A New Diagnosis Method of Vibration Fault of Rotating Machinery Based on Information Exergy

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Abstract. Vibration signal analysis is a foundation of fault diagnosis, while the common used method is to analyse the characteristic quantities extracted from an original waveform of a particular measuring point in a particular moment. It lacks of abilities in fault classification. Based on information fusion of process, two kinds of information exergy indicators are proposed and defined in this paper, to represent the change rule between different states in a same process and the rule of corresponding state changes in different processes. On this basis, a new fault diagnosis method of information exergy of rotating machinery based on space-time feature spectrum in frequency domain is first proposed. The method has been validated by analysing vibration signals and diagnosing faults of a rotor test platform.

Keywords: Rotating machinery, fault diagnosis, process, information exergy, space close degree of information exergy.

1. Introduction

Vibration waveform of rotating machinery is periodic in a short time-window. Thus, vibration signal used to analyze is usually a period of waveform recorded by a particular measuring point in a moment, and it includes the state information of that moment. In a longer period which is larger than the sampling cycle, the states of rotating machinery may have significant changes. The chance of finding a fault may be increased substantially, when the investigated process consists of many states. The vibration behavior caused by a fault in a particular moment or in a particular state performs with dispersion and random, while in a process, the vibration behavior may show regularity. So, fusing the multi-states information of a process is an effective approach to improve diagnostic accuracy. The traditional tools to analyze the process are 3D figures of frequency spectrum and Bode diagram, which are inconvenience in application for lacking of quantitative indicators [1~3]. Other information fusion fault diagnosis methods, such as support vector machine, wavelet analysis, information entropy, neural network, fuzzy theory, and so on, mainly focus on qualitative diagnosis, and without effective quantitative indicators either [4~7].

To represent the change rule of processes, two kinds of information exergy indicators are proposed and defined in this paper, on reference to the theory of information entropy and thermodynamic exergy. And on this basis, a new fault diagnosis method of information exergy is first proposed.
2. Information exergy
In engineering thermodynamics, entropy is a thermodynamic property defined as the dimension of energy divided by temperature, and it is also a measure of disorder or unpredictability in system. To measure the uncertainty associated with a random variable in information theory, information entropy has been proposed to quantify the expected value of the information contained in a message. Although fused a lot of information, information entropy still cannot be achieved in completing the diagnosis based on process, as the information fused in is mostly used to describe states. In thermodynamics, the exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir, and it is a measure of available energy in the system. To find a quantitative indicator measured available messages of all the state information in an operation process of rotating machinery, a new concept based on the information fusion of process, named as information exergy, has proposed in this paper.

2.1. Information exergy of different states in a same process
According to the description of information entropy, information exergy can be defined based on different kinds of information entropy. Let function \( S(t) \), which mathematically describes information entropy of a vibration signal, integrates with time from \( t_1 \) to \( t_2 \), just like the relationship of entropy and exergy in thermodynamics. The simplest expression (kernel or primary function) of information exergy is achieved as [8~9],

\[
Y_{p}(t) = \int_{t_1}^{t_2} S(t) dt \quad (1)
\]

The sampling process of a measuring point includes a series of collected data of different rotate speeds, i.e. it implies with a series of operation states. So, information exergy defined by eq. (1) can be used to reflect the change rule between different states in a same process. The samplings of the simulating experiment and the vibration signal from actual rotating machinery are collected at the same test points of rotate speed, for it is convenient to compare the results.

2.2. Information exergy of the corresponding state changes in the different processes
It is also significant to compare the different sampling processes at the same measuring point in the same rotate speed, for the difference between them represents the rule of corresponding state changes in different processes. And the process change rules of the corresponding states of the different sampling process at the same rotate speed constitutes the overall variation rule between different sampling processes.

The characteristic function of a vibration signal of the measuring point is denoted by \( X(t) \), and the subscript \( A \) and \( B \) represent the process \( A \) and \( B \) respectively. To describe the change rule of processes, the state-point (time-point) \( t \) is regarded as a short period of time (unit time interval) as \([t-1/2, t+1/2]\). The characteristic functions of process \( A \) and \( B \) are integrated at the unit time interval, and the difference of them shows the processes change rule at the state-point \( t \), which is defined in this paper as information exergy of the corresponding state changes in the different processes \( (A \) and \( B) \) as \( Y_{D}(t) \),

\[
Y_{D}(t) = \int_{t-1/2}^{t+1/2} (X_B(t) - X_A(t)) dt = X_B(t) - X_A(t) \quad (2)
\]

For the sampling processes \( A \) and \( B \) with \( m \) rotate speed test points and \( n \) measuring points, an information exergy matrix (IEM) \( U_{BA} \) with \( m \) rows and \( n \) columns can be established by eq.(3). The element \( U_{BA}(i,j) \) in the matrix represents the change rule of the sampling process \( A \) and \( B \), and the
sampling is collected by the \( j \)-th measuring point, when rotor system is running at the \( i \)-th rotate speed. The matrix not only shows the overall variation rule between different sampling processes (A and B), but also shows state change rules of any measuring points at any state-points in corresponding states.

\[
U_{BA} = \begin{bmatrix}
X_{i0}(1,1) - X_{i0}(1,1) & X_{i0}(1,2) - X_{i0}(1,2) & \cdots & X_{i0}(1,n) - X_{i0}(1,n) \\
X_{i0}(2,1) - X_{i0}(2,1) & X_{i0}(2,2) - X_{i0}(2,2) & \cdots & X_{i0}(2,n) - X_{i0}(2,n) \\
\vdots & \vdots & \ddots & \vdots \\
X_{i0}(m1) - X_{i0}(m1) & X_{i0}(m2) - X_{i0}(m2) & \cdots & X_{i0}(mn) - X_{i0}(mn)
\end{bmatrix}
\]  

(3)

Regarded as a stillness process, the rest state of rotor system also includes \( m \) sampling rotate speed test points and \( n \) measuring points, while all eigenvalues of the rest state are zero. Meanwhile, an information exergy matrix can be established for any process and the stillness process by eq. (3) as well.

3. The fault simulation experiment of rotor system

To study the change rule of vibration signal with faults of rotating machinery in speed-up process, the typical fault simulation experiments are carried out in a rotor test platform, which includes rotor imbalance, shaft misalignment, rubbing between shaft and rotor, pedestal looseness, and a complex fault that the pedestal looseness and rubbing between shaft/rotor happen at same time. For every kind of fault, a series of situations are simulated. And in every situation, vibration signals are collected several times both in the speed-up process and speed-down process, to ensure the repeatability. The rotate speed range of the test is from 1000r/min to 3000r/min, while speed changing rate is 50r/min. Because several eddy current sensors and acceleration sensors are installed in the platform, over hundred groups of vibration signals are collected and recorded. Each group of vibration signals corresponds to a waveform of one sampling channel with one rotate speed as a kind of typical state description, and its characteristics can be described by the collected data in the process of a speed-up or speed-down. All faults in the test plan are obtained enough original data by experiments.

The amplitude spectrum of every group of vibration signal waveform is calculated. On this basis, a Three-dimensional amplitude spectrum matrix can be obtained as a sampling matrix of the fault, by calculating all amplitude spectrums of the multi channels and multi rotate speed points experiment which can best represent the fault characteristics.

4. The fault diagnosis method of information exergy based on space-time feature spectrum in frequency domain

The 3D amplitude spectrums in frequency domain (waterfall plots) of rotor system speed-up process with typical faults are different when rotor system works with different faults. In another word, it reflects the process change rules. If the amplitude spectrum data of the vibration signals can be directly used to the fault diagnosis method of information exergy, it will make every fault symptom that happens in the speed-up process illustrated clearly. And accuracy of fault diagnosis will be highly improved.

If amplitude spectrum of vibration signal in frequency domain is regarded as an eigenvalue and IEM as eq. (3) is established when one of the process is stillness, the calculated amplitude spectrum is not a numerical value any more, but a vector. Hereby, in this situation, IEM is a 3D matrix, as an \( r \times m \times n \) matrix, where \( r \) represents the number of sampling points for any one of rotate speed and any one of measuring point.

4.1. Definition of space-time feature spectrum in frequency domain

The data in amplitude spectrum are vibration signal amplitude of integer frequency and fractional frequency, and represent the absolute magnitude of amplitude. If it is used directly into fault diagnosis method of information exergy, due to the order of magnitude difference, the change rule of different process will be not comparable. And it leads wrong fault identification or incorrect judgment. So the
data of amplitude spectrum in every measuring point should be normalized. For an array \(\{x_i\}\) which includes \(n\) elements, the normalized formula is,

\[
x_i^* = \frac{x_i - \bar{x}}{\sigma}, \quad i = 1, 2, \cdots, n
\]  

(4)

Where \(\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i\) and \(\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}\).

Be normalized, amplitude spectrum in frequency domain with multi-measuring points not only reflects the change rule of single measuring point in speed-up process, but also reflects the spatial distribution of measuring point. So in this paper, the normalized amplitude spectrum in frequency domain with multi-measuring points, which reflects the spatial and temporal characteristics of vibration signals, has been defined as space-time feature spectrum in frequency domain.

4.2. The fault diagnosis method of information exergy based on space-time feature spectrum in frequency domain

Based on the definition and eq. (3) mentioned above, an \(r \times m \times n\) matrix named as \(U_{A_O}^*\) can be established as a 3D-IEM which is relative to any typical faults in speed-up process (process \(A\)) and the stillness process (process \(O\)). In a similar way, a 3D-IEM \(U_{B_O}^*\) can be established to describe the relation between any vibration signal to be identified in speed-up process (process \(B\)) and the stillness process. And IEM \(U_{B_A}^*\) of vibration signal to be identified in speed-up process \(B\) and typical fault in speed-up process \(A\) can be established based on eq. (3), and calculated as,

\[
U_{BA}^* = U_{BO}^* - U_{AO}^*
\]  

(5)

Processes of vibration signal to be identified and processes of typical faults are regarded as space-points in the \(r \times m \times n\) dimensional space. For a vibration signal, if it is more similar to one change rule of a typical fault process than others, the Euclidean distance of their represented point in the \(r \times m \times n\) dimensional space will be closer, or described in a mathematic way, the square sums of all elements in the 3D-IEM \(U_{BA}^*\) is minimum. And its square root \(T(U_{BA}^*)\) which is defined as Space Close Degree of Information Exergy (SCDIE), can be calculated by eq. (6), while its square deviation is figure out by eq. (7).

\[
T(U_{BA}^*) = \sqrt{\sum_{i=1}^{r} \sum_{j=1}^{m} \sum_{k=1}^{n} [U_{BA}^*(i, j, k)]^2}
\]

(6)

\[
D(U_{BA}^*) = \frac{1}{r \times m \times n - 1} \sum_{i=1}^{r} \sum_{j=1}^{m} \sum_{k=1}^{n} [U_{BA}^*(i, j, k)]^2 - \frac{1}{r \times m \times n} \sum_{i=1}^{r} \sum_{j=1}^{m} \sum_{k=1}^{n} U_{BA}^*(i, j, k)^2
\]

(7)

To calculate and find a minimum SCDIE and a minimum square deviation is helpful for fault identification, as there is a positive significantly correlation between SCDIE and overlap situation of information exergy distribution ranges. A smaller SCDIE means the vibration signal information exergy distribution range is closer to a typical fault information exergy distribution range, and it implies a more possibility that the vibration signal belongs to this typical fault.
If distribution range of the vibration signal information exergy is close to more than one typical fault, fault identification of that vibration signal will be based on square deviation of IEM which reflects the similarity of the matrix elements distribution. Similar to identify method based on SCDIE, a smaller square deviation of IEM means the vibration signal process change rule is closer to a typical fault signal process change rule, and it implies a more possibility that the vibration signal belongs to this typical fault.

5. A fault diagnosis example
The typical fault signals have been recorded on the test platform, which includes rotor imbalance (fault a), shaft misalignment (fault b), rubbing between shaft and rotor (fault c), pedestal looseness (fault d), and a complex fault that the pedestal looseness and rubbing between shaft/rotor happen at same time (fault e). And IEMs have been calculated with two channel of vibration signal in the speed-up processes from 1000r/min to 3000r/min of these five typical faults. Channel 1 is a shaft vibration signal recorded by eddy current sensors, and it is chosen from multiple shaft vibration signals as the best one in indicating the fault symptom. While channel 2 is a bearing vibration signal recorded by acceleration sensors. And it is also chosen from multiple bearing vibration signals as the best one in indicating the fault symptom.

The calculation results of sampling IEM of these five typical faults are shown in Figure 1~5. As the sample interval is 50r/min, for every channel, there are 41 rotate speed test points in speed-up process. Sampling frequency in this paper is 64 times fundamental frequency, so there are 512 measuring points for each vibration waveform. But for calculating, vibration amplitude is taken into consideration only for 8 time’s fundamental frequency and below. So, there are 64 sampling points for every channel at one rotate speed. The typical fault sampling IEM based on space-time feature spectrum in frequency domain in this paper is a $64 \times 41 \times 2$ matrix.

(a) Normalized amplitude spectrum of shaft vibration
(b) Normalized amplitude spectrum of bearing vibration

Figure 1. Sampling IEM of rotor imbalance fault
Figure 2. Sampling IEM of shaft misalignment fault

Figure 3. Sampling IEM of rubbing between shaft and rotor fault

Figure 4. Sampling IEM of pedestal looseness fault
Another vibration signal of a complex fault that the pedestal looseness and rubbing between shaft/rotor happen at same time is simulated in the test platform as a vibration signal to be identified. The speed-up process also follows the earlier test process as rotate speed rising from 1000r/min to 3000r/min, 2 sampling channels and every 50r/min for a sampling. The sampling IEM of the vibration signal is shown in Figure 6.

Subtraction matrixes of the vibration signal sampling IEM and the typical fault sampling IEM are shown in Figure 7~11. Each matrix reflects an information exergy of the vibration signal to be identified in speed-up process and the typical fault in speed-up process. So that, the similarity between the vibration signal and the typical faults can be easily indicated.

**Figure 5.** Sampling IEM of pedestal looseness + rubbing between shaft and rotor fault

**Figure 6.** Sampling IEM of vibration signal to be identified
Figure 7. Sampling IEM between vibration signal to be identified and rotor imbalance fault.

(a) Normalized amplitude spectrum of shaft vibration
(b) Normalized amplitude spectrum of bearing vibration

Figure 8. Sampling IEM between vibration signal to be identified and shaft misalignment fault.

(a) Normalized amplitude spectrum of shaft vibration
(b) Normalized amplitude spectrum of bearing vibration

Figure 9. Sampling IEM between vibration signal to be identified and rubbing between shaft and rotor fault.

(a) Normalized amplitude spectrum of shaft vibration
(b) Normalized amplitude spectrum of bearing vibration
From eq.(5), it is known that each subtraction matrix of the vibration signal sampling IEM and the typical fault sampling IEM also reflects the IEM of the vibration signal and the typical fault. SCDIE and square deviation of these IEMs are calculated and shown in Table 1. The minimum SCDIE and square deviation both appear in the IEM which represents the situation of comparing vibration signal and the typical fault e. So it can be verified that the vibration signal to be identified is a fault with pedestal looseness and rubbing between shaft/rotor. The conclusion is consistent with the fault setting.

Moreover, the set fault is a complex fault mixed by pedestal looseness (fault d) and rubbing between shaft/rotor (fault c). In other words, the characteristics of fault c and d also display in the vibration signal. So, it can be seen in Table 1 that SCDIE and square deviation of IEMs are smaller in c and d than that in a and b. It also proves the accuracy of fault diagnosis method in this paper.
Table 1. SCDIE and square deviation of IEMs of vibration signal and some typical fault

| Number | Type of faults                      | Corresponding IEM | SCDIE | Square deviation |
|--------|------------------------------------|-------------------|-------|------------------|
| a      | rotor imbalance                    |                   | 93.22 | 100.6            |
| b      | shaft misalignment                 |                   | 102.23| 126.9            |
| c      | rubbing between shaft/rotor        |                   | 80.90 | 89.7             |
| d      | pedestal looseness                 |                   | 59.35 | 60.1             |
| e      | pedestal looseness + rubbing between shaft/rotor | | 19.53 | 9.8             |

6. Conclusion
In this paper, information exergy has been defined based on information fusion of process. Two kinds of information exergy indicators have been proposed to reflect the change rule between different states in the same process and the rule of corresponding state changes in different processes. On this basis, a new fault diagnosis method of information exergy of rotating machinery based on space-time feature spectrum in frequency domain is first proposed. Analysis shows that the fault diagnosis method is quantitative, high diagnostic accuracy, strong adaptability for rotating machinery.

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