Reliability evaluation technique of compressor using pressure pulsation and vibration signals

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Abstract. This paper dealt with the technique for determining the reliability of a compressor using pressure pulsation and vibration signals of the refrigerant compressor for a domestic refrigerator. Experiments were conducted according to the failure level and type of failure of the compressor. Experiments on the failure level of the compressor proceeded according to the degree of damage of the port of the valve. Experiments on the type of compressor failure were made according to the refrigerant leakage position. The pulsation of the refrigerant was measured in the suction and discharge valve of the compressor, and the vibration signal was measured on the surface of the compressor. Fisher's linear discriminant method was used to select the health index for reliability discrimination. The pressure pulsating signal of the suction valve was effective in most cases in the reliability discrimination of the domestic refrigerator compressor. The compressor surface acceleration was effective in some cases, and the pressure pulsating signal of the discharge valve was not effective in most cases.

1. Introduction
Many studies have been made on the fault diagnosis of compressors. Yang et al (2005) identified compressor failure using ANN (artificial neural networks) and SVM (supported vector machine) [1]. AlThobiani et al (2014) uses TKEO (Teager-Kaiser energy operator) and DBN (deep belief networks) to determine the compressor failure [2]. Ledesma et al (2015) determined the failure while controlling the speed of the compressor [3]. This study also uses ANN. Wang et al (2015) proposed a method for diagnosing the failure of a compressor valve by applying a combination of compressor experiment and computation [4]. Pichler et al (2016) proposed a method to detect the failure of a compressor valve by controlling the load applied to the compressor [5]. In this paper, we will comprehensively examine the fault detection with the pressure pulsation of the compressor valve and the acceleration of the compressor surface for the fault level and fault type. The compressor used in the experiment was a compact compressor for refrigerators using refrigerant. The failure level was selected as the magnitude of the breakage of the compressor valve port. The failure of the compressor according to the leakage position of the refrigerant was selected as the failure type. The health index to identify faults was selected in the time and frequency domains, respectively. The objective function for selecting the health index was Fisher's linear discriminant method.

2. Experiment
The failure of a small compressor for a refrigerator is largely due to the breakage of parts and the leakage of refrigerant due to poor assembly. Particulate damage occurs mainly in the valve port of the
compressor, and poor assembly occurs mainly in the suction and discharge piping of the refrigerant. Deep cracks in the valve port resulting from the piercing of the valve lead to fatal defects in the compressor drive unit and the suction valve and cause the compressor to break down. Also, leakage of refrigerant due to poor assembly can adversely affect compressor efficiency and stability.

2.1. Fault level
The failure level of the compressor was divided into three stages of normal, crack and hole according to the degree of damage of the corner of the compressor valve port. The state change of the system according to the fault level is shown in table 1. Figure 1 shows the appearance of the valve port and the crack location. Figure 2 and 3 shows the shape of the crack and hole in the state of failure of the valve port, respectively.

| Fault level | Performance down | Breakdown |
|-------------|------------------|-----------|
| Normal      | X                | X         |
| Crack       | O                | X         |
| Hole        | O                | O         |

2.2. Fault type
The types of faults were mainly classified as failure point, that is, discharge pipe, suction pipe, and suction valve (poor side clearance assembly).

2.3. Measured signal information
Generally, a data signal used for fault diagnosis of a refrigerator compressor in an industrial field is a pressure pulsation signal of a refrigerant measured at an inlet and an outlet of a compressor refrigerant. The pressure pulsation signal of the refrigerant has the advantage of being able to detect the fault level intuitively without additional signal processing, but it has a disadvantage that it is difficult and time-consuming to embed the sensor in the piping to acquire the signal. On the other hand, the surface acceleration signal of the compressor tends to require additional signal processing, but the advantage is that the signal can be acquired relatively easily without additional work. In this study, the acceleration sensor is attached to the outer surface of the compressor to obtain the vibration signal of the compressor and compare it with the pressure pulse signal of the refrigerant.
3. Reliability evaluation

The signals obtained from the experiment pass through the filter and have a statistical representative value for each factor. And the factors 1st to 2nd that maximize the FDR are selected. The optimal reliability evaluation technique is then determined through linearization.

3.1. Fisher’s linear discriminant ratio

Fisher's linear discriminant ratio (FDR) is a useful discriminator that can simply classify each of the clusters with their variance and mean. The generalized FDR can be expressed as equation (1) [6].

\[
FDR_{\text{class}} = \sum_{i} \sum_{j} \frac{(\mu_i - \mu_j)^2}{\sigma_i^2 + \sigma_j^2}, \quad M > 2
\]

3.2. Health index candidates

The procedure for selecting a suitable health index to perform a fault diagnosis analysis is divided into a signal processing section and a factor selection section. In this study, a total of 120 health index candidates were selected. The information for each filter is shown in the table 2.

| Data domain | Filter | Description |
|-------------|--------|-------------|
| Raw         | Raw data |             |
| Band (1-3)  | Bandpass filter 60Hz, 120Hz, 180Hz+10 |
| Time        | High   | Cut-off frequency 1000Hz |
|             | Low    | Cut-off frequency 1000Hz |
|             | Envelope | Enveloped raw data |
| Frequency   | FFT    | Fast Fourier transformed data |
|             | FFT with envelope | FFT with enveloped raw data |

The formula for each feature is shown in the table 3 [7]. Where \( s(f_i) \) is the power spectrum function. Modified frequency domain features use \( \sqrt{s(f_i)} \) instead of \( s(f_i) \).

| Data Domain | Feature Name | Formula | Remarks |
|-------------|--------------|---------|---------|
| Time        | Mean         | \( \bar{X} = \frac{1}{N} \sum_{i=1}^{N} X_i \) | Root mean square |
|             | rms          | \( X_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} X_i^2} \) | |
|             | Skewness     | \( \frac{1}{N} \sum_{i=1}^{N} (X_i - \bar{X})^3 \) \( \left( \frac{1}{N} \sum_{i=1}^{N} (X_i - \bar{X})^2 \right)^{3/2} \) | |
|             | Kurtosis     | \( \frac{1}{N} \sum_{i=1}^{N} (X_i - \bar{X})^4 \) \( \left( \frac{1}{N} \sum_{i=1}^{N} (X_i - \bar{X})^2 \right)^2 \) | |
|             | FC           | \( FC = \frac{\int f_i \times s(f_i) \, df}{\int s(f_i) \, df} \) | Frequency center |
| Frequency   | RMSF         | \( \int f_i^2 \times s(f_i) \, df \) \( \int s(f_i) \, df \) | Root mean square frequency |
|             | RVF          | \( \int (f_i - FC)^2 \times s(f_i) \, df \) \( \int s(f_i) \, df \) | Root variance frequency |
3.3. Health index selection by FDR and linearize

The top two factors are optimized by projecting on one straight line that maximizes the FDR. The results are shown in Figure 4 and 5. The red line is the line where the FDR is maximized when two indices are reduced to one dimension.

![Figure 4. Health index selection of compressor fault level.](image)

![Figure 5. Health index selection of compressor fault type](image)
4. Conclusion
A reliability evaluation technique for the fault level and fault type of the compressor was established and proceeded using the pressure pulse signal and the surface acceleration signal of the compressor for the refrigerator. The reliability evaluation according to the type of failure should be clearly distinguished between each group. In the case of the reliability evaluation according to the failure level, the tendency should also be clearly shown according to the level. The results are summarized in table 4. The symbol ○ stands for a clearly classified signal. △ generally refers to signals that are separated. X indicates that the signal is indistinguishable at all.

| Data domain | Data description | Fault level | Fault type |
|-------------|-----------------|-------------|------------|
| Inlet pulsating pressure | ○ | ○ | |
| Time | Outlet pulsating pressure | X | △ |
| Shell acceleration | X | △ |
| Inlet pulsating pressure | X | ○ |
| Frequency | Outlet pulsating pressure | X | X |
| Shell acceleration | ○ | △ |

In this study, the inlet pulsating pressure was most suitable for determining the fault level and type. On the other hand, the outlet pulsating pressure was inadequate value for reliability determination in this study. The acceleration of the compressor surface showed the possibility of reliability discrimination.

5. References
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