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In Processing Fault Detection of Machinery Based on Instantaneous Phase Signal

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ABSTRACT The instantaneous phase signal contains abundant information about the health state of machineries, which plays an important role in fault detection of machineries, rotor dynamic balance, transmission error of Rotate Vector reducer, etc. Traditional methods use signal processing methods based on encoders, EMD and Hilbert transforms or fractional delay filters to extract instantaneous phase information indirectly. These traditional methods are state-of-art, however those algorithms are slightly complicated and time-consuming, which is not conducive to online prognostics and health management to some extent. In fact, high precision and high reliability sensor technology can effectively reduce the complexity of subsequent signal processing. In this paper, an instantaneous phase direct detection technique based on eccentric demodulation principle is proposed. The method is derived from the kinematics between the cam and the pushrod. The laser displacement sensor is used to replace the pushrod to realize non-contact measurement. The instantaneous phase is modulation by the cam, and the proposed method can realize the obtain of the theoretical phase infinite resolution, which reaches 16,000-line resolution. Compared with the traditional encoder and other inspection technologies, the proposed method is also suitable for the measurement of broadband shifting and reciprocating motion. By means of simple signal processing methods, this paper realizes the fault diagnosis of the rolling bearing with typical defectives, and realizes the extraction and identification of the fault signal of the reciprocating compressor. Experimental results proved that the proposed inspection technology can serve as an effective technology for mechanical fault diagnosis.

INDEX TERMS Fault diagnosis, signal processing, measurement.

I. INTRODUCTION

Vibration-based fault diagnosis is mostly used in detection of machinery fault. With the development of signal processing, data-driven methods [1] such as data mining and artificial intelligence technology [2], [3] are becoming more and more important in the fault diagnosis of machineries. A series of papers surrounding signal processing have also appeared [4]–[12].

In fact, sensor techniques often play a more important role in fault diagnosis of machineries, and advanced sensor techniques have shorter transfer path [13]. For example, the instantaneous angular speed (IAS) method has shorter transfer path than the vibration-based method [14], [15]. Its advantage is to suppress noise interference and reduce the signal offset caused by the long transfer path, so the active components in the signal are less likely to be lost [16], [17]. The advanced sensor technology with high precision and high reliability can effectively reduce the complexity of subsequent signal processing methods. Taking the eddy current displacement sensor as an example to judge the quality of rolling bearings by detecting the Hertz deformation of the outer ring of rolling bearings [18], the advanced sensor technology can obviously obtain the signal with high signal-to-noise ratio (SNR). Stator current signal and acoustic emission signal is also advanced detection technology used

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to inspect bearing damage. Induction machine faults diagnosis using stator current parametric spectral estimation was proposed by El Bouchikhi *et al.* [19]. Mixed eccentricity diagnosis in Inverter-Fed Induction Motors via the adaptive slope transform of transient stator currents was proposed by Pons-Llinares *et al.* [20]. Statistic-based spectral indicator for bearing fault detection in permanent-magnet synchronous machines using the stator current was proposed by Picot *et al.* [21]. The reflection of evolving bearing faults in the stator current's extended park vector approach for induction machines was proposed by Bram *et al.* [22].

Instantaneous amplitude, instantaneous frequency and instantaneous phase [23]–[26] are the transient characteristics of signals and play an important role in fault diagnosis of machineries. At present, a series of papers using the instantaneous amplitude and instantaneous frequency to obtain the time-frequency distribution of the signal related to signal analysis, feature extraction and fault diagnosis [27], [28]. New procedure for multistage gearbox fault detection and diagnosis using instantaneous angular speed were proposed by Li *et al.* [29], [30]. Indicators for monitoring chatter in milling based on instantaneous angular speeds was proposed by Lamraoui *et al.* [31]. In fact, the instantaneous phase signal also contains rich signal features. Some scholars have used the instantaneous phase for fault diagnosis, and the instantaneous phase acquisition technique based on signal processing methods such as EMD and Hilbert transform [32], [33], the fractional delay filter [34], [35] the accurate estimation method of the parking phase [36], [37] and the instantaneous phase calculation method of the encoder. Instantaneous speed jitter detection via encoder signal and its application for the diagnosis of planetary gearbox was proposed by Zhao *et al.* [38]. Natural roller bearing fault detection by angular measurement of true instantaneous angular speed was proposed by Renaudin *et al.* [39]. Application of instantaneous rotational speed to detect gearbox faults based on double encoders was proposed by Liang *et al.* [40]. Those methods rely on advanced signal processing methods and represents the state-of-art of prognostics and health management.

Drawing on the advantages of the above fault detection techniques, this paper focuses on the direct measurement of instantaneous phase. Instantaneous phase is integral with time of the IAS, and the appearance of instantaneous phase and IAS is always complementary. The machinery fault diagnosis method based on instantaneous speed are based on the assumption that effects of bearing faults can be considered as load fluctuations in time associated to impact of rolling elements when passing through the point of defect [41]–[45]. The main assumption made in this work assumes that very small revolution speed fluctuations are induced by the presence of local faults only by changes in the kinematics. The principle of the proposed method is derived from the kinematics between the cam and the pushrod. The non-contact measurement is realized by replacing the ejector with a laser displacement sensor, and the

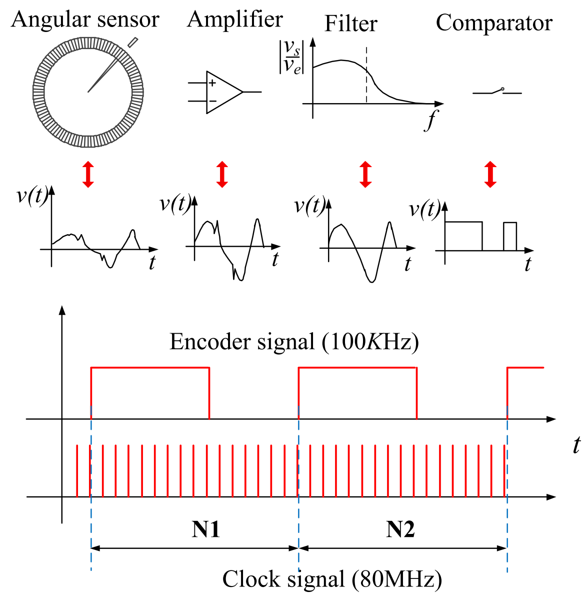

FIGURE 1. Measurement principle of encoder.

instantaneous phase modulation is realized by using a cam in the form of an eccentric sleeve, and the theoretical phase infinite resolution can be obtained. This paper realizes the fault diagnosis of rolling bearings of typical defectives, and realizes the extraction and identification of fault signals of reciprocating compressors.

The first section of the paper is devoted to the traditional instantaneous phase detection method, measurement principle of encoder and vibration-based detection method based on EMD and Hilbert transform is introduced in detail. Then, the second section clarify the general presentation of instantaneous phase measurement method with eccentric modulation principle. The measurement principle applies the proposed method for high precision. Then, the third section exhibits results obtained on a bearing fault diagnosis test bench and reciprocating compressor fault diagnosis. The forth section presents some perspectives for this proposed eccentric modulation instantaneous phase. The last section presents some conclusions for this promising way of fault detection in machineries.

II. TRADITIONAL INSTANTANEOUS PHASE DETECTION METHOD

A. MEASUREMENT PRINCIPLE OF ENCODER SIGNAL

The encoder is traditional instantaneous phase detection method and is widely used in industrial field. The principle of the encoder [39] is shown in Fig.1.

According to the prior research [29], [46] measurement performance of fault signals is based on two basic principles: counting the number of pulses in a given time duration and measuring the elapsed time for a single cycle. The definition equation is shown in Equation 1-2 as follow.

$$\omega = \frac{2\pi}{N} \cdot \frac{f_H}{N_i} (rad\ s^{-1}) \tag{1}$$

$$\Delta = \omega \times \Delta t \tag{2}$$

where, f_H represents the clock frequency or sample frequency; N_i is the number of data points between two rising edges of the encoder signal; N is the resolution of the encoder. $\Delta\varphi$ is instantaneous phase angular displacement and Δt is the corresponding time duration.

The encoder has certain precision and resolution, and has obvious advantages. It is widely used in many occasions and is an important part of industrial measurement and control. However, the general encoder resolution is limited, the installation position is relatively fixed, mostly in the shaft end, not suitable for reciprocating motion.

B. VIBRATION-BASED DETECTION METHOD BASED ON EMD AND HILBERT TRANSFORM

The vibration-based detection method based on EMD and Hilbert transform to extract instantaneous phase signal includes the following steps [32], [33].

(1) Conduct EMD analysis on the original signal to obtain its IMF components $C_1, C_2 \ldots C_n$; $C_i(t)$.

(2) Hilbert transformation was performed for each IMF component $C_i(t)$, and the following formula was obtained, failure frequency calculation and formula of various bearings were calculated according to the actual size.

$$H\left[C_i(t)\right] = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{C_i(\tau)}{t-\tau}d\tau \tag{3}$$

Construct analytic function

$$Z_i(t) = C_i(t) + H\left[C_i(t)\right] \tag{4}$$

Then the amplitude function can be obtained

$$a_i(t) = \sqrt{C_i^2(t) + H^2[C_i(t)]} \tag{5}$$

$$\theta_i(t) = arctan(\frac{H[C_i(t)]}{C_i(t)}) \tag{6}$$

III. INSTANTANEOUS PHASE DIRECT DETECTION TECHNIQUE PROPOSED IN THIS PAPER

A. THEORETICAL BACKGROUND OF THE PROPOSED METHOD

The theory of instantaneous phase direct measurement technique proposed in this paper is derived from the kinematics of cam mechanism, as shown in Fig. 2. The conventional cam pushrod movement principle is shown in Fig. 2a). When the eccentric circle is selected as the cam, the trajectory of the pushrod is a cosine-like signal, as shown on the right side of Fig. 2b).

The instantaneous phase direct inspection method proposed in this paper is further evolved by the cam mechanism. As shown in Fig. 2, the push rod moves up and down the track as the cam rotates. In the push process, the stroke of the push rod increases from 0 to h, and in the return, the stroke of the push rod decreases from h to 0. According to the motion of the putter, the laser displacement sensor or the eddy current displacement sensor can be used to replace the pushrod for non-contact measurement, and the

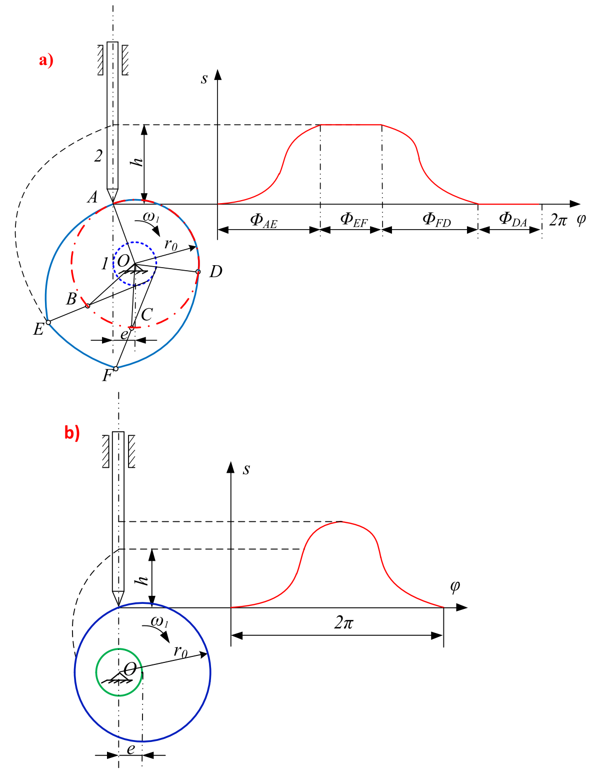

FIGURE 2. The kinematics principle of the cam mechanism.

cam in the form of an eccentric sleeve is used to realize the instantaneous phase modulation. The schematic diagram is shown in Fig. 3. The point O is the rotation center of the eccentric sleeve, and the eccentric sleeve eccentricity is 4 mm. The points A and B in the Fig.3 are the highest point and the lowest point of the eccentric sleeve respectively, that is, the displacements measured by the corresponding laser sensors are s_{min} and s_{max} respectively. θ is the rotation angle between the eccentric sleeve and the y-axis. When the spindle is running at the speed of ω_1, the laser sensor measures the displacement s. The measured displacement s can be converted into the phase θ by the simple mathematical relationship of ΔOO_2M. The conversion relationship [47] is shown in Equation 7-9.

$$r^2 = (h-s)^2 + e^2 - 2(h-s)ecos\theta \tag{7}$$

$$\theta = arccos\{[(h-s)^2 + e^2 - r^2]\big/2e\,(h-s)\} \tag{8}$$

$$h = r + e + s_{min} \tag{9}$$

where o, θ are the axis of the spindle, rotation angle, respectively. o_i is the outer-circle centre of an eccentric sleeve. e is the eccentricity between the inner circle and outer circle of an eccentric sleeve. ω_3 is the rotation speed of the shaft. s is the instantaneous distance between the probe of an eddy current sensor and an eccentric sleeve. h is the fixed distance between an eddy current sensor and the axis of the spindle. $r = d\big/2$ is the radius of the eccentric sleeve.

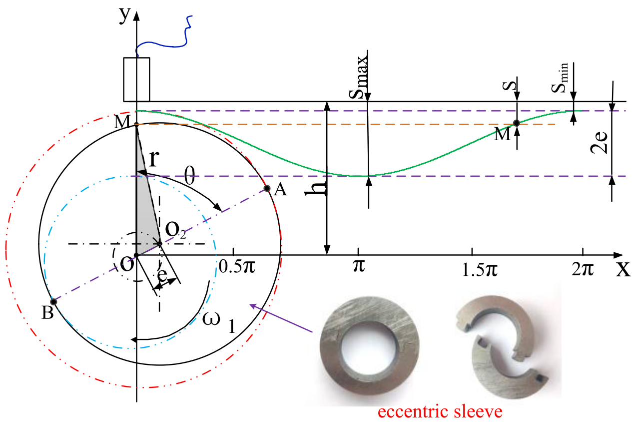

FIGURE 3. Measuring principle for instantaneous phase.

TABLE 1. Laser displacement sensor and eddy current displacement sensor parameters.

Name	Model	Measuring center distance	Measuring range	Resolution
Laser displacement sensor	HL-G103-S-J	30mm	±4mm	0.5μm
Eddy current displacement sensor	GW-DO	2mm	±1mm	1μm

B. QUANTITATIVE ANALYSIS

When the eccentric sleeve rotates at a constant speed, the displacement signal with cosine-like characteristic on the right side of Fig.3 is obtained, and the instantaneous phase information can be obtained by calculating Equation 8.

In this paper, the laser displacement sensor and the eccentric sleeve are used together for the measurement of phase signal. The specific parameters of the laser displacement sensor used in this paper are shown in Table 1. The resolution of the laser displacement sensor is $\varepsilon = 0.5\mu m$, the eccentricity of the eccentric sleeve is e = 4mm, and the eccentric stroke is 2e = 8mm. The accuracy of the direct measurement phase method proposed in this paper is obtained as in Equation 10.

$$\gamma = 2e/\varepsilon = \frac{8 \times 10^3}{0.5} = 16000 \tag{10}$$

$$\sigma = \frac{360^\circ}{\gamma} = \frac{360^\circ}{16000} = 0.0225^\circ \tag{11}$$

where, γ is the accuracy of the direct measurement phase method, σ is the resolution of the direct measurement phase method.

It can be known from Equation 10 and Equation 11 that the accuracy of the instantaneous phase measurement method proposed in this paper is related to the eccentricity of the eccentric sleeve. The accuracy can be further improved, when the measurement range of the laser sensor is wider.

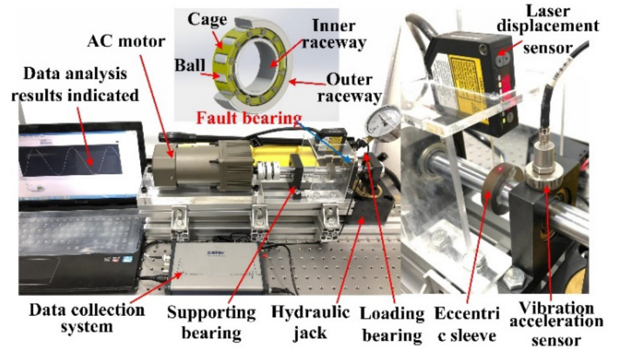

FIGURE 4. Bearing test set-up.

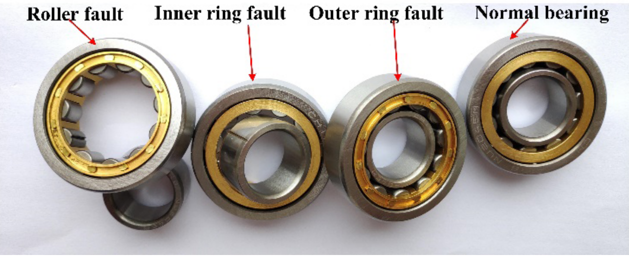

FIGURE 5. Test bearings.

IV. INSTANTANEOUS PHASE APPLIED IN MECHANICAL FAULT DIAGNOSIS

A. EXPERIMENT TEST ON TYPICAL ROLLING BEARINGS

In order to validate the proposed instantaneous phase detection technology, this paper designs a rolling bearing fault diagnosis test bench, as shown in Fig.4. The test set-up consists of motor controller, AC motor, supporting bearing, testing bearing, loading bearing, load device, hydraulic jack and the eccentric sleeve, laser displacement sensor, vibration acceleration sensor, and a NI- (16-bit) data acquisition system. Sample equipment based on LabVIEW software is used to acquire and analyze signals. The rotating speed of main shaft is 600 rev/min (the frequency of the axis is F_r = 15.63Hz) and the test load is 100 N. The sampling frequency is 51.2kHz. Parameters of test Bearings are shown in Table 2, test bearing samples are shown in Fig.5.

$$\text{Cage fault frequency: } F_C = \frac{1}{2}(1 - \frac{D_B}{D_C}\cos\beta)F_R \tag{12}$$

$$\text{Inner race fault frequency: } F_I = \frac{N_B}{2}(1 + \frac{D_B}{D_C}\cos\beta)F_R \tag{13}$$

$$\text{outer race fault frequency: } F_O = \frac{N_B}{2}\left(1 - \frac{D_B}{D_C}\cos\beta\right)F_R \tag{14}$$

$$\text{ball fault frequency: } F_B = \frac{D_C}{D_B}\left(1 - \left(\frac{D_B}{D_C}\cos\beta\right)^2\right)F_R \tag{15}$$

TABLE 2. **Test bearing parameters.**

Name	Parameter
Model	NU204EM
Pitch diameter D_C(mm)	30
Number of rollers (N)	11
Roller diameter D_B(mm)	10
Contact angle β(°)	0
Axis frequency shift $F_R(Hz)$	15.63
Outer ring fault frequency $F_O(Hz)$	57.4
Inner ring failure frequency $F_I(Hz)$	114.6
Roller failure frequency $F_B(Hz)$	41.7
Cage failure frequency $F_C(Hz)$	5.2

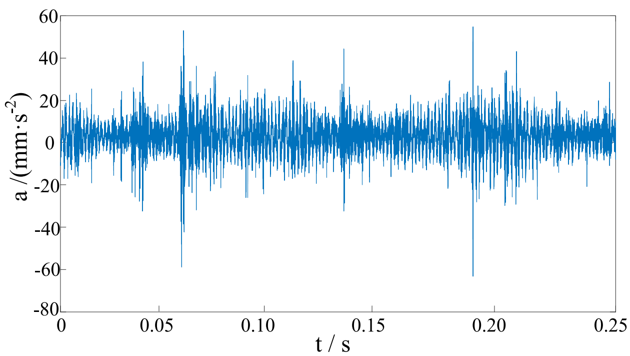

FIGURE 6. **Time domain waveform of bearing outer ring fault.**

1) COMPARATIVE ANALYSIS OF DETECTION METHODS: VIBRATION-BASED DETECTION METHOD BASED ON EMD AND HILBERT TRANSFORM

In this part, the traditional transient phase detection method based on EMD and Hilbert [32], [33] is researched to compare with the proposed method. Vibration signals of bearing with defective in outer ring is studied.

The time domain diagram of the bearing with defective in the outer ring obtained by the vibration acceleration sensor is shown in Fig. 6. The SNR of the original vibration acceleration sensor is very low and no useful information can be obtained directly. Fig. 7 and Fig. 8 are IMFs and phase diagrams obtained by EMD and Hilbert transforms. Figure 9 can be obtained by performing a Choi-Williams [48], [49] distribution on θ_7 in Fig. 8. The dotted line in Fig. 9 indicates the bearing outer ring fault reference frequency F_O= 57.4Hz, and the cloud map indicates the bearing outer ring fault signal Choi-Williams distributed frequency band. It can be found that there is 57.4Hz frequency component on the time-frequency surface, that is, the obvious outer ring fault frequency information.

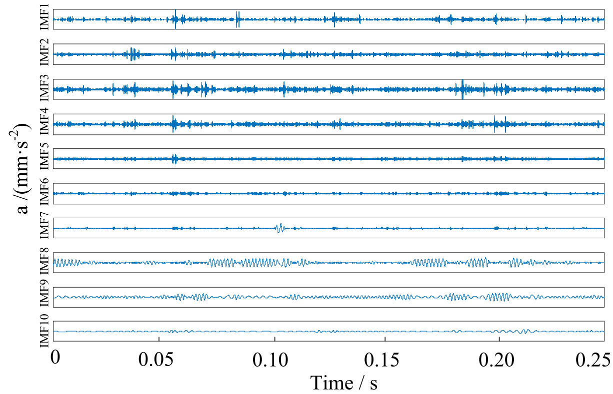

FIGURE 7. **IMFs signals based on EMD decomposition.**

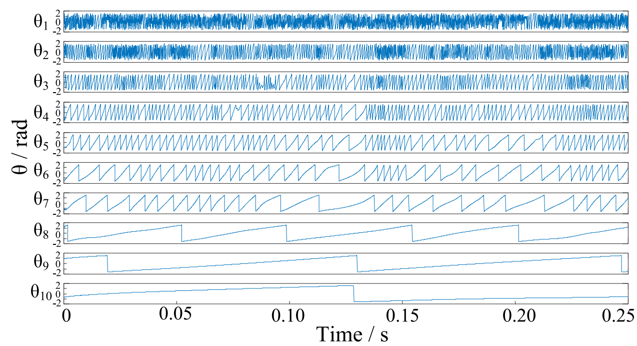

FIGURE 8. **Instantaneous phase of each IMF component of bearing outer ring fault signal.**

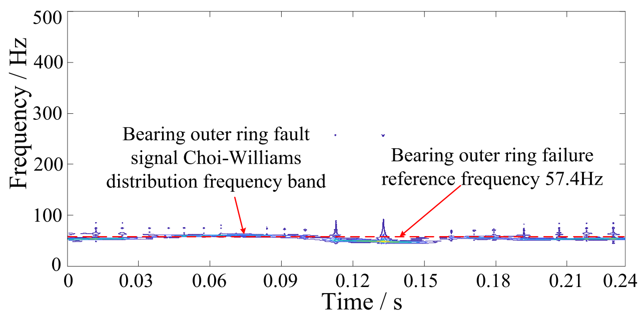

FIGURE 9. **Choi-Williams transform of instantaneous phase θ_7.**

2) COMPARATIVE ANALYSIS OF DETECTION METHODS: INSTANTANEOUS PHASE DIRECT DETECTION METHOD PROPOSED IN THIS PAPER

(1) the instantaneous displacement signal collected by the laser displacement sensor is shown in Fig. 10. The signal-to-noise ratio is higher than that in Fig. 6. The time domain waveform of normal bearing and bearings with fault is quite different.

(2) the instantaneous phase obtained by Equation 8 is shown in Fig.11.

(3) the fault diagram obtained by FFT analysis is shown in Fig. 12.

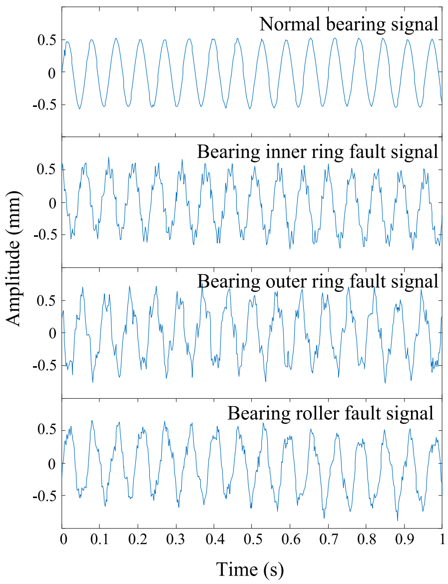

FIGURE 10. The time-domain signal measured by the laser displacement sensor.

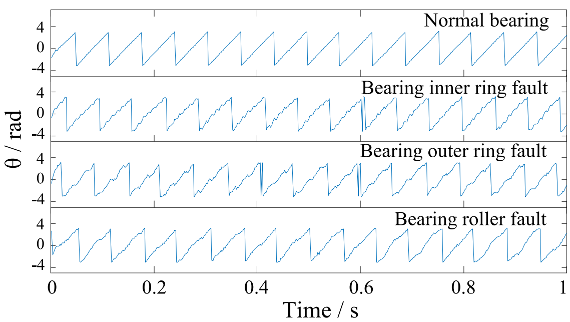

FIGURE 11. Phase diagrams of the four fault signals.

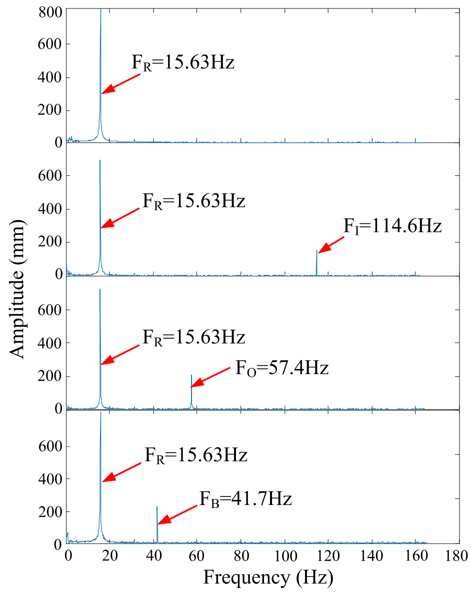

FIGURE 12. Four instantaneous phase FFT transformations.

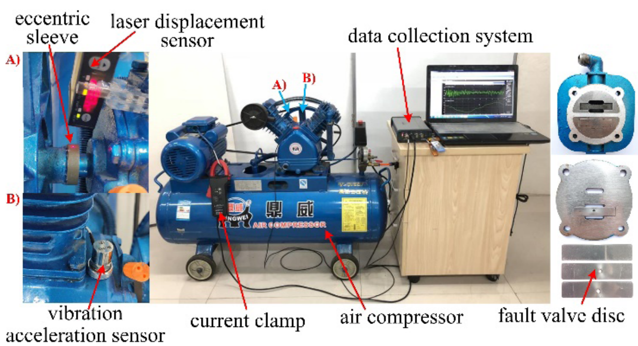

FIGURE 13. Compressor test set-up.

As shown in Fig. 12, fault frequency of each components of bearings are clearly appeared. Comparing with the traditional method, the proposed method offers with high SNR. The other advantage of the proposed method is that the Hilbert transform [50] is only fit for the narrowband signal, which may be ignored. Besides, selection of IMF in Fig. 7 and Fig. 8 is not easily, and wrong selection will result in mistake fault diagnoses result. The method proposed in this paper is not necessarily superior to other methods, but provides a new way of thinking.

B. INSTANTANEOUS PHASE AND ITS APPLICATION IN RECIPROCATING COMPRESSOR FAULT DIAGNOSIS

In order to validate the proposed instantaneous phase detection technology, a compressor fault diagnosis test set-up was designed in this paper, as shown in Fig. 13. The sensor designed in this paper is mounted on the crankshaft of the compressor as marked A in Fig.13. An NI data-acquisition system is used to sampling signals. In fact, the signal processing method of the reciprocating compressor or the reciprocating internal combustion engine based on the instantaneous speed and phase has been widely recognized. The motor speed of the compressor is $v_c = 2800r/min$, and the maximum pressure of the compressor is $p_{max} = 1.6Mpa$.

The instantaneous angular speed fluctuations of a diesel engine are closely related to the fluctuations of the total power torque acting on the crankshaft. The total power torque is then affected by gas pressure in the cylinder [51], vertical imbalance inertial force, friction force, engine load, etc. A sampled dynamic model of the diesel engine, and the torque balance equation is derived by

$$I \cdot \frac{d^2\theta}{dt^2} = T_X - T_L \tag{16}$$

where crankshaft angle is a function of time t, I_0 is the inertial moment of the power unit device (consisting of a diesel engine, an electric motor, a power transmission shaft connected the engine and the motor). T_L *is* the load torque of the power unit device, and T_X is the total power torque of a

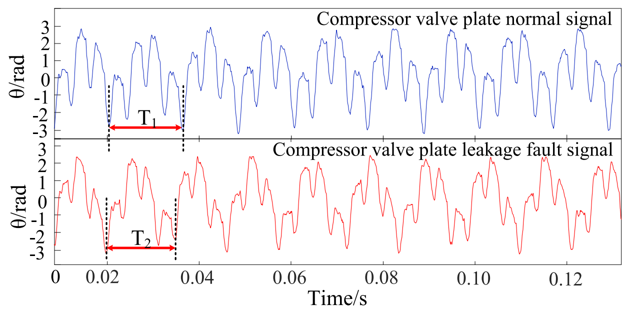

FIGURE 14. Time domain signal of compressor measured by laser sensor.

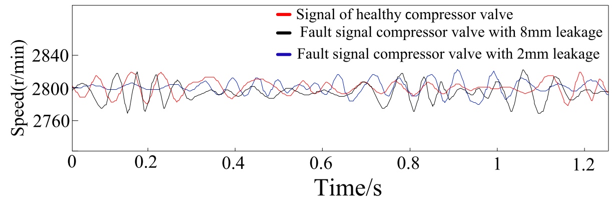

FIGURE 15. The speed signal of compressor measured by encoder sensor.

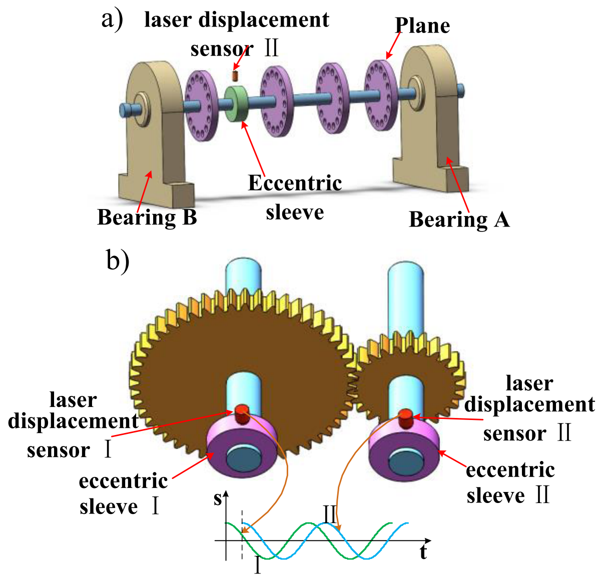

FIGURE 16. a) Rotor dynamic balance. b) Gear transmission error.

multiple-cylinder engine.

$$
\begin{aligned}
\frac{\dot{\theta}}{I_0} &= \int \frac{d^2\theta}{dt^2} = \int \frac{d\dot{\theta}}{d\theta}\frac{d\theta}{dt} \\
&= \int \left[R \sum_{i=1}^{n} p_i \left(\sin(\theta + \varphi_i) + \frac{\lambda}{2} sin2(\theta + \varphi_i) \right) \right] d\theta \\
&\quad + \Omega \int \left[\frac{1}{2} mR^2\omega^2 \sum_{i=1}^{n} (-\frac{\lambda}{2} \sin(\theta + \varphi_i) + sin2(\theta + \varphi_i) \right. \\
&\quad \left. + \frac{3\lambda}{2} sin3(\theta + \varphi_i)) \right] d\theta \\
&\quad - \omega \int T_L d\theta = f_2(\theta) .
\end{aligned} \tag{17}
$$

The instantaneous angular phase fluctuation is closely related to the gas pressure in all cylinders. When the faults influencing the gas pressure occur in a cylinder, such as fuel leakage or exhaust valve leakage in a cylinder, the power produced by the faulty cylinder decreases and the torque contribution to the total power torque reduces, which results in the distortion of the phase waveforms. Therefore, the phase waveform can be used to detect the faults relating to the gas pressure. Using Equation 8 to treat the sampling signals of laser displacement sensor, the phase information is obtained as shown in Fig. 14. Due to the existence of air leakage fault, the load and torque of the compressor will be reduced in the process of intake and exhaust. The larger the air leakage fault is, the faster the motor speed will be. The fault can be qualitatively diagnosed by rotating the motor for one week. The time of healthy compressor is $T_1 = 0.020s$, and the time of compressor in case of air leakage fault is $T_2 = 0.017s$.

The signal of the encoder fixed on the end-side of axile is shown in Fig. 15. All the signals are acquired after 1 minute from start to obtain stationary signals. Those signals are fluctuant and coupling interference because of the loose and tension vibration of belt and signals of encoder cannot be used to detect the fault of reciprocating compressor with small leakage fault.

V. DISSCUSSION

The purpose of this paper is to through the fault detection of rolling bearing and reciprocating compressor to verify the proposed instantaneous phase in the effectiveness of fault diagnosis. The cases selected in this paper are all classic cases, and many existing detection technologies and fault diagnosis methods can also realize those fault diagnoses. But it can be seen that the superiority of the proposed approach reduces the difficulty of signal processing. Compared with traditional EMD and Hilbert transforms method, the proposed approach is easier to be applicated online. Relative to the encoder, the proposed sensor can be mounted on the shaft easily, and its resolution can reach $\sigma = 0.0225°$.

It can be seen from the above theoretical analysis and experiments that the instantaneous phase detection technology proposed in this paper can provide instantaneous phase and PHM with high efficiency and precision. However, in order to correctly apply this detection technology, there are still some problems to be discussed, for example the Eccentricity compensation of the eccentric sleeve. An eccentric sleeve is need to be installed on the shaft. The eccentricity is artificially introduced. If the eccentricity is not dealt with, it cannot be directly applied to the machinery.

Besides the two set-up tests in the above analysis. This detection technology can also play a role in other occasions.

For example, the balance position of the rotor dynamic balance can accurately capture the eccentric phase is shown in Fig. 16a). Gear transmission error [52], [53] (e.g. Rotate Vector reducer) is shown in Fig. 16b).

The proposed method can also be used in reciprocating mechanical fault diagnosis, holographic dynamism balance, machine tool error assessment, machine tool vibration source tracing, and so on. The author will expand the use of this sensor in the subsequent research.

VI. CONCLUSION

This paper proposed a novel inspection technology for instantaneous phase to identify mechanical conditions. The proposed principle comes from the kinematical rule between cam and pushrod. A laser displacement sensor is used replace plunger to realize the non-contact measurement. Using eccentric sleeve form of cam to achieve instantaneous phase modulation, which can obtain infinite resolution in theory aspect, the detection technology is also suitable for broadband speed, reciprocating motion measurement. By the means of a Traditional Fourier Transform, this paper realizes the fault diagnosis of rolling bearing with typical defectives, and realizes the extraction and identification of the fault signal of reciprocating compressor. The experimental results prove that the proposed inspection technology can serve as an effective technology for mechanical fault diagnosis.

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