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Research on Low Frequency Noise Caused by Beat Vibration of Rotary Compressor

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ABSTRACT

With a typical rotary compressor as the research object, the discontinuity of low frequency noise caused by beat vibration of rotary compressor is studied in this paper. Based on theoretical analysis of beat vibration, the internal pressure pulsation components of the compressor are tested. At the same time, an FEM model is established to generate motor harmonics simulation and time domain signal of motor torque obtained by over the FEM simulation. The root cause of the beat vibration is studied, and related optimization schemes are developed. The test results show that the reduction of discharge pressure pulsation and improvement of motor harmonics are effective to reduce the compressor low frequency noise caused by beat vibration.

1. INTRODUCTION

The rotary machinery may suffer a time domain periodicity beat vibration from time to time, the vibration maybe jointly caused by residual medium on compressor rotor and imbalance of the rotor itself. Or it may be caused by frequency of one or more stable vibration sources in the system. The traditional beat vibration research does not take account of the interaction between the electromagnetic force and the pressure pulsation with finite element simulation. The excitation force of beat vibration is obtained by finite element simulation in this paper, and the torque ripple is analyzed by Fourier decomposition method. The simulation results coincide with the test results, which can guide the optimization and reduction of beat vibration and noise. This paper provides a good reference for the study of vibration and noise of rotary compressors.

2. THEORY OF BEAT VIBRATION

2.1 Beat Vibration Principle

The beat vibration is formed by two vibrations with a small frequency difference superimposing each other. Suppose that these two vibration components respectively are:

$$X_1 = A_1 \cos(\omega_1 + \emptyset_1), X_2 = A_2 \cos(\omega_2 + \emptyset_2) \tag{1}$$

In which, A_1 and A_2 are amplitudes of two vibration components respectively. ω_1 and ω_2 are angular speeds. Φ_1 and Φ_2 are initial phase angles. Superimpose these two signals will form the equation:

$$X = X_1 + X_2 = A_1 \cos(\omega_1 + \emptyset_1) + A_2 \cos(\omega_2 + \emptyset_2)$$

$$= \sqrt{A_1^2 + A_2^2 + A_1 A_2 \cos[\frac{\omega_1 - \omega_2}{2} t + \frac{\emptyset_1 - \emptyset_2}{2}]} \times \sin\left(\frac{\omega_1 + \omega_2}{2} t + \emptyset + \frac{\emptyset_1 + \emptyset_2}{2}\right) \tag{2}$$

In which, $\tan\emptyset = \frac{A_1 - A_2}{A_1 + A_2} \tan(\frac{\omega_1 - \omega_2}{2} t + \frac{\emptyset_1 - \emptyset_2}{2})$

The Figure 1 shows the synthesized beat vibration waveform. The beat vibration is the vibration signal with $(\omega_1 - \omega_2)$ / (4π) as amplitude modulation frequency. The frequency of vibration signal itself is $(\omega_1 + \omega_2)$ / (4π).

2.2 The Beat Vibration of Rotary Compressor

The beat vibration frequency calculation equation of induction for compressor is:

$$f_n = f_{n2} - f_{n1} = (1 + S)\frac{f_1}{p} - (1 - S)\frac{f_1}{p} = 2S\frac{f_1}{p} \tag{3}$$

In which, f_n is beat vibration frequency, f_1 is frequency of the grid, S is slip, p is pole pairs of motor.

So it is concluded that the calculation equation of the frequency due to modulation is:

$$f = nf_0 + mf_n \tag{4}$$

In which, f_0 is the actual operation frequency of the motor, n=1，2，3…, m=0，1，2，3….

The operation frequency of a certain rotary compressor is 57.5Hz, p=1. According to equation (3), the beat vibration frequency f_n is calculated as:

$$f_n = 2S\frac{f_1}{p} = 2 \times \frac{60 - 57.5}{60} \times \frac{60}{1} = 5 \text{ Hz} \tag{5}$$

The noise spectrum of the tested compressor can be seen in Figure 1. It can be seen from the frequency spectrum signal feature that due to noise peak values between 115Hz and 120Hz, 173Hz and 178Hz have approximate frequencies, the beat vibration appears. This agrees with the calculation results shown above.
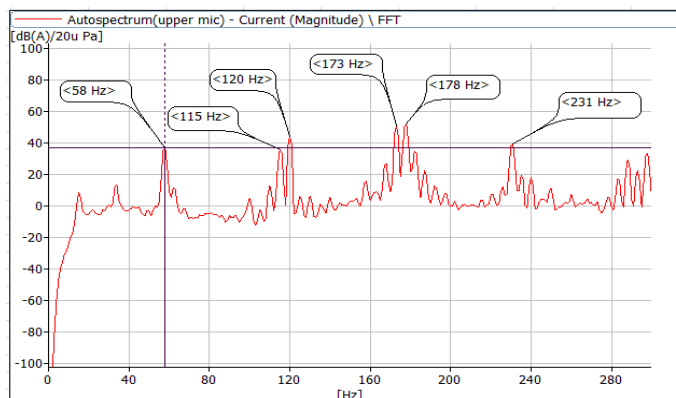
Figure 1: Near Field Noise Spectrum of the Compressor

As per the frequency formed after modulation which is calculated with equation (4). The errors between the calculated frequencies and the tested frequencies are small in Table 1.

Table 1: Calculation table of modulated frequencies

| Items	n	m	Calculated value(Hz)	Tested value(Hz)	Error
1	1	0	58	58	0%
2	2	0	116	115	0.8%
3	2	1	117	/	/
4	2	2	122	120	1.6%
5	3	0	174	173	0.6%
6	3	1	177	177	0%
7	4	2	232	231	0.4%

3. INVESTIGATION OF BEAT VIBRATION REASION

3.1 Pressure Pulsation Analysis

The pressure pulsations at suction end and discharge end inside the compressor are measured with high precision pressure transducers, as is shown in Figure 2(a). Compressor noise is measured at near field at the same time. It can be seen from Figure 2(b) that amplitudes of pressure pulsation at discharge end are high at double frequency 115Hz and triple frequency 173Hz, excluding fundamental frequency. This agrees with that of some beat frequencies causing low frequency noise. Meanwhile, from coherence spectrum chart of discharge pressure pulsation with near field noise, it can be seen that the discharge pressure pulsation within low frequency range relates well with noise, as is shown in Figure 3,thus the discharge pressure pulsation is one of the reasons causing the beat vibration.

Figure 2（a）:Photos of compressor pressure pulsation testing
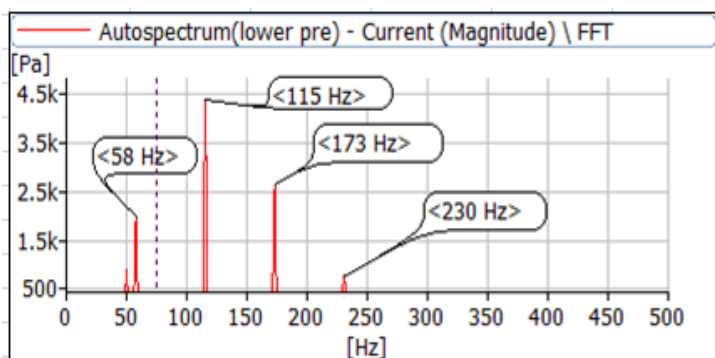
Figure 2（b）:Spectrum of compressor discharge pressure pulsation
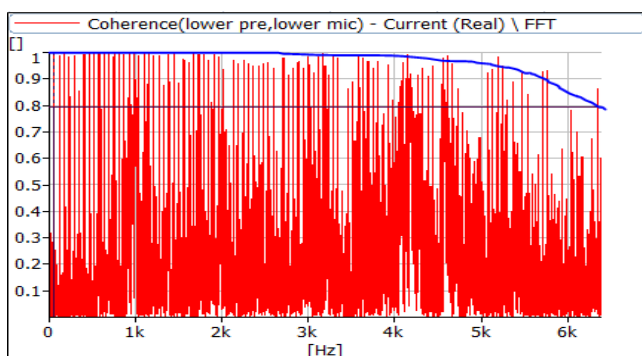
Figure 3: Coherence spectrum chart of pressure pulsation with near field noise
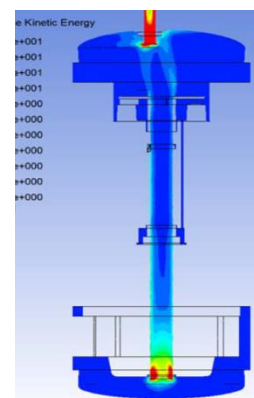
To reduce discharge pressure pulsation of the compressor, a ventilation tube as showed in Figure 4(a) is made inside the compressor. FEM model of compressor discharge chamber is established, and improvement of discharge pressure pulsation is obtained with fluid simulation software, see Table 2.

Figure 4（a）: Structure of Ventilation tube
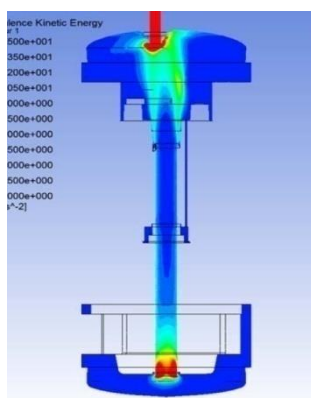
Figure 4（b）:Discharge chamber pressure without ventilation tube

Figure 4（c）:Discharge chamber pressure with ventilation tube

**Table 2:** Calculation table of discharge pressure pulsation

scheme	monitor point	57.5Hz pressure pulsation(Pa)	115Hz pressure pulsation(Pa)	173Hz pressure pulsation(Pa)	230.5Hz pressure pulsation(Pa)
	Pressure pulsation reduction percentage of top chamber – motor with ventilation tube	-4.3%	5%	63.6%	84.6%
	Pressure pulsation reduction percentage of bottom chamber --motor with ventilation tube	-11.6%	20.6%	68.3%	85.6%

3.2 Electromagnetic Torque Harmonic Analysis of Motor

Vibrations in three directions of compressor shell show that the vibrations at 120 Hz and 178 Hz are mainly in tangential direction. Capacitor-operating single-phase asynchronous motor is used in the analyzed compressor, negative sequence field will cause big tangential vibration of the motor, so the conclusion is that this tangential vibration is caused by electromagnetic torque pulsation of the motor.

A 2D model of compressor motor is established，see Figure5, inflicting gas torque, proceeding transient electromagnetic simulation, let it operate for 60 mechanic cycles. When it operates stably, the actual motor speed is 3480rpm(fundamental frequency 58Hz), the average speed of the simulated motor which is operating stably is 3510rpm(fundamental frequency58.5Hz).
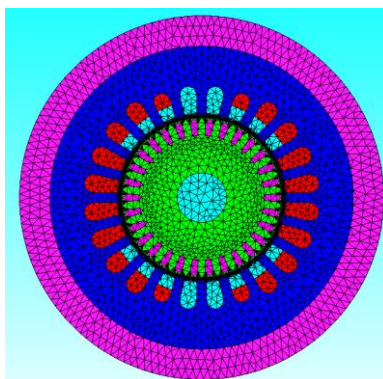
Figure 5: 2D model of motor
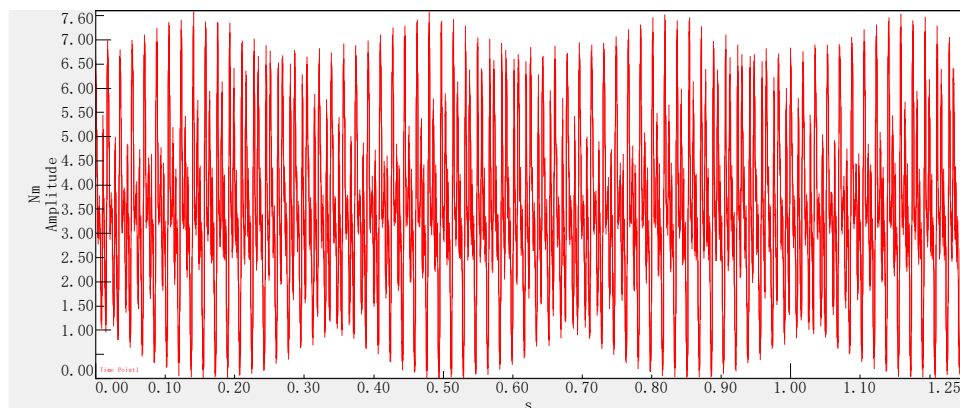
Figure 6（a）: Time domain spectrum of electromagnetic torque
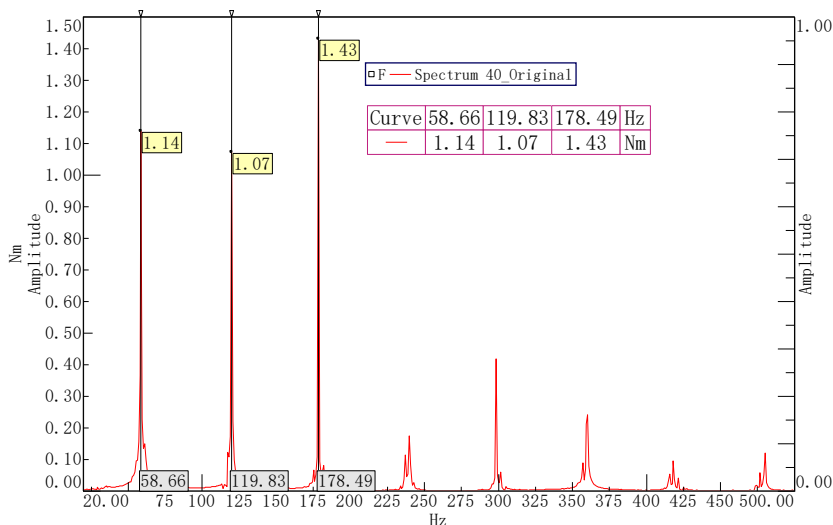
Figure 6（b）: FFT spectrum chart of electromagnetic torque

From Figure 6, it is known that there are harmonic peaks near 120 Hz and 178 Hz, and the magnitudes are high. The slight difference between actual operation speed and simulated speed results in minor difference between harmonic frequency and measured frequency, but these two frequencies are basically identical. Considering that the main winding of the motor is not suitable to be changed, it is planned to optimize motor harmonic by changing value of capacitance, turns of auxiliary winding and wire diameter, as is shown in Table 3.

Table 3: Improved motor scheme

items	Description			peak value of electromagnetic force harmonics at 120 Hz(Nm)	peak value of electromagnetic force harmonics at 178 Hz(Nm)
	capacitance	Wire diameter	turns of auxiliary winding		
Original design	40uF	1.05mm	35，23，15，11	1.07	1.43
Design A	45uF	1.0mm	38，26，18，13	1.03	1.09

4. TEST VERIFICATION

To verify the accuracy of the schemes, the tested noises among original motor, motor sample with discharge pressure pulsation optimized and motor sample with torque harmonic optimized are compared. The noises of compressor samples are tested in semi-anechoic chamber, the results see Table 4 and Table 5.

Table 4: Test data of pressure pulsation after optimization

item	scheme	peak value of noise at 115Hz（dB）	peak value of noise at 173Hz（dB）	peak value of noise at 230Hz（dB）
1	Original design	25.3	31.2	29.9
2	Design with ventilation tube	24.7	25.3	22.9
	Δ	0.6 ↓	5.9 ↓	7 ↓

Table 5: Test data of motor harmonic after optimization

item	scheme	peak value of noise at 120Hz（dB）	peak value of noise at 178Hz（dB）
1	Original design	28.1	32.5
2	Design with motor optimization	27.3	27.8
	Δ	0.8 ↓	4.7 ↓

Analysis the data in Table 4 and 5, we can know that optimize discharge pressure pulsation or optimize torque harmonic of motor can improve the beat vibrations of the compressor, so the low frequency noise of the compressor can also be improved, it's consistent with academic analysis.

5. CONCLUSIONS

The low frequency noise caused by beat vibration of rotary compressor is studied in this paper, the conclusions are:

1）The beat vibration will cause discontinuous low frequency noise of the compressor, and it is verified with theoretical algorithm.

2）The gas flow pulsations inside the compressor discharge chamber appear mainly at double and triple frequency, and the magnitudes are high. This results the beat vibration of compressor. The gas flow pulsations are reduced via changing the structure of fluid passage, discharge valve and muffler design, so that the beat vibrations of the compressor are reduced.

3）There are considerably big second and third electromagnetic torque harmonics exist in compressor motor, this is another reason of the occurrence of the beat vibration. By changing motor design to improve electromagnetic harmonic, the low frequency noises caused by beat vibrations are reduced.

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