Adaptive Peak Decomposition Approach for the Fault Diagnosis of Reciprocating Compressor based on General Frequency

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Abstract: Vibration signals of reciprocating compressor mainly include multiple impact and noise signals, traditional fault diagnosis approaches could not reveal the fault feature accurately. In this study, a novel notion of general frequency is proposed and some simulation signals are used to compare its performances with the traditional frequency and the instantaneous frequency. Based on the notion, an adaptive peak decomposition approach is investigated and applied to the fault diagnosis of reciprocating compressor gas valve in four states including normal valve state, gap valve state, fractured valve state and bad spring valve state. The results show the effectiveness and the superiority of the proposed approach in extracting the fault feature of reciprocating compressor.

Keywords: Adaptive peak decomposition, general frequency, fault diagnosis, reciprocating compressor, feature extraction

INTRODUCTION

Reciprocating compressor plays an important role in petrochemical industry. With the rapid development of petrochemical industry, machine maintenance is required much more strictly about reliability as well as performance costs. Once the key parts of reciprocating compressor exist failure, considerable economy losses and safety problems will be brought (Liu and Arg, 2002). Therefore, it is of great significance to diagnose the faults of reciprocating compressor effectively (You-Fu et al., 2012). Because of the complexity of structure and motion reciprocating compressor, its vibration signals include various multiple impact and noise signals. Some useful information is corrupted and it is difficult to diagnose reciprocating compressor faults from such signals. Traditional signal processing techniques, including time-domain statistical analysis, Fourier transform and Wavelet transform, have been proved to be suitable for the fault diagnosis of rotating machinery. However, these techniques are not effective in the fault diagnosis of reciprocating compressor. The process of reciprocating compressor is are non-stationary and non-linear which is more obvious when some faults happen. To process the non-stationary and non-linear signals, some advanced techniques, including empirical mode decomposition (Courtney et al., 2010; Srinivasan et al., 2009), ensemble empirical mode decomposition (Khiluendu et al., 2011; Quan and Jiang, 2006), cyclestionary (Shi et al., 2009; Cheng et al., 2009) and spectral kurtosis (Eftekharejad et al., 2011; Wang and Liang, 2012), have been applied to the fault diagnosis of reciprocating compressor. Most of these techniques are based on the spectral analysis in frequency domain or time-frequency domain. Frequency feature always contains some useful state information for fault diagnosis of reciprocating compressor gas valve, so it is of course very important to try ways and means possible to improve frequency feature accuracy.

At present, there are two kinds of frequency notions: one is called traditional frequency, and the other is called instantaneous frequency (Liu et al., 2008). The traditional frequency has been well known for the Fourier spectral analysis. The traditional frequency is defined for the period function spanning the whole data length of signal with constant amplitude (Rocci and Pennacchi, 2011). Some signal processing techniques, including Fourier transform (Zhao et al., 2005; Yufeng et al., 2011), Wavelet transform (Kim et al., 2006; Zou et al., 2004) and Wigner-Ville distribution (Minghui et al., 2012; Jiasheng et al., 2012), are based on traditional frequency analysis. Although traditional frequency shows some meaningful explanations for signal analysis, it often produces some false frequency or cross frequency in the result (Elhaj et al., 2008). However, most signals such as non-stationary signal are not periodic signal. Until 1990s,

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instantaneous frequency was proposed and it has been widely applied in time-frequency analysis for recent years (Yang and Tavner, 2009). Instantaneous frequency is defined as the derivative of phase for arbitrary signal and it gives one frequency value corresponding to any instantaneous time. Some signal processing techniques include Hilbert-Huang transform and local wave approach, are based on instantaneous frequency analysis (Huang et al., 1999; Quek et al., 2003). Instantaneous frequency has been proved to be effective in signal processing, but the existence of a meaningful instantaneous frequency is still highly controversial (Huang et al., 1998). It seems that instantaneous frequency only represents the existence of frequency at one instantaneous time and it is not in connection with the past and future. In practice, the calculation of instantaneous frequency needs whole time series (Nho and Loughlin, 1999).

To avoid the problem mentioned above, a novel notion of general frequency is proposed. Compared with traditional frequency and instantaneous frequency, general frequency not only alleviates the problem of false frequency and cross frequency, but also shows some clear physical meanings. To identify the feasibility and effectiveness of the proposed approach, some simulation signals are analyzed. Based on the notion, an adaptive peak decomposition approach is investigated and applied to the fault diagnosis of reciprocating compressor gas valve in four states including normal valve state, gap valve state, fractured valve state and bad spring valve state.

**GENERAL FREQUENCY**

**Adaptive peak decomposition algorithm:** As is known to all, peak represents the limit state of vibration signal in a period and it can be used as the flag of beginning and end of each period. So the peak information is more important than the non-peak information. In order to extract the useful peak feature, a novel adaptive peak decomposition algorithm is proposed. The principle of adaptive peak decomposition is shown in Fig. 1.

For an arbitrary time series, \( x(i), (i = 1, 2, \ldots, n) \), the first peak series, \( p_1(i), (i = 1, 2, \ldots, n) \) can be given by local maximum of \( x(i) \), as follows:

\[
p_1(i) = \begin{cases} x(i) & x(i) = \max(x(i-1), x(i), x(i+1)) \\ 0 & x(i) = \max(x(i-1), x(i), x(i+1)) \end{cases}
\]  

(1)

Taking \( p_1(i) \) as a new time series, then go to step (1), the second peak series, \( p_2(i), (i = 1, 2, \ldots, n) \), can be gotten.

![Fig. 1: Diagram of adaptive peak decomposition](image)

Fig. 1: Diagram of adaptive peak decomposition

![Fig. 2: Adaptive peak decomposition of x(t)](image)

Fig. 2: Adaptive peak decomposition of \( x(t) \)

Repeat step (2), until the maximum peak series of \( x(i) \) is found, which is denoted by \( p_m(i), (i = 1, 2, \ldots, n) \), where \( m \) measures the numbers of decomposition layers.

Finally, the time series \( x(i) \) can be decomposed into intrinsic peak series, \( p_j(i), (j = 1, 2, \ldots, m) \). It is obvious that the procedure is adaptive and the level of peak series ranges from low to high.

In order to clarify the detail process, take the following simulation signal as an example, the time decomposition result is shown in Fig. 2:

\[
x(t) = 3\sin(2\pi t) + 5\cos(4\pi t) + 12\sin(6\pi t)
\]  

(2)

where, \( t \) is 6 s and sample frequency is 100 Hz.
In Fig. 2, time series \( x(t) \) is decomposed into 3 intrinsic peak series \( p_1, p_2 \) and \( p_3 \) by using the adaptive peak decomposition approach. And frequency bands of \( x(t) \) is intrinsic and ranges from high to low.

**Definition of general frequency:** The concepts of traditional frequency and instantaneous frequency are well accepted at present. Traditional frequency for an arbitrary signal \( x(t) \) can be calculated by Fourier transform, as follows (Liu et al., 2010):

\[
\omega(t) = \frac{1}{\tau} \int_{t-	au}^{t} x(t) e^{-j2\pi f dt}
\]

where, \( \omega \) is traditional frequency, and its unit is denoted by Hz.

Instantaneous frequency for an arbitrary signal \( x(t) \) can be given by Hilbert transform, as follows (Rato et al., 2008):

\[
\omega(t) = \frac{d}{dt} \left( \frac{1}{2\pi} \int_{t-	au}^{t} \frac{1}{x(t)} dt \right)
\]

where, \( \omega \) is instantaneous angle frequency and its unit is denoted by rad sec\(^{-1}\).

As an extension of traditional frequency and instantaneous frequency, a novel concept of general frequency is proposed. For an arbitrary time series of zero mean normalization \( x(i), (i = 1, 2, \ldots, n) \), it can be decomposed into some intrinsic peak series \( p_1(i), p_2(i), \ldots, p_n(i), (i = 1, 2, \ldots, n) \) by using the adaptive peak decomposition algorithm. Assuming that one of the peak series is \( p(i), (i = 1, 2, \ldots, n) \), as given in Eq. 1, the non-zero value of \( p(i) \) reflects the peak variety of \( x(i) \). Peak series \( f(j), (j = 1, 2, \ldots, N) \) and time interval series \( \Delta t(k), (k = 1, 2, \ldots, N-1) \), can be defined as:

\[
f(j) = i, \quad (p(i) > 0)
\]

\[
\Delta t(k) = f(j+1) - f(j)
\]

where, \( N \) is the number of non-zero value of \( p(i) \).

Then, pick out the repeat time interval from \( \Delta t(k) \) and a new time interval series denoted by \( \Delta l(i), (i = 1, 2, \ldots, L) \). Moreover, count the corresponding number of the repeat time interval and compose a time series \( l(i) \), the general frequency \( v_i \) and its local energy density \( \eta_i \) can be defined as:

\[
v_i = \frac{1}{\Delta t(k)}
\]

\[
\eta_i = \frac{s(i)}{\sum_{k=1}^{L} s(k)}
\]

where, \( L \) is the number of non-duplication time intervals, \( v_i \) measures the number of periods per unit time and \( \eta_i \) represents the probability of the corresponding general frequency \( v_i \) that appear in peak series of \( p(i) \).

According to the above definition of general frequency, the same signal \( x(t) \) defined by Eq. 5 is analyzed. The result is shown in Fig. 3.

From Fig. 3, it is noticed that general frequency contains 4, 2 and 1 Hz, which represent the original frequency feature in simulation signal \( x(t) \).

Time-frequency distribution based on general frequency:

A time-frequency distribution is a signal representation in which time, frequency and energy (or amplitude) are displayed jointly on a 2-D plane. According to the definition of general frequency above, the time-frequency distribution also can be gotten by defining the instantaneous general frequency \( v_i \) as follow:

\[
\mu_i = \frac{1}{\Delta t(k)}
\]

where, \( \Delta t(k) \) is the time interval series that mentioned in Eq. 6, \( N \) is the number of non-zero value of \( p(i) \) which is defined in Eq. 1. Figure 4 represent the time-frequency analysis result of \( x(t) \) based on instantaneous general frequency.

Figure 4 shows that the instantaneous general frequency of signal \( x(t) \) contains the feature frequency: 4, 2 and 1 Hz and each frequency varies in different time.
Fig. 4: Time-frequency analysis result of \( x(t) \)

period. The length of time of 4 Hz is the longest and the length of time of 1 Hz is the shortest.

In summary, the definition of the general frequency \( v_g \) and the instantaneous general frequency \( v_i \) is very similar, but their physical meaning are very different. The former represent the frequency information of whole time period which can be applied in frequency domain analysis. The latter represent the frequency information varies with time which can be applied in time-frequency domain analysis.

**PERFORMANCE**

As is known to all, vibration signals of reciprocating compressor gas valve represent the multiple impact source characteristics. In order to test and verify the effect of frequency feature extraction of the general frequency defined above, the simulation impact signal is analyzed in frequency domain and frequency time-frequency domain by comparing with the traditional frequency and instantaneous frequency. The impact signal is given as follows:

\[
y(t) = 2e^{-5t}\cos(20\pi t)
\]  

(10)

where, time \( t = 0-1 \) sec, sample frequency is 100 Hz, sample time is 1 sec. The impact signal contains five same signals of \( y(t) \).

The time waveform of impact signal and its decomposition result is shown in Fig. 5. The frequency domain analysis of impact signal based on general frequency and traditional frequency is shown in Fig. 6 and its time-frequency domain analysis based on

**Fig. 6: Feature extraction of impact signal in frequency domain, (a) General frequency (b) Traditional frequency**

**Fig. 7(a-b): Feature extraction of impact signal in time-frequency domain, (a) Instantaneous general frequency and (b) Instantaneous frequency**
instantaneous general frequency and instantaneous frequency is shown in Fig. 7.

Figure 5 indicates that the impact signal is decomposed into 2 intrinsic peak series p₁ and p₂ by using the adaptive peak decomposition approach. In Fig. 6, the general frequency of impact signal contains two frequency 1 Hz and 10 Hz that represent the feature frequency. However, the traditional frequency of impact signal not only indicates frequency 1 Hz and 10 Hz, but also produces some cross and harmonic frequency including 2, 3, 4 and 5 Hz etc. Figure 7 reflects the instantaneous general frequency of impact signal can effectively extract two frequency 1 and 10 Hz varies in different time period. Though the instantaneous frequency of impact signal also has the frequency 10 Hz, the feature frequency 1 Hz of original signal get lose. Otherwise, the instantaneous frequency has some false frequency nearby 1, 2, 3, 4 and 5 sec.

In summary, traditional frequency contains the information of frequency and amplitude. Although it shows some meaningful frequency in practice, it cannot show the frequency information at different times and it usually produces some false or cross frequency. Conversely, the instantaneous frequency contains the information of frequency and time. It shows the varieties of frequency information with times, but it cannot show a meaningful discrete frequency in period of time. However, general frequency contains the information of frequency and scales. It has the advantage of both the traditional frequency and the instantaneous frequency. So, it can be used for the feature detection of vibration signals in practice.

In summary, the proposed time-frequency analysis technique based on LF is feasible and effective in feature extraction of non-stationary signals. It shows more meaningful frequency components of signals. Compared with WVT, WT and HHT, LF can obtain higher resolution and more accurate feature from the investigated signals, especially for the time-frequency analysis of multiple impulse source signal. In addition, the simulation results indicate that each time-frequency technique has their own advantages, which is more suitable for analyzing some certain signals. Of course, so far there has been not any time-frequency technique which can process all kinds of signals. LF also has some limitations, such as the anti-noise performance and end effect, so it needs to be improved in the next work.

APPLICATION

In order to verify the effectiveness of this newly developed approach, four states i.e., normal state, gap valve sheets state, fractured valve sheets state and bad spring state, are tested on reciprocating compressor gas valve.

In order to extract fault features of multiple impulse signals of reciprocating compressor, the reciprocating compressor gas valve is taken as the research object and the vibration data in four states including normal valve state, gap valve state, fractured valve state and bad spring valve state are investigated by proposed time-frequency analysis technique based on general frequency. Figure 8 displays the experimental equipment installation for reciprocating compressor. Vibration signals were collected by vibration acceleration transducers fixed on gas valve cover. Sample frequency is 50000 Hz and sample time is 0.4 sec. Time waveform of gas valve vibration signal in four states is shown in Fig. 9.

Figure 8 displays the components and interconnection of the experimental equipment installation and Fig. 9 shows the structure sketch of reciprocating compressor test-bed. Vibration signals were collected by vibration acceleration transducers fixed on gas valve cover. Sample frequency is 50000 Hz and Sample length is 20000 points. Time waveform of gas valve vibration signal in four states are shown in Fig. 10.

From Fig. 10, it clearly shows that the cycle periodic of signal is \( T = 0.12 \) s in normal state and there are four process in a periodic. Each time of the process is \( t_1 = 0.02 \) sec, \( t_2 = 0.025 \) sec, \( t_3 = 0.04 \) sec and \( t_4 = 0.037 \) sec and the feature frequency are 50, 40, 25 and 27 Hz, respectively. However, the above information from the vibration signal in other three valve fault states can not be identified clearly. In order to solve this problem, the proposed approach is applied in feature extraction for multiple impact source signal of reciprocating compressor.
Fig. 9(a-d): Time waveform of reciprocating compressor gas valve in four states, (a) normal state, (b) gap valve sheets state, (c) fractured valve sheets state and (d) bad spring state.

Fig. 10: Continue.
Fig. 10: General frequency of gas valve signal in four states

Fig. 11: Instantaneous general frequency of gas valve signal in four states

gas valve. The general frequency of gas valve signal in four states are shown in Fig. 11.

Figure 11 shows the existence of large impact signal in four gas valve states and the general frequency feature
Fig. 12: Zoom in lower instantaneous general frequency of gas valve signal in four states

are much different and the energy amplitude are mainly local in high frequency bands. The maximal characteristic frequency are as follows: 7140, 6250, 7100 and 5560 Hz. In order to get more detailed frequency information of gas valve signal, zooming in the lower frequency bands district of Fig. 11, the results are shown in Fig. 12. The same primary general frequency 25 and 50 Hz can be extracted which are the feature frequency of gas valve signal that mentioned above.

The multiple impact source signal of gas valve amplified in Fig. 11 shows the time-frequency analysis results of gas valve signal based on instantaneous general frequency. Compared with Fig. 10 and 11, the instantaneous general frequency not only contains the feature information of impact time location, but also contains the characteristic high frequency bands including 7140, 6250, 7100 and 5560 Hz in four states. Figure 11 shows more detailed time-frequency information of gas valve signal in the lower frequency bands. Similarly, The primary general frequency are nearby 25 Hz and 50 Hz which are the feature frequency in a periodic of the vibration signal of reciprocating compressor gas valve. Moreover, the time-frequency feature based on instantaneous general frequency are obviously, and it can be applied into fault diagnosis of gas valve.

CONCLUSIONS

In this study, an novel notion of general frequency based on adaptive peak decomposition has been investigated. It provides a novel tool for the multiple impact source vibration signal that are typical non-linear and non-stationary. The impact signal can be decomposed into some intrinsic peak series and the frequency bands of decomposition results ranges from high to low. The decomposed peak series are analyzed by
The general frequency in frequency domain and time-frequency. Compared with the traditional frequency and the instantaneous frequency, the general frequency alleviates the problem of cross frequency or harmonic frequency and it also shows the varieties of meaningful frequency information in period of time. Based on the approach, the features of the vibration signal for reciprocating compressor gas valve in four states, including normal state, gap valve sheets state, fractured valve sheets state and bad spring state, are extracted. The results show that the proposed approach is able to extract the fault feature information and identify the faults effectively. And it shows the superiority of the proposed approach is demonstrated in feature extraction for the multiple impact source signal of reciprocating compressor gas valve.

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