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Production Test of Rotary Compressors with Wavelet Analysis

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ABSTRACT

Detection of electro-magnetic sound is an important step in compressor production process. First the paper introduces the mechanics of electro-magnetic sound and the concept of wavelet analysis method. Then the energy of vibration signals in different frequency band of wavelet was calculated. After that we map the energy in different frequency bands to two different compressors: one with collision between stator and rotor, the other without such collision. By this way the compressor with collision can be detected. Finally several tests were done to prove the effectivity of this method.

1. INTRODUCTION

Today in line test of compressors there is a step called magnetic sound test. That is for man to listen to the sound caused by collision between rotor and stator. This is a subjective test performed under difficult circumstances, influenced by background noise, varying concentration level, and varying mood of the test person etc, all leading to varying results.

Compressor's electro-magnetic sound is caused by collision between rotor and stator when motor starts up. Its main part is transient energy which lasts very short and is composed of wide frequency, and it is nonlinear.

Traditional Fourier Frequency Transform method is not suitable for analyzing transient signal because its frequency component is often submerged by noises.

Wavelet analysis is a time-frequency method, it can catch transient signal. So as a new mathematic tool it has been widely used in the detection, separation and quantitative measurement of transient signal. Wavelet method has reliable mathematical theory and mature algorithm and has been successfully used in many cases. So in this paper we use wavelet method to detect electro-magnetic sound of rotary compressor by establishing the relationship between vibration's wavelet characters and electro-magnetic sound.

2. STATIC WAVELET ANALYSIS METHOD

2.1 Discrete wavelet transform and static wavelet transform(SWT)

The wavelet transform of any function $f(t) \in L^2(\mathbb{R})$ is defined as

$$W_f(a, b) = \int_{-\infty}^{\infty} f(t) \psi_{a,b}(t) dt = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) dt \quad (1)$$

where $\psi(x)$ is wavelet function, a is scale factor, b is shifting factor.

When a is continuous variable, (1) is called continuous wavelet transform. When $a = 2^j$, $b = k2^j$, (1) is called discrete transform. Many wavelet is orthogonal and the transform $w(a, b)$ is non-redundant

By applying low-pass and high-pass filter, signal will be decomposed into low frequency approximation and high frequency details. The decomposition process can be iterated, with successive approximations being decomposed in turn, so that one signal is broken down into many lower resolution components. This is called the wavelet decomposition tree.

The SWT method can be described as follows. At each level, when the high-pass and low-pass filters are applied to the data, the two new sequences have the same length as the original sequences. To do this, the original data is not decimated. However, the filters at each level are modified by padding them out with zeros.

Supposing a function $f(x)$ is projected at each step j on the subset. This projection is defined by the scalar product $c_{j,k}$ of $f(x)$ with the scaling function $\phi(x)$ which is dilated and translated

$$c_{j,k} = \langle f(x), \phi(x)_{j,k} \rangle \quad (2)$$

$$\phi_{j,k}(x) = 2^{-j} \phi(2^{-j}x - k) \quad (3)$$

Where $\phi(x)$ is the scaling function, which is a low-pass filter. $c_{j,k}$ is also called a discrete approximation at the resolution 2^j .

If $\psi(x)$ is the wavelet function, the wavelet coefficients are obtained by

$$w_{j,k} = \langle f(x), 2^{-j} \psi(2^{-j}x - k) \rangle \quad (4)$$

$w_{j,k}$ is called the discrete detail signal at the resolution 2^j .

As the scaling function $\phi(x)$ has the following property:

$$\frac{1}{2} \phi\left(\frac{x}{2}\right) = \sum_n h(n) \phi(x - n)$$

$c_{j+1,k}$ can be obtained by direct computation from $c_{j,k}$

$$c_{j+1,k} = \sum_n h(n - 2k) c_{j,n}$$

$$\frac{1}{2} \psi\left(\frac{x}{2}\right) = \sum_n g(n) \phi(x - n) \quad (5)$$

The scalar products $\langle f(x), 2^{-(j+1)} \psi(2^{-(j+1)}x - k) \rangle$ are computed with

$$w_{j+1,k} = \sum_n g(n - 2k) c_{j,n} \quad (6)$$

Equations (5) and (6) are the multi resolution algorithm of the traditional DWT. In this transform, a down sampling algorithm is used to perform the transformation. That is, one point out of two is kept during transformation. Therefore, the whole length of the function $f(x)$ will reduce by half after the transformation. This process continues until the length of the function becomes one.

However, for stationary or redundant transform, instead of down sampling, an up sampling procedure is carried out before performing filter convolution at each scale. The distance between samples increasing by a factor of two from scale j to next. $c_{j+1,k}$ is obtained by

$$c_{j+1,k} = \sum_l h(l) c_{j,k+2^j l} \quad (7)$$

and the discrete wavelet coefficients

$$w_{j+1,k} = \sum_l g(l) c_{j,k+2^j l} \quad (8)$$

The redundancy of this transform facilitates the identification of salient features in a signal, so it can be used to identify the sound of collision between rotor and stator.

2.2 Multi Band Detail Energy Analysis Method

Just like frequency in Fourier Transform, the discrete detail coefficients represent the energy of signal in the corresponding scales. So this paper the multi-band detail energy method is used to classify signal, especially signals containing transient components.

A discrete signal with length of 2048 is used to illustrate the above method. The 4th Daubechies Wavelets db4 is chosen as wavelet function to decompose signal. For $2^{11} = 2048$, the signal can be decomposed to 10 levels and obtain the wavelet coefficients at 10 resolution 2^j , the coefficients are combined as matrix w with row 10 and column 1024. every row represent the energy of signal at scale $2^1, 2^2 \dots$ and 2^{10} . the smaller the scale, the higher the frequency, and steeper the signal.

The detail energy *Index* at different resolution is defined as follow:

$$Index(j) = 10 \log\left(\frac{\frac{1}{N} \sum_k w(j,k)^2}{A_{ref}^2}\right) \quad (9)$$

Where j represent decomposed level, $j = 1, 2, \dots, 10$

k is sequence number of wavelet coefficient, $k = 1, 2, \dots, 2048$

N is length of discrete signal, 2048

A_{ref} is reference acceleration, $0.01 \text{ m} / \text{s}^2$

2.3 Detection of Electro-Magnetic Sound by Detail Energy Index

Because there is strong background noise in workshop it is hard to detect the collision between rotor and stator by analyzing the sound. Alternatively we measure acceleration of shell. Because the stress wave translate to shell from stator directly, so this method is more reasonable

When motor starts up the main coil is electrified and second coil is not electrified, the rotor dose not rotate. A lateral magnetic force is imposed on rotor. The force pull the rotor, make the crank curve, and cause the rotor and stator to collide, simultaneously a sharp sound is produced called electro-magnetic sound.

Experiences show that three factors influence magnetic sound: (1)the position of crankshaft, (2)voltage of stator and (3)gap between rotor and stator. By combining the three factors we get 12 operating modes. At each of the 12 modes we measure acceleration on the shell shown in Fig 2, here we use #3. At same time we listen to the sound by and watch the lateral moving process of rotor by eye to judge whether there is collision happened. The acceleration measuring use B&K PULSE system, the sampling frequency is 64K Hz.

Using formula (9), for every test mode we can get a detail energy *Index* to represent detail energy at 10 different decomposing levels. By superimpose the 12 *Index* we can get Fig 4. The abscissa represents band sequence, the vertical ordinate represents energy index.

It is shown from figure 3 that curve 6, 8, 9 are quite different from the rest 9 curves, in band 1~6 the index of 6,8,9 is higher than the rest 6 curve, It means that the 3 curves have high energy in high frequency. This corresponds to the facts that collision between rotor and stator produces high-frequency acceleration signal on shell. This result match the fact in Table 1.

The above experiment proved that wavelet-energy-band method can detect electromagnetic sound effectively.

Tab.1 Collision condition between rotor and stator

No	1	2	3	4	5	6	7	8	9	10	11	12
Result	N	N	N	N	N	Y	N	Y	Y	N	N	N

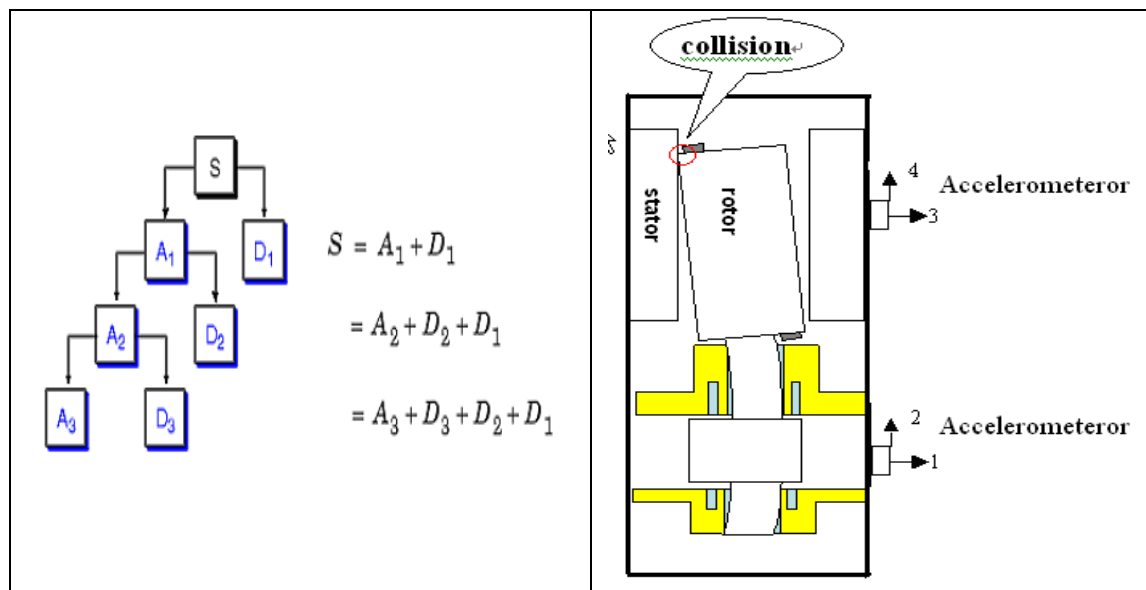


Fig 1 Multiple-Level Decomposition

Fig.2 Position of Collision and Accelerators

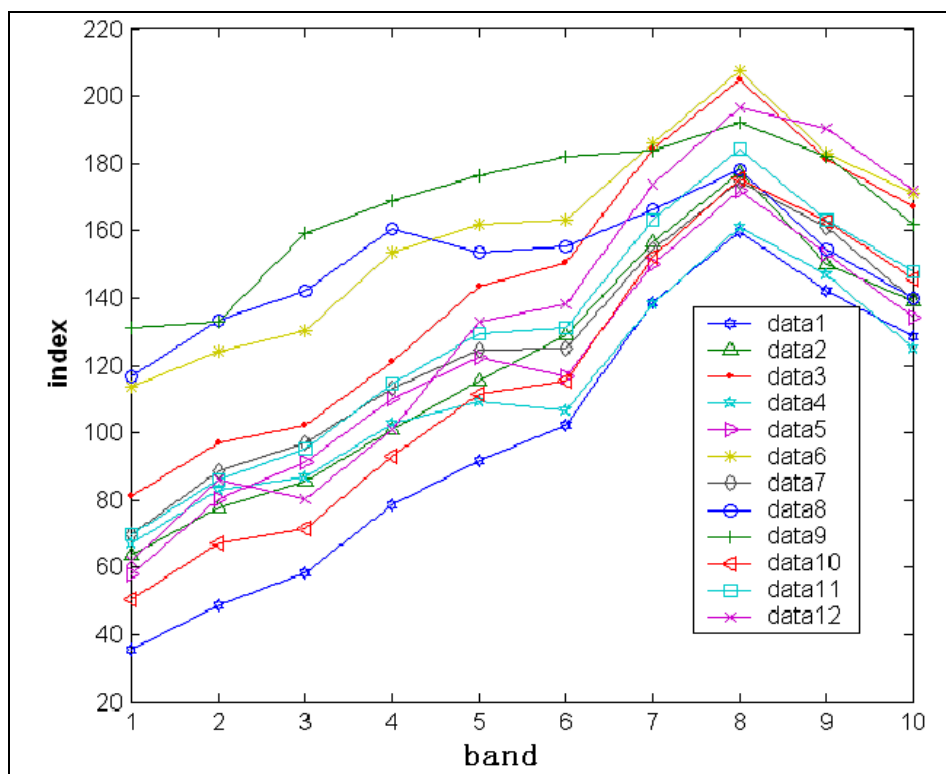


Fig.3 Detail Energy Index

3. SOUND SOURCES IDENTIFICATION

Even though the above method is effective to detect whether electromagnetic sound exists, there is a risk: vibration wave can propagate to accelerator 3 from other places and the acceleration can be very high at accelerator 3, that will led to misjudge. In rotary compressors the mechanical collision can also happen in pump, for example collision between crankshaft and main bearing, or between piston and blade. The stress wave produced by both collisions can propagate to shell through welding part. To simulate human ears, we use 4 accelerators to receive accelerating signal simultaneously, # 1 and # 2 are located at welding position, # 3 and # 4 are at middle position of stator, #1 and #3 are for normal acceleration, #2 and #4 are for vertical shear acceleration. The sound sources can be identified by comparing delay times of stress wave to different accelerators.

The delay times of two time sequences $X(n)$ and $Y(n)$ can be obtained by calculating their correlation function

$$\gamma_{XY}(m) = \frac{E\{X^*(n)Y(n+m)\}}{\sigma_X \sigma_Y} \quad (10)$$

Where σ_X 、 σ_Y are variances of X and Y . m is sampling delay. γ_{XY} is between -1 and 1 . the delay time m corresponds to maximal absolute value of γ_{XY} .

Figure 4 shows results of two group of accelerators. Fig 4a represents results of normal vibration, the delay is 10 sampling points. Fig 4b represents result of vertical vibration., the delay is 3 sampling points. They both show that the wave propagates from the high part to the low part of shell, that is from stator position to welding position. The different delay times can be explained as follow: normal vibration represent flexural wave, vertical vibration represent longitudinal wave, and the velocity of longitudinal wave is larger than that of flexural wave.

4. CONCLUSIONS

Firstly the paper introduces static wavelet analysis method and then presents the method of identifying electromagnetic sound resources by wavelet analysis. In order to locate sound sources ,4 accelerations are measured and time delays are calculated by calculating their correlation function. By the two methods, the collision sound sources can be located correctly.

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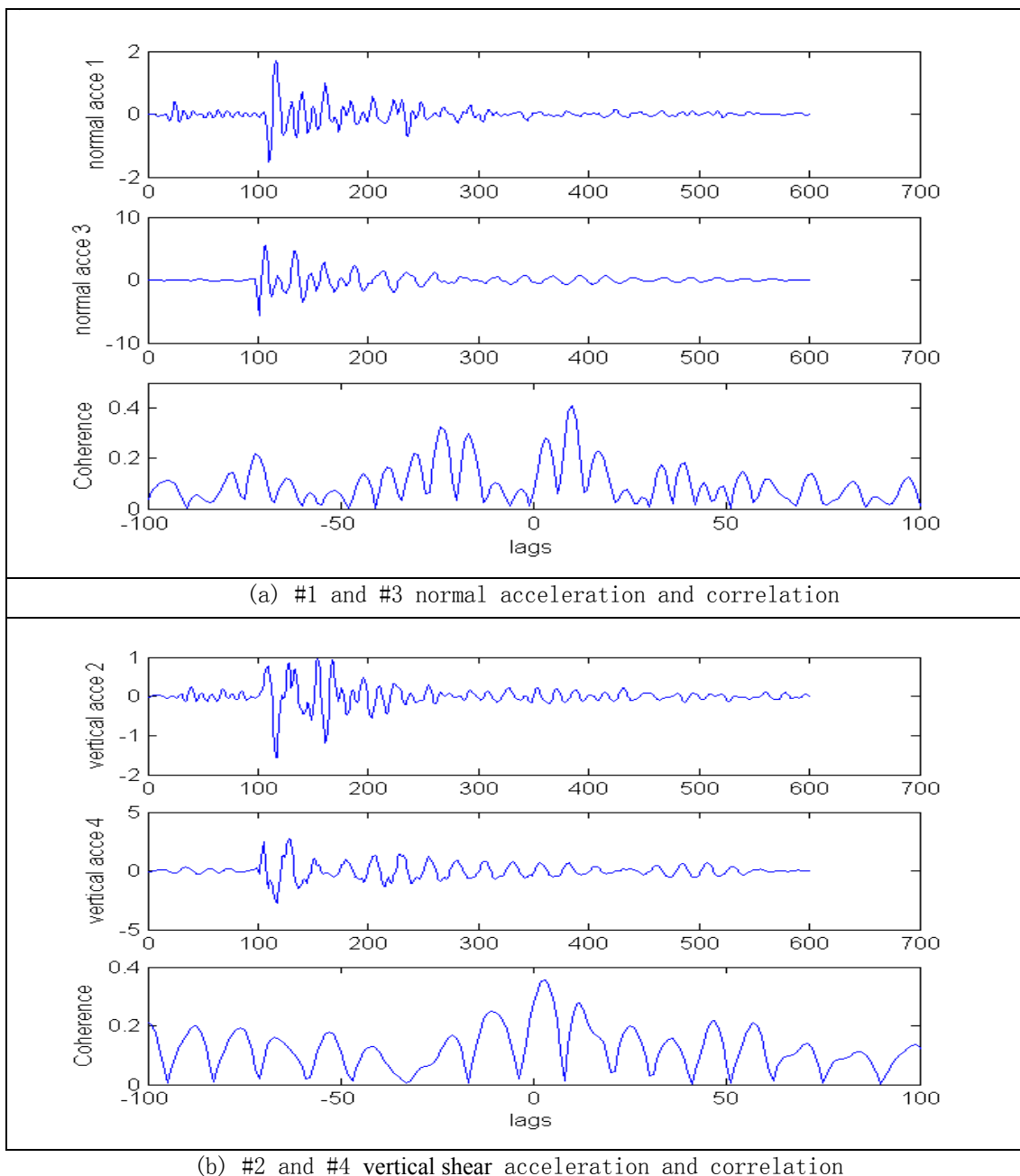


Fig.4 Accelerations and Correlations