Instantaneous frequency extraction of full rub in touchdowns of AMBs based on polynomial chriplet transform

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***Abstract*—In this paper, polynomial chriplet transform (PCT) is introduced to extract the time-frequency characteristics of the rotor orbit during full rub in active magnetic bearings (AMB). In order to analyze the advantages and disadvantages of different time-frequency methods in the analysis of time-frequency characteristics of the signal, the short-time Fourier transform (STFT), Wigner-Ville distribution, general linear chirplet transform (GLCT) and PCT have been used to process the sample signal. Comparison between the four methods have been made and it is found that PCT has the highest accuracy in extracting the instantaneous frequency (IF) of the signal. Finally, PCT has been used to extract the IF during full rub in touchdowns of AMBs.**

I. Introduction

Active magnetic bearings (AMB) have been increasingly used in rotary machines due to its advantages such as non-friction, suitable for high speed and adjustable stiffness and damping.

When AMB components or power fails, the rotor and touchdown bearings (TDB) will contact. As defined in ISO 14839-4[1], the rotor may exhibit three typical orbit responses which are pendulum vibration, combined rub and bouncing, and full rub during the rotor-TDB interaction in touchdowns. Full rub has the largest rotor-TDB contact forces and the vibration frequency, thus it may lead to the most serious damage to the system. Because of this, it is necessary to monitor full rub in case of touchdowns.

The literature[2] pointed out that IF of full rub has obvious non-steady-state characteristics. At present, a lot of research work has been carried out on the principle and application of time-frequency analysis methods, such as Short-time Fourier transform (STFT)[3], Wavelet transform (WT)[4-7], Bilinear distribution[8-11]. For time-frequency analysis based on inner product, time-frequency concentration is a key indicator for measuring time-frequency analysis methods, which will affect the correctness of time-frequency feature extraction. STFT and WT are difficult to implement, because the time-frequency characteristics of frame atom is fixed. General linear chirplet transform (GLCT) is a combination of multi-frequency analysis window and maximal search method [12]. Analyze the frequency of the window function and adapt it to get the ideal time-frequency concentration. However, GLCT needs to perform multiple STFT calculations with a large amount of calculation.

Polynomial chirplet transform (PCT)[13-15] can construct frame atoms based on the time-frequency characteristics of the signal and enhance the time-frequency concentration of the transform. Here, the PCT is introduced into the time-frequency analysis of the vibration of the shaft system in the case of full rub. An attempt is made to obtain IF with ideal calculation accuracy.

II. Comparison of Time-Frequency Analysis Methods

The characteristics of IF during full rub is non-steady-state. In order to extract frequency characteristics of the full rub accurately. The signal processing methods of STFT, Wigner-Ville distribution, GLCT and PCT have been compared. Figure 1 shows a sample signal waveform. The STFT, Wigner-Ville, GLCT and PCT distribution are shown in Fig. 2-5, respectively. Peak scan method is used here to extract the IF in each method.

As can be seen in Fig. 2, with the increase of the IF, the energy spreads in a wider area, in other words, the time-frequency concentration becomes worse, which affects the calculation accuracy of the instantaneous frequency. From Fig. 2(b), we can see that due to the poor time-frequency focus ability of the STFT, the peak energy will rapidly decrease in the part where the frequency changes rapidly and is easily affected by the colored noise. When calculating the instantaneous frequency, it brings a large calculation error.

Although the time-frequency resolution of Wigner-Ville distribution reaches the lower limit of the uncertainty principle, it has better time-frequency concentration. From Fig. 3, we can see that there are cross terms in the Wigner-Ville distribution, which confuses the real time-frequency distribution of the signal and brings errors to the calculation accuracy of IF. From Fig. 3(b), Wigner-Ville distribution is affected by the cross terms, and it also brings a large calculation error.

From Fig. 4, we can see that GLCT has a better adaptive ability to the change of the signal's IF modulation frequency, so that the time-frequency conversion of the signal has an ideal time-frequency concentration. This will greatly improve the noise resistance and ensure the accuracy of the calculation of IF. From Fig. 4(b), the GLCT is more robust to noise because of its ideal time-frequency concentration.

From Fig. 5 (a-c), it can be found that the time-frequency concentration is getting better after several iterations of PCT and the accuracy is also become higher. From Fig. 5(d), The IF calculated by PCT has the highest time-frequency resolution, which lead a higher accuracy of calculation of IF, as shown in Fig. 6.

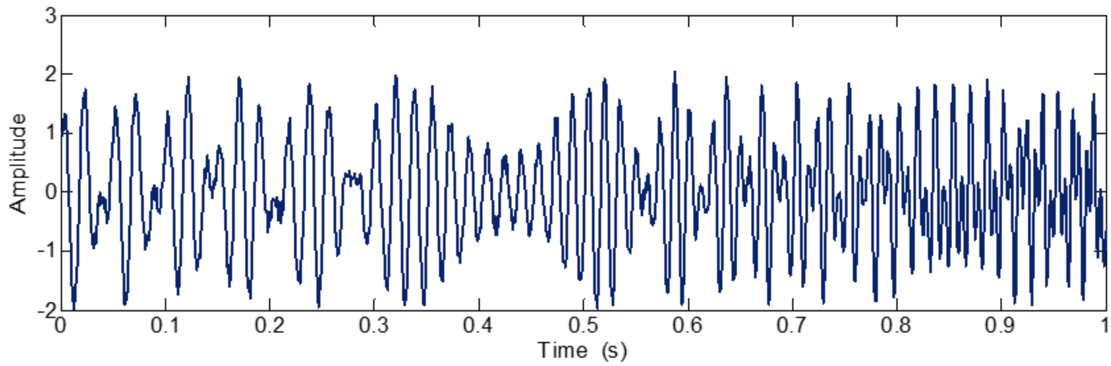

Figure 1. Sample signal waveform

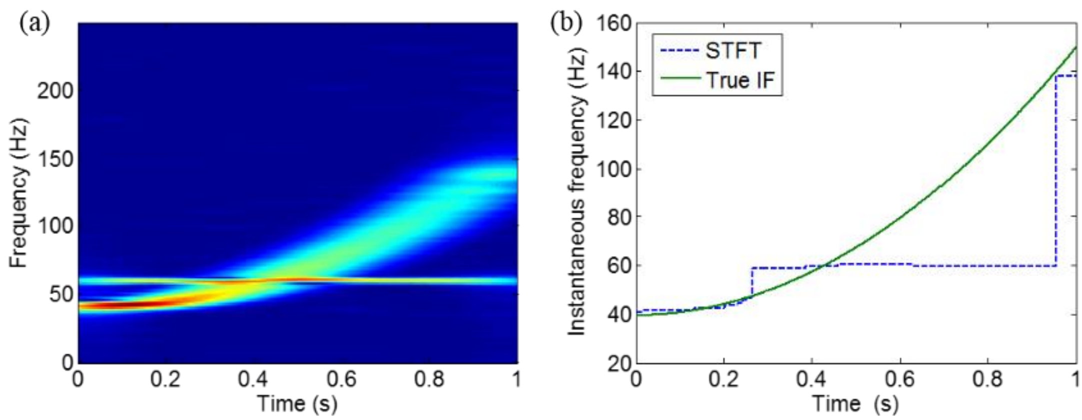

Figure 2. (a) Short-time Fourier transform and (b) IF of the signal

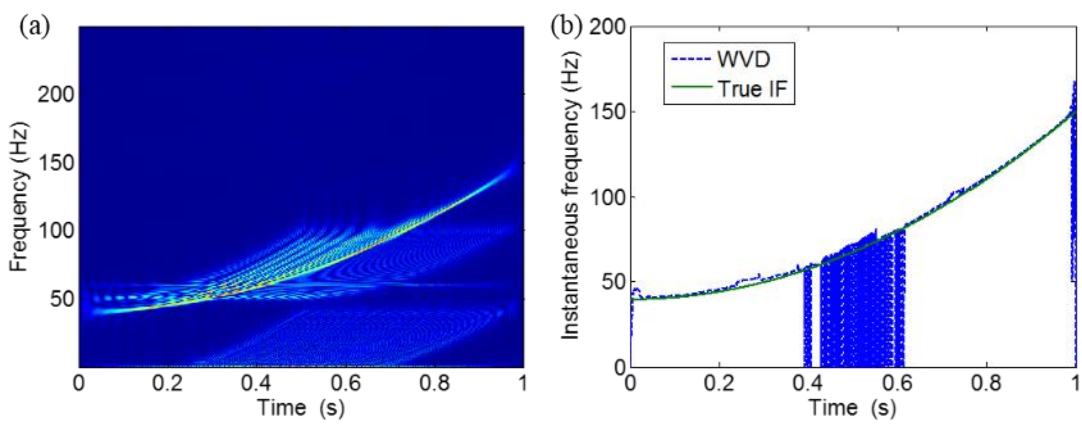

Figure 3. (a) Wigner-Ville distribution and (b) IF of the signal

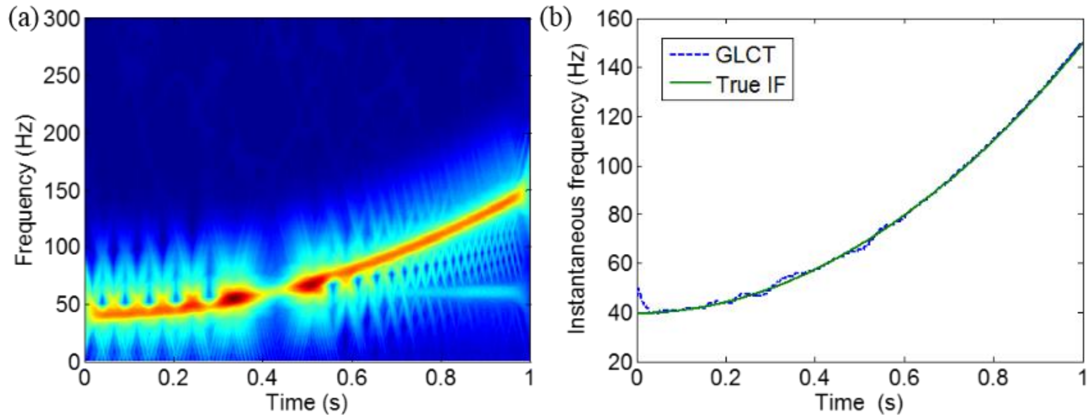

Figure 4. (a) GLCT distribution and (b) IF of the signal

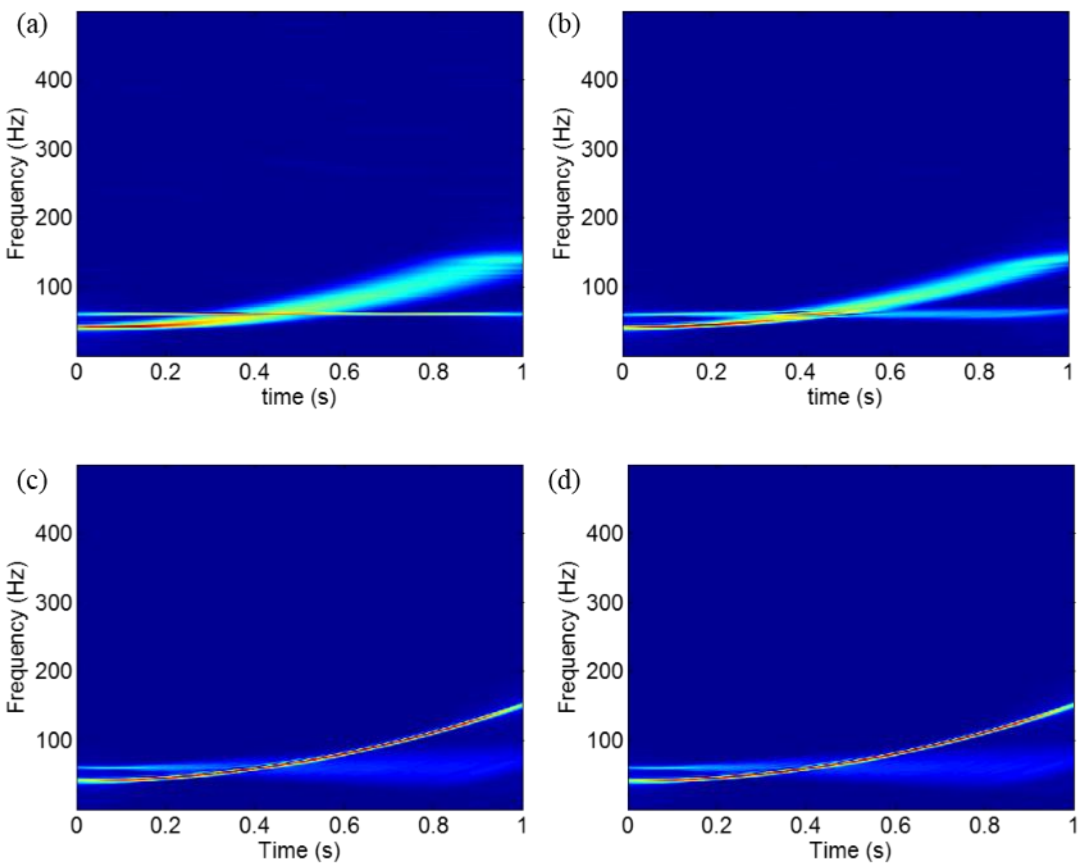

Figure 5. Multiple iterations of PCT

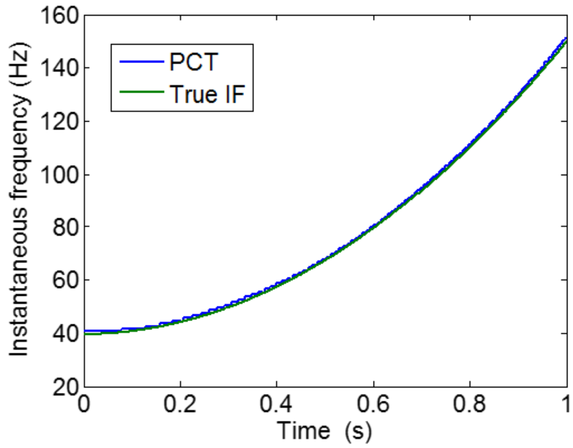

Figure 6. IF obtained from Fig. 5(d).

III. IF EXTRACTION OF FULL RUB BASED ON PCT

The thermo-dynamic model in Ref. [6] has been used to obtain the rotor displacement signal during full rub. Figure 6 shows an example signal of the rotor displacement in vertical direction during full rub of AMBs. In order to make the simulation result closer to the actual situation, white noise has been added in the signal.

As shown in Fig. 7, the distribution of PCT spread in a wide area after the first iteration. However, the distribution concentrated in a very small area after the second iteration. The results after the second and third iterations are similar and the accuracy of the results is very high. IF during full rub is extracted by peak scan method, as shown in Fig. 7（d）. The IF showed an increasing trend during the initial phase of full rub which is identical to the results shown in Ref. [6].

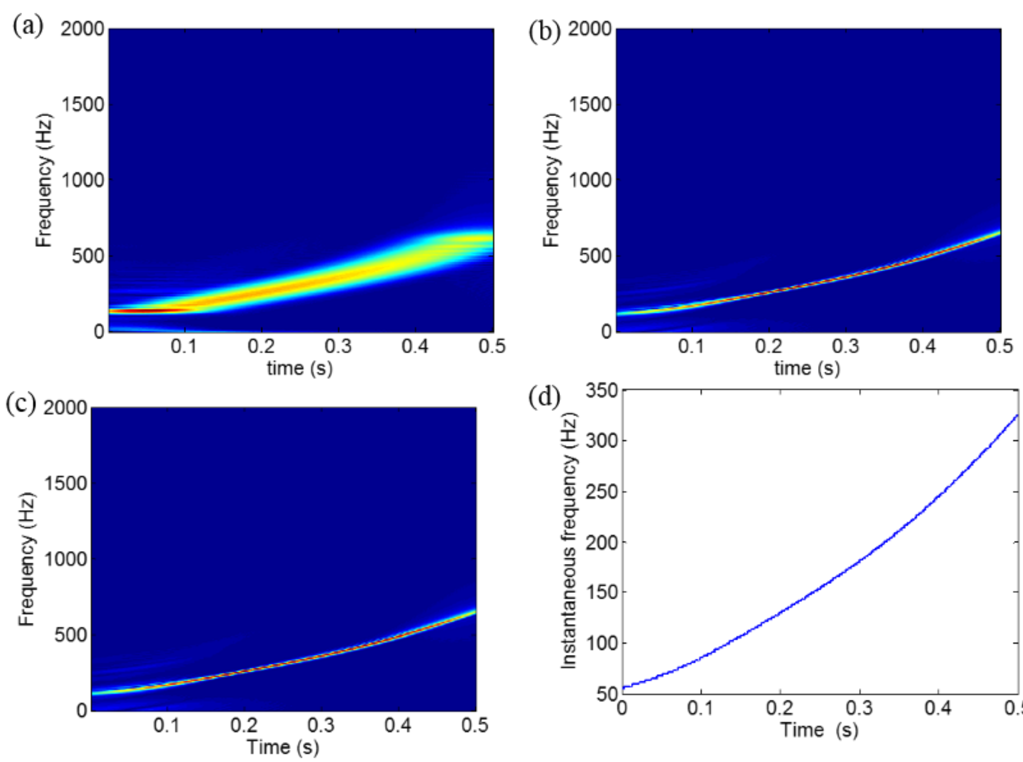

Figure 7. PCT after multiple iterations and the corresponding IF.

IV. CONCLUSION

This paper analyzes the time-frequency characteristics of the rotor displacement signal during touchdowns in AMBs with the STFT, Wigner-Ville distribution, GLCT and PCT methods. The results show that the time-frequency resolution of STFT is not ideal, and it will bring the calculation error. In Wigner-Ville distribution, the cross term confuses the real time-frequency distribution and also affects the accuracy of instantaneous frequency. The GLCT has a better time-frequency resolution. PCT is able to construct the frame atoms according to the time-frequency characteristics of the signal itself to enhance the time-frequency concentration of the transform. Subsequent work can be based on PCT to extract the full rub response, and realize the orbit response recognition based on the rotor displacement signal.

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