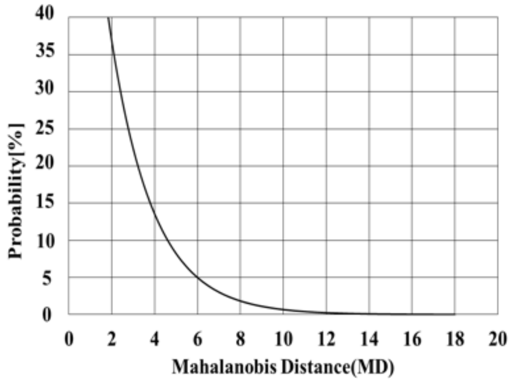

Figure 2: Distribution of MD

In the MT method, in order to normalize the average of the squared values of MD to 1, an operation of dividing the value of $MD = D^2$ by the number of items k is added. Therefore, the calculation formula of MD used in the MT method is as follows.

$$\begin{aligned} \therefore \quad D &= \sqrt{MD} \\ &= \sqrt{\frac{1}{k}(u_1 \cdots u_k) \begin{bmatrix} 1 & \cdots & r_{1k} \\ \vdots & \ddots & \vdots \\ r_{k1} & \cdots & 1 \end{bmatrix}^{-1} \begin{bmatrix} u_1 \\ \vdots \\ u_k \end{bmatrix}} \end{aligned} \quad (6)$$

3.3 Discrimination method With the MT Method, normality / abnormality is determined by comparing MD of target data with the threshold value. When the MD is small close to 1, it is judged that it belongs to the unit space, and if MD is larger than the set threshold value, it is judged not to belong to the unit space. The judgment threshold with the MT Method is generally said to boil down to 4 or thereabouts. This is because, for all practical statistical mathematics purposes, if the MD exceeds 4, the probability of unknown (target) data being a member of the Unit Space shrinks to a small possibility. [8]

However, it is currently reported that the method of setting a threshold using the χ 2 distribution is highly effective. For this reason, we set the threshold using the χ 2 distribution in this research.

In Fig. 2, the horizontal axis represents the MD, the vertical axis represents the probability, and the graph curve means the probability that the MD value takes. [1]

3.4 Feature extraction The features of waveforms include frequency and amplitude, categories such as average frequency, magnitude of oscillation, and maximum magnitude of oscillation have been commonly used. Frequency analysis (FFT: Fast Fourier Transform), wavelets, etc. Frequency analysis is a technique of expressing the characteristics of waveforms in terms of a frequency axis and an energy axis. A wavelet is a technique of expressing the characteristics of waveforms in terms of a time axis, in addition to the frequency axis and the energy axis.

Frequency analysis and wavelets are excellent methods of explaining the characteristics of waveforms. Nonetheless, it cannot quite be said that both convey sufficient information

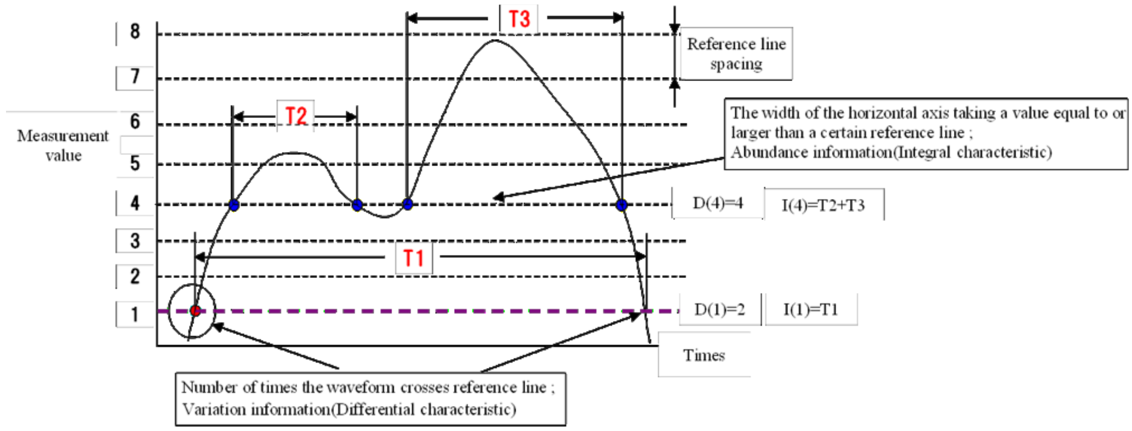

Figure 3: Variation and abundance information

on the characteristics of the given waveform pattern. For instance, frequency analysis is a processing method dealing with waveforms over a relatively long period of time and is therefore not adept at capturing waveform changes that may be occurring within short time spans. Furthermore, both frequency analysis and wavelets presuppose the human operator's evaluation and judgment of the results they produce.

The variation and abundance information extraction method was proposed as a means of expressing the characteristics of waveform patterns in more accurately quantified terms.

In this research, variation and abundance information are extracted from the radiated sound waveform from compact fan motor, and the waveform characterized. First, a parallel line (reference line) is drawn on the time axis at a constant interval in the waveform in the time domain, and a section on the time axis (extraction width) for calculating the characteristic amount is set. Next, the number of times of intersection with the reference line within interval of extraction width is taken as the variation, and sum of the values in the range above the reference line is obtained as the abundance information. Performing calculation of this variation and abundance information in all sections of the waveform data is called "waveform analysis". [1] [6]

Fig. 3 shows the concept of variation and abundance information (Differential and Integral characteristics) in feature extraction.

4. Experiment method

4.1 Noise level of the test fan As shown in Fig. 4 , fan motors generally rotate in both directions, so that the blades of the fan use radial blade (same type as the test fan). Radial blades have low cooling efficiency and high noise. The noise level is obtained from equation (7). However, the evaluation position of the noise is the axial center height of the motor, and the distance is 1m. [10]

$$\text{Noiselevel} \quad : A[db] = 70\log D + 50\log N + k \qquad (7)$$

D : Outerdiameteroftheblades[m]

N : numberofrotations[rps]

k : constant(= 32 ∼ 36)

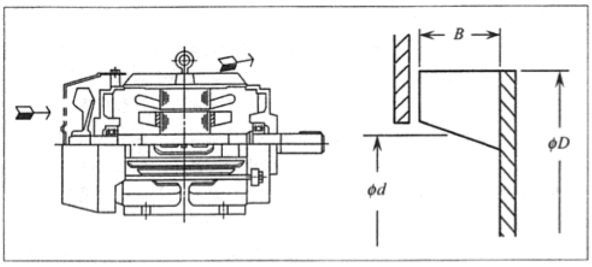

Figure 4: Fan shap

4.2 Test fan In this research, we used two kinds of compact fan motors. Sample items shown in Fig. 5 (& Table 1) are five normal products (♯ 9701 to ♯ 9705), sample items shown in Fig. 6 (& Table 2) include 10 normal products (fan 1 to fan 10) are five abnormal products (fan ♯ 1 to fan ♯ 5). The abnormal product has surface buckle, and each displacement is 14μm for fan ♯ 1, 25μm for fan ♯ 2, 50μm for fan ♯ 3, 70μm for fan ♯ 4 and 90μm for fan ♯ 5. Surface buckle refers to the size when the end face rotating around a certain axis deviates from a plane perpendicular to this axis during rotation.

Table 1: Specification of fan

Fan flame size	$92.5 \times 92.5 \times 25.4[mm]$
Blade number	5
Rated Voltage	DC12V
Rotational speed	3400[rpm]

Table 2: Specification of fan

Fan flame size	$42 \times 42 \times 10[mm]$
Blade number	5
Rated Voltage	DC24V
Rotational speed	10000[rpm]

4.3 Measurement of sound radiation Measurement of the sound of compact fan motor was done in a quiet room.

Figure 5: Test fan

Figure 6: Test fan

A schematic diagram of recording is shown in Fig. 7 .

The sound collection was set to 30mm above the rotation axis center from the rotation surface on the fan suction side by a 1/2-inch condenser microphone. The reason is based on the distance between ear and fan when inspector performs sensory test. Fan recording time was 10 seconds, sampling frequency was 51.2 [kHz], and signal from microphone was saved in PC via A / D converter.

Figure 8 shows the waveform data obtained by measuring the radiated sound of fan. Measurement sample number and time of fan's radiated sound is "512000 samples = 10 seconds" at sampling frequency 51.2 [kHz]. However, it was judged that a more accurate analysis could be performed by capturing a behavior change for a short time, and waveform data of "5120 samples = 0.1 second" was analyzed.

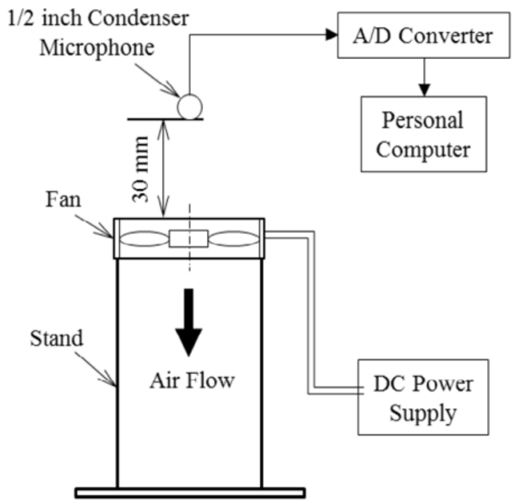

Figure 7: Recording system

4.4 Analysis procedure The analysis procedure of the radiated sound waveform is as follows.

1. Feature extraction
   In order to characterize the waveform, extraction width and reference line set, and variation and abundance values are extracted as the feature value.

2. Creating Unit Space
   Although the unit space consists of a plurality of samples and their variables (feature items), MT method has a condition that the number of samples in unit space must be larger than the number of variables, and more than 3 times the variable is considered ideal.

3. Setting a threshold
   The threshold was determined with a probability of 5% according to the χ^2 distribution. This value is considered to be the boundary value when judging things in statistics, and it is called the significance level.

4. MD calculation of target data
   The waveform analysis of the abnormal fan and feature

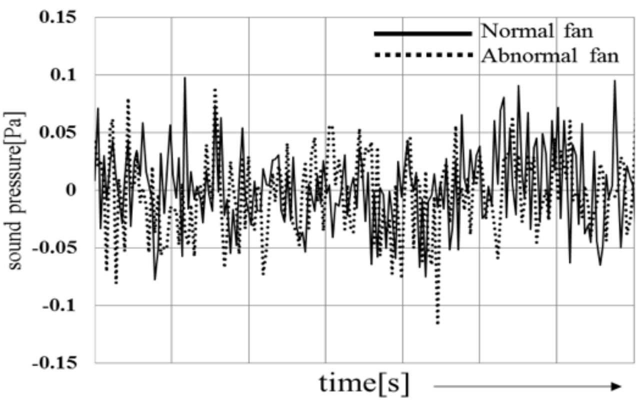

Figure 8: Waveform data

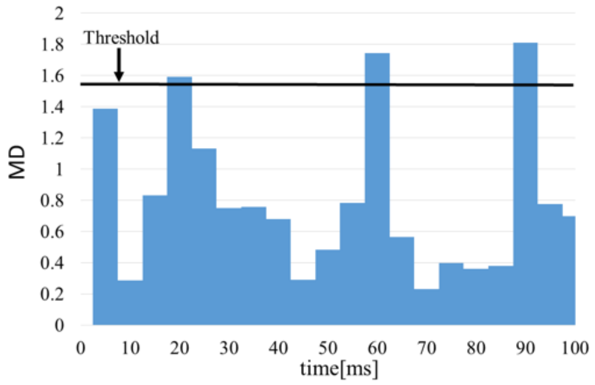

Figure 9: MD calculation result of Normal products

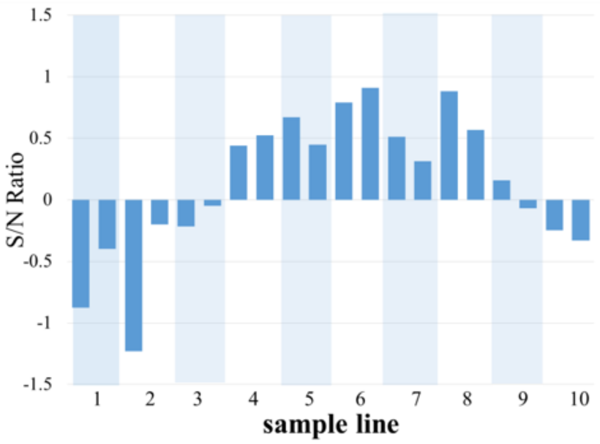

Figure 10: Effectiveness analysis result

value of unit space are extracted, and the MD value is calculated by Eq. (3).

5. Effectiveness analysis
   Effectiveness analysis is a process of evaluating which item is effective for abnormality detection by SN ratio.
   The SN ratio is calculated by Eq. (8).

$$\eta = -10 \log \left\{ \frac{\frac{1}{D_1^2} + \frac{1}{D_2^2} + \cdots + \frac{1}{D_k^2}}{k} \right\} \tag{8}$$

5. Analysis result

5.1 Analysis result of normal product First, we analyzed a waveform in the fan of Fig. 5 and extracted feature value. The fixed value is extraction width 20, reference line 10. Therefore, 20 samples can be obtained from one waveform. In addition, since the reference line calculates the variation and abundance information for each extraction width, the number of variables is 20 pieces. Next, taking these into consideration, three waveforms were arbitrarily selected from five normal products (♯ 9701 to ♯ 9705) so as to be three times the number of variables, and a unit space was created. Finally, waveform analysis was also performed on normal products not belonging to the unit space, and the MD value was calculated. Fig. 9 shows the calculation result of the MD value of the normal product.

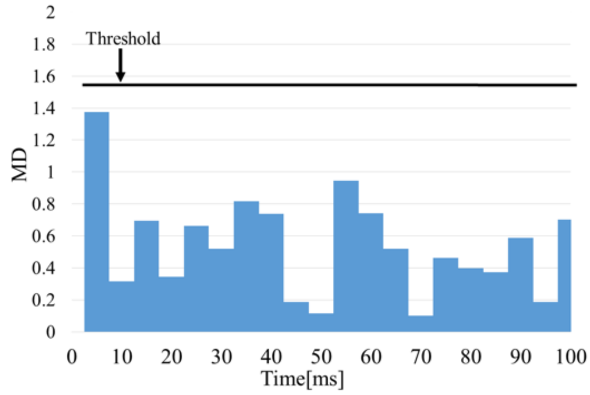

Figure 11: MD calculation result after analysis

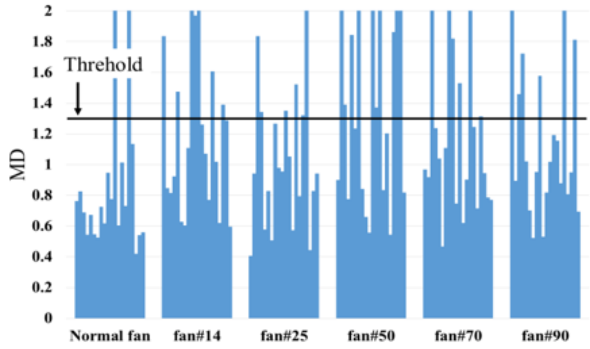

Figure 12: MD calculation result of each sample

On the graph, it is judged to be abnormal because the MD value exceeding the threshold can be confirmed. However, it is understood that because the normal product is the target, it is not an appropriate analysis result. It is estimated that variables invalid in discrimination are included in feature values. Therefore, it is necessary to analyze and evaluate which items are highly effective.

Fig. 10 shows the results of the effectiveness analysis on the target data. The horizontal axis represents the variable, and vertical axis represents the SN ratio, which means that the item with the highest value is valid for the judgment.

Therefore, Fig. 11 shows the result of calculating the MD value using the variable with the positive SN ratio as the feature value. On the graph, it is judged that the MD value is equal to or less than the threshold value and it is judged to be normal, and it is judged that the effective feature value can be extracted.

5.2 Analysis result of abnormal product Next, we analyzed a waveform in a fan of Fig. 6 and extracted feature value. The fixed value is extraction width 20 and reference line 30. The number of variables is 60.

In the unit space, nine waveforms were arbitrarily selected from 10 normal products (fan 1 to fan 10) so that the number of samples was three times as large as the variable. Waveform analysis was performed on abnormal products (♯ fan 1 to ♯ fan 5). Fig. 12 shows MD values of normal and abnormal items not belonging to the unit space.

From the results, MD values above the threshold were

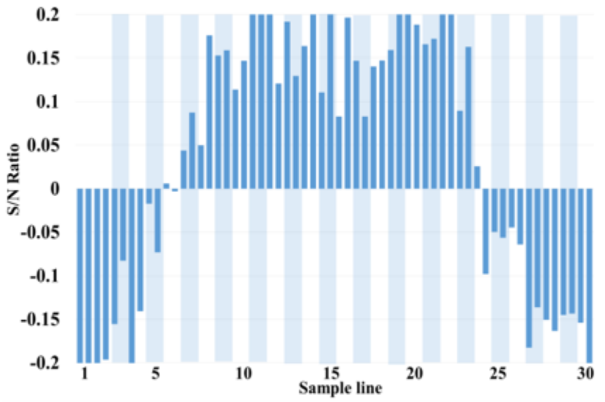

Figure 13: Effectiveness analysis result

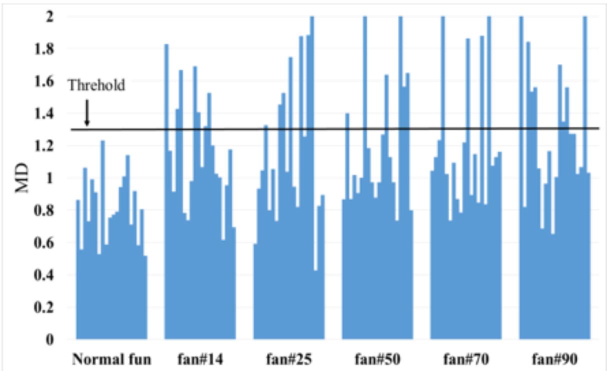

Figure 14: MD calculation result of each sample

shown for all abnormal items, and it was determined as abnormal. However, among the normal products, items which are judged to be abnormal items beyond the threshold were confirmed. Fig. 13 shows the effectiveness analysis result of the waveform of the abnormal product (♯ fan 1).

From the figure, the SN ratio shows a positive value in the central part, and all values are negative at both ends.

The same tendency was shown also in the effectiveness analysis of other abnormal items. A variable taking a negative value is variation and abundance information of reference line. By using variation and abundance information of reference line at the central portion of the waveform as the feature value, it is shown that accurate abnormality determination is possible.

Figure 14 shows the result of calculating the MD value using the variable whose SN ratio is a positive value as the feature quantity from the result of effectiveness analysis of all abnormal items. From the results in the figure, it is found that the normal value is equal to or less than the threshold value and the abnormal item is the MD value that is equal to or more than the threshold value, so it is an appropriate discrimination.

6. Conclusion

In general pattern recognition methods, it is said that classification of abnormal patterns can be performed with high accuracy if a large number of assumed abnormal pattern data can be collected. However, in reality, normal data can be collected, but abnormal data collection becomes more difficult as the scale of the facility becomes more complicated. Since the MT method evaluates the measurement data with the difference from the normal data group as the reference, data collection for learning only needs to be normal data, and this method can cope with an unknown abnormal pattern.

In this research, we applied the method to extract the feature value from the shape information of the waveform proposed by MT system for the sound measurement result of the compact fan motor. And we evaluated the effectiveness of provided feature value and examined improvement of the detection precision of the distinction.

Finally, in the waveform of the radiated sound from the small fan motor, by extracting the feature value effective for the abnormality detection by the effectiveness analysis, appropriate judgment results of the normal product and the abnormal product were obtained. [2] [3]

Frequency analysis (spectral analysis, fast Fourier transform analysis, etc.) and wavelets are generally used as waveform characterization techniques. The differences between these techniques and variation and abundance information of the MT method are summarized below.

1. Because of the frequency analysis and wavelet, the nature and homogeneity of the waveform are displayed by graphs and figures, so it is an expression understood by humans.
2. Since variation and abundance information are numerical information expressing the waveform feature, it is difficult to grasp the properties of the waveform by merely looking at the information by a person. However, since it is information that can be directly given to a computer, it can be used as it is for pattern recognition.
3. Since frequency analysis shows the average property of a sufficiently long waveform, it is difficult to capture the change occurring in a short time. On the other hand, feature extraction by variation and abundance information extracts feature values every fixed time width, so it is possible to detect a pattern difference in units of time width. [6]

In the future research, we will increase the number of samples to be evaluated, obtain the data of the vibration waveform in addition to the waveform of the radiated sound of the fan motor, further clarify the problem in the measurement of the radiated sound, and evaluate the usefulness / novelty I would like to pursue the research logically.

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