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Analysis of Impact Fatigue Life for Valve Leaves in Small Hermetic Reciprocating Compressors

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Abstract

Impact fatigue life of valve leaves has great influence on energy saving performance and lifetime of small hermetic reciprocating compressors. This paper presented a test system that intended to analysis and evaluate of impact fatigue life of valve leaves used in small hermetic reciprocating compressors. Firstly, an incentive system was designed to simulate real work condition for valve leaf. Then, a data acquisition system was built to collect the sound signal while valve leaf was being under test. Simultaneously, the system could control the working state of incentive system so that test could be terminated automatically once fatigue was detected. Finally, fatigue detection system was designed to detect fatigue of valve leaf. Fatigue detection was the key point of this test system. Fast Fourier Transform (FFT) and Wavelet Packet Transform (WPT) were applied to analyze sound signal, both of which were effective in detecting the damage through analyzing. Facts showed that the test system provided a feasible approach to evaluate impact fatigue life for valve leaf manufacturing.
Keywords: *Valve leaf, Impact Fatigue, Fatigue detect, FFT, Wavelet Packet*

1. Introduction

In recent years, energy shortage problem is becoming worse and worse. More and more people care about energy saving performance of household appliances, like refrigerators, air conditions and so on. Usually, a refrigerator can work for more than eight years. With the increment of the working time, the refrigerating performance will degrade gradually [1]. The main reason is that inlet valve leaf of the compressor was being fatigued. The small hermetic reciprocating compressor is the core component of household refrigerator, which has two valves, an inlet valve and an exhaust valve. As work condition and structure of the valve leaves are different, the inlet valve leaves are more likely to be fatigue. This will result in the refrigerating performance degradation and more energy consumption. If the fatigue problem of inlet valve leaf can be optimized by valve leaf manufactures, energy saving performance of refrigerators will be improved obviously.

During work condition, valve leaves are mainly subject to bending stresses and impact stresses [2]. High bending strength steel is adopted by valve leaf manufactures in order to prevent bending fatigue failure. At present, most high-quality valve leaf manufactures adopt strip steel imported from Switzerland and Japan. But how to choose steel which can bear long time impacting is still a problem, because there is no existing equipment to evaluate the impact fatigue life.

Valve leaf is a light and thin elastomer, where incentive method is not available. Sensors cannot be set on valve leaf. In order to solve this problem, noncontact incentive system is designed, noncontact measurement is applied and detection method with sound signal models used is adopted. This paper presents an accelerated test system with both hardware and software which contains a noncontact incentive system, a data acquisition system, a control module used to control the working state of incentive system and a fatigue detection system to evaluate the valve leaf's impact fatigue life. The noncontact incentive system simulates the behavior of the valve leaf during work condition so that the test has more practical significance. Fast Fourier Transform method and Wavelet Packet Transform method are applied to analyze sound signal. When fatigue detection system detected the difference with sound signal from good valve, incentive system will be terminated by the control module,

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time will be recorded and a warning will be created to remind the operator. This test system is automatic and controllable.

2. Impact Fatigue Life Test System

Testing the valve leaf directly while compressor is working is very inconvenient. Firstly, under normal work condition, valve leaf has a very long life, usually 8 years or even more. Secondly, Structure of compressor is compact and totally-enclosed, so it is very difficult to set up sensors. Thirdly, noise from mechanical structure will affect test if acoustical detecting method is applied [3].

The test system is built to get impact fatigue lifetime of the valve leaf under certain test condition. Valve leaf is subjected to periodical impact. The principle is simulating the real behavior of valve leaf and detecting the fatigue of valve leaf. Lifetime of same type valve leaf is affected by three factors: work frequency, impact velocity which determined by air pressure, and temperature [2]. This paper mainly concerns about work frequency and impact velocity. Temperature factor can be included by just putting the noncontact incentive system into a thermostat.

2.1. Hardware Architecture

This test system includes a noncontact incentive system shown in Figure 1. A fixture is designed to fix valve plate and valve leaf. Compressed air is adopted instead of refrigerant in compressor as working medium to keep the test safe and convenient. A high speed solenoid valve which can work at the speed of 0-280Hz is controlled by function generator to generate pulse air flow. High speed solenoid valve work at voltage of 24VDC, but function generator cannot provide 24V voltage pulse, so a solid state relay and a 24VDC power source are needed. Pulse air flow impacting valve leaf to simulate opening and closing of the valve [4]. Working frequency can be changed using function generator. Pressure of the air source should be stable. Compressed air pressure can be measured with a pressure meter and pressure can be regulated with a pressure regulating valve so that the pressure can be set in the test. The short pipe connect the high speed solenoid valve with the fixture should be as short as possible because long pipe will be result in attenuation of the airflow. To reduce noise produced by the system itself, some sponges are put under fixture. And fixture should be strong to avoid resonance.

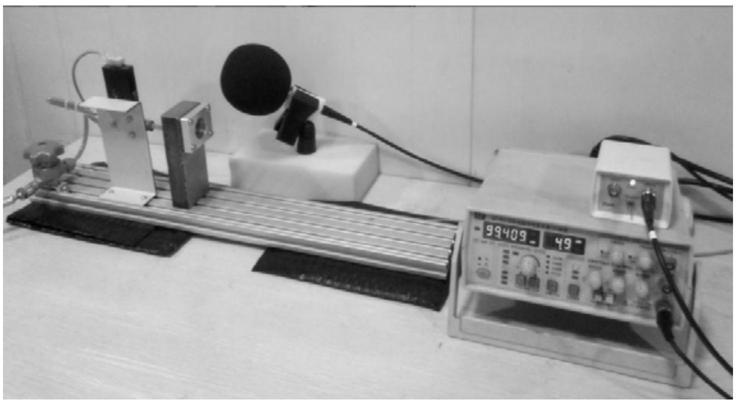

Figure 1. Noncontact Incentive System and Microphone

Data acquisition system contains a high sensitive microphone which is used to convert the sound pressure signal to electrical signal when valve leaf is working. This microphone has wide frequency response, high sensitivity, and wide dynamic range, lower background noise so that the sound data can be collected more accurately which is very important to fatigue detection system. An industrial computer with Data Acquisition Card (DAQ card) collects the electrical signal. The highest sampling rate is 500KHz, and the resolution is 12-bit. Because there are no power supply ports on the DAQ card, a power source that matches the microphone is necessary. The microphone output port connects to DAQ card with an I/O connector board. To protect the microphone from dust, a cover should be set up. Microphone should be placed near valve leaf to get the best effect. But do not put the microphone in front of valve leaf because pulse air flow will affect the result.

Control module contains an isolated output card installed in computer and a relay board. Isolated output card can be controlled by computer output 1 or 0 state. Relay board triggered by isolated output card control the state of high speed solenoid valve. This module makes the test system an automation system.

2.2. Software Architecture

Isolated output card and DAQ card manufacturer provide drivers and basic examples for different develop environments, like, VC, Delphi, LABVIEW, VB. In this paper, data acquisition and control module software is programmed in graphical language named LABVIEW developed by National Instrument. It's easy to create a graphical operation interface with it. LABVIEW has a great convenience in developing data acquisition software and has been widely used in measurement field.

LABVIEW program for this test system mainly has three modules: data acquisition module, signal processing module, control module. Data acquisition module and control module can be programmed base on VI examples provided by Data Acquisition Card and Isolated output card manufacture. LABVIEW has great advantages in measurement field. But in signal processing field, its function is limited. MATLAB is powerful in numerical calculation and have all kinds of tool box applied in all kinds of fields. LABVIEW provide a VI named MATLAB script node to call MATLAB program processing signal data. Thus, signal processing module is programmed with MATLAB called by MATLAB script node. By this way, this system can combine the advantages of LABVIEW and MATLAB makes it acquire and process signal data very well.

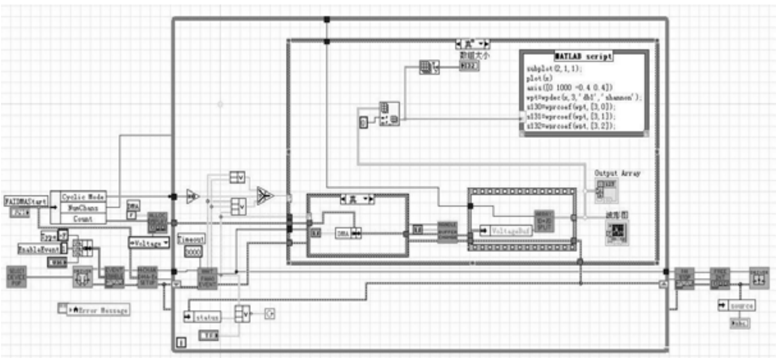

Figure 2. LABVIEW Program of the Test System

3. Method Analysis and Evaluate

As normal lifetime of valve leaf is usually over eight years. In order to evaluate impact fatigue lifetime, accelerate test method is adopted. As noticed above, the impact fatigue life is affected by three factors, impact frequency, impact velocity and temperature. This incentive system can set frequency with function generator and change impact velocity by changing the air pressure. In test, frequency and air pressure are set much higher than they are under the normal work condition to accelerate the fatigue process [5].

Fatigue detection is the most important technology in this system, and signal processing algorithm plays a very important role in detecting fault accurately. During the last decades, many people work on detecting and diagnosing faults and have find out some ways to detect faults which have been widely used in mechanical products fault diagnosing, such as fan, engine, air compressor [6].There are several kinds of fault detection methods: detection with limit checking or trend checking, detecting with signal models detection with process models used and detection with multivariate data analysis [7]. At present, methods that based on mathematical signal and process models to generate fault symptoms like spectrum analysis and wavelet analysis are the most frequently-used methods [8]. So, both Fourier Transform and Wavelet Transform have been tried in this system to analyze the sound signal.

3.1. Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT)

The Discrete Fourier Transform is the most important transform and has been widely used in many practical applications. In digital signal processing, the function is transform time based data into frequency based data, such as the pressure of sound wave, electromagnetic wave. In data compression, it is used to filter useless data to reduce the size of data [9]. The DFT is also used to efficiently solve partial differential equations, and to perform other operations such as convolutions or multiplying large integers.

The sequence of N-periodic is transformed into an N-periodic sequence of complex numbers according to the DFT formula:

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j\omega nk} = \sum_{n=0}^{N-1} x(n)e^{-j\frac{2\pi}{N}nk} \tag{1}$$

It describes the Discrete Fourier Transform of an N-periodic sequence, *X(k)* is coefficients of discrete frequency components.

This is the inverse DFT (IDFT):

$$x(n) = \frac{1}{N}\sum_{n=0}^{N-1} X(k)e^{j\omega nk} = \frac{1}{N}\sum_{n=0}^{N-1} X(k)e^{j\frac{2\pi}{N}nk} \tag{2}$$

This notation uses *j* for the imaginary unit, *n* and *k* for indices that run from *0* to *N–1*. *N* is the length of sample data.

Discrete Fourier Transform is applied to analyze sound data acquired from valve leaf because sound signal data acquired by computer is time domain, it’s hard to find the symptom and detect [4]. Spectral analysis is the process of identifying component frequencies in signal data. For discrete data, the computational basis of spectral analysis is the discrete Fourier transform (DFT). The DFT transforms time domain data into frequency domain data. With this method, the sound signal data are observed in frequency domain and characteristic frequency can be found. Frequency components can be analyzed. But there is a problem with DFT method, when processing signal data, calculating mount is too huge, computer can’t do it effectively.

FFT is an efficient method for computing the DFT. When FFT algorithm is applied, there is a difference between the window length and the transform length. The window length is the length of input data vector. It is determined by DAQ card and the way data transform. As test system detecting in real time, data translation and calculation should be rapid. DMA data transform method is applied to transform data at the best speed. The transform length is the length of the output, the computed DFT. The execution time of an FFT algorithm depends on the transform length. It is most effective when the transform length is a power of two. According to Nyquist Sampling Theorem, sample frequency should be greater than twice as much as signal frequency. Revolution of frequency spectrum is *fs/N*. After several experiments, in order to achieve the appropriate revolution and calculation speed, sample rate is set to 10 KHz, and transform length is set as 10000. The revolution of frequency is 1Hz. FFT algorithm will pads or chops the input to achieve the desired transform length. It hardly affects the speed because FFT algorithm in MATLAB is high efficient.

With FFT algorithm applied, valve leaves are tested under the condition of impact frequency is 100Hz and compressed air pressure is 0.1MPa. Because it is visualized to center the spectrogram at 0, ‘fftshift’ function in MATLAB is used to rearranges the output from FFT with a circular shift to produce a 0-centered spectrogram. Experiment results show as follow two figures:

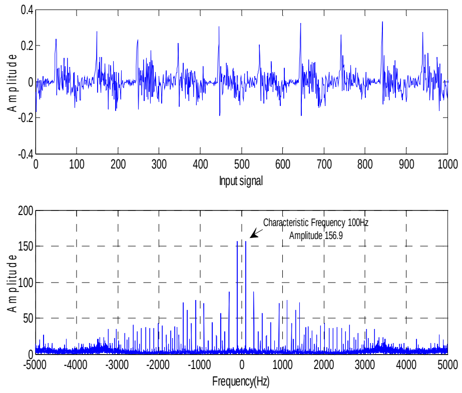

Figure 3. Sound Signal from Good Valve Leaf and Frequency Spectrum

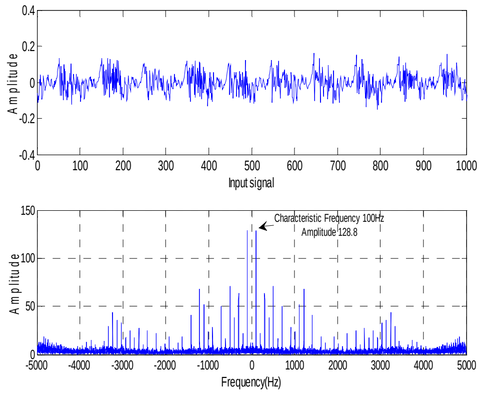

Figure 4. Sound Signal from Fatigue Valve Leaf and Frequency Spectrum

The two figures above clearly show the difference between signal from good valve leaf and signal from fatigue valve leaf. These two frequency spectrums are different, and the most difference is the amplitude at characteristic frequency. Figure 3 shows the amplitude at characteristic frequency is 156.9. Figure 4 shows the amplitude at characteristic frequency is 128.8. Thus, a value as threshold can be set, if the amplitude at characteristic frequency is greater than threshold that shows the valve leaf under test is good. Otherwise, the valve leaf is fatigue. Program will terminate the solenoid valve, record the time and send a warning.

3.2. Wavelet Transform and Wavelet Packet Transform

Fourier transform takes a signal in the time domain and transforms it into the frequency domain, where the Fourier transform result represents the frequency components of the signal. Once the signal is transformed into the frequency domain, all information about time will be lost, only frequency remains [10]. In contrast to the Fourier transform, wavelet transform enables analysis of data at multiple levels of resolution. When wavelet transform is applied to a signal in the time domain, the result is a two-dimensional, time-scale domain analysis of the signal.

While wavelet transform provides flexible time–frequency resolution, it suffers from a relatively low resolution in the high-frequency region. The wavelet packet method is a generalization of wavelet decomposition that offers a richer signal analysis [11]. It decomposes the signals into different frequency ranges and allows extraction of features relating to quality.

The Wavelet Packet transform has been proven very useful for analysis of signals and has been successfully applied to detect machine fault. The procedure is split the approximation coefficient vector into two parts, a vector of approximation coefficients and a vector of detail coefficients can be obtain, both at a coarser scale. Then next step, using the same way as in approximation vector splitting to decompose both the vector of approximation coefficients and the vector of detail coefficients. This offers the richest analysis. Here is a level-3 decomposition procedure figure [12].

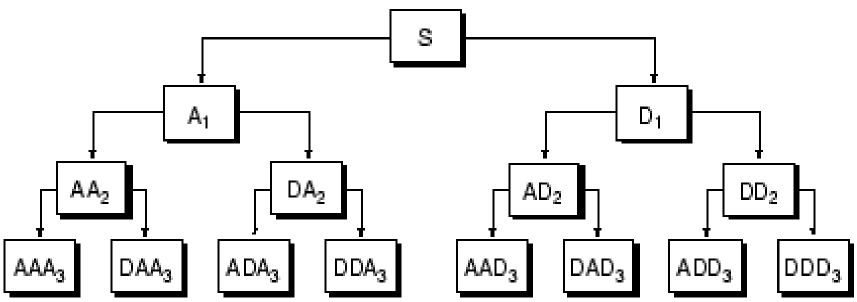

Figure 5. Decomposition in Level 3

Considering the calculation amount will increase rapidly with the decomposition level goes higher, this paper chose level-3 decomposition to ensure this test system runs fluently.

After the decomposition, there will be eight coefficients, which can be calculated the band energy of every frequency band and construct a feature vector with that. From comparing the feature vector of sound signal with feature vector of sound signal acquired from good valve leaf, the state of valve leaf during test can be estimated [13].

Following two figures show results of using wavelet packet transform. Apparently, the feature vector is different in vector components' magnitude which means the band frequency energy is different. This can be the basis for judging state of valve leaf comparing the difference with the sound from a good valve leaf [14]. A threshold is set, if the difference exceed threshold, the system will remind operator the valve leaf is broken. Then, the lifetime of the valve leaf is recorded.

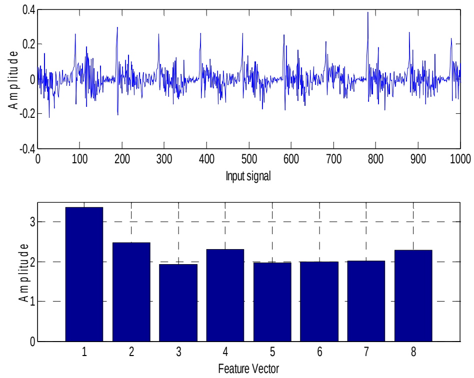

Figure 6. Sound Signal from Good Valve Leaf and Feature Vector

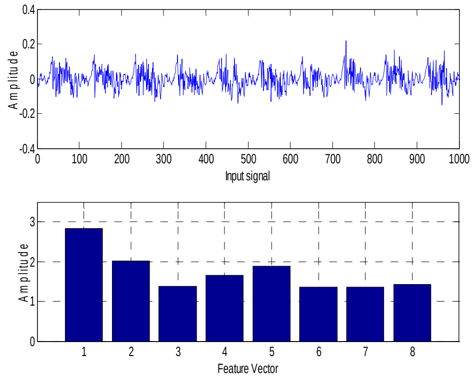

Figure 7. Sound Signal from Fatigue Valve Leaf and Feature Vector

4. Conclusion

In order to analyze and evaluate the impact fatigue life of valve leaf used in small hermetic reciprocating compressors, an evaluation system based on real work condition of valve leaf is designed, which is made up of a number of devices include high speed solenoid valve, fixture, function generator, compressed air source to simulate the open and close behavior of valve leaf. Sound signal data is acquired by using a sensitive microphone, power source for microphone, data acquisition card (DAQ card) and LABVIEW program. Sound signal data is processed with MATLAB program which is called by MATLAB script node in LABVIEW. To detect the fatigue valve leaf, both FFT transform and Wavelet Packet transform are proven feasible. But in fact, sound pressure signal is unstable, because amplitude of characteristic frequency is sensitive with the pressure of compressed air source. Fatigue detecting with FFT may be less reliable. Meanwhile, fatigue detecting with Wavelet Packet Transform base on band energy has a higher accuracy. This test system provides a way for valve leaf manufactures to estimate impact fatigue life and has practical value.

Acknowledgements

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