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Micro frequency-shift based spectral refinement algorithm and its application in spectrum analysis during milling process

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ABSTRACT

The purpose of spectral refinement is to obtain a finer spectrum structure so as to realize a more accurate spectral measurement. In this paper, a micro frequency-shift based spectral refinement algorithm (MFS-FFT) is introduced. This algorithm can efficiently perform any multiple spectral refinement and achieve the refinement over the entire frequency axis without band selection. Two kinds of micro frequency shifters suitable for this algorithm are discussed. The influence of window functions on this algorithm is also analyzed. Compared with the Chirp Z-transform (CZT), the proposed algorithm can achieve the same accuracy as CZT. Our complexity analysis has shown that when the refinement multiple is less than six, the computational cost is always smaller than that of CZT. A spindle speed ramp-up milling experiment has been performed in order to verify the proposed algorithm. Experimental results show that the MFS-FFT algorithm can effectively improve the accuracy of spectral estimation.

1. Introduction

Spectral analysis plays an important role in measurement systems. The accuracy of spectral analysis directly affects the accuracy of a measurement system. Since the fast algorithm for discrete Fourier transforms (DFT) was proposed by Cooley and Tukey in 1965 [1], the DFT-based spectral analysis has been widely used in scientific fields such as equipment condition monitoring, radar signal analysis, audio analysis and magnetic field detection [2–5]. However, the two drawbacks of DFT including spectral leakage and picket-fence effect (PFE), can severely reduce the accuracy of spectrum analysis. Reduction of spectrum leakage and PFE to improve the accuracy of spectrum analysis using DFT on finite length sequences has long been a topic of interest in signal processing.

There are two approaches to improve spectral estimation accuracy: spectral refinement and spectral correction. The role of spectral refinement is to improve the spectral resolution without increasing the length of the time domain signal. Spectral refinement is mainly used for identifying dense spectral components. Generally used methods include Chirp Z-transform (CZT), zoom FFT (ZFFT), zero-padding FFT, Fourier transform continuous zoom based method and some improved algorithms. The role of spectral correction is to improve the estimation accuracy of signal parameters, including frequency, amplitude and phase. Common methods are interpolated DFT [6–8], phase difference methods [9–11], least squares-based methods [12,13] and energy-based methods [14,15]. In addition, spectral refinement can also be combined with spectral correction for enhanced purposes. For example, spectral refinement is used to distinguish dense spectral components following which, a spectral correction algorithm is applied to obtain more accurate spectral parameters [16]. In this paper, spectral refinement is focused. The proposed algorithm MFS-FFT is designed to improve spectral resolutions and reduce the picket-fence effect error with which, the accuracy of spectral estimation can be improved.

The CZT was introduced in 1969 by Rabiner et al. Its fundamental idea is to sample more points with equal angular interval in a selected frequency band (an arc on a unit circle) in order to improve the frequency resolution [17]. Theoretically, CZT can achieve high enough accuracy; however, its accuracy is limited by the sample sequence length, signal truncation methods and so on. The CZT algorithm is appropriate for the frequency measurement of transient signals which have a short duration of observing period, such as infrared signals [18]. Recently, plenty of modified CZT algorithms have been proposed some of which, are combined with other algorithms to improve the accuracy of spectral analysis [19–21].

The ZFFT was introduced in 1977 by E. Hoyer, R. Stork. Its basic idea is reducing the sampling rate by decimation to improve the frequency resolution [22]. First specifying the desired center frequency, bandwidth, and target frequency resolution, then the signal is resampled, modulated and low pass filtered. ZFFT is simple in calculation and high in accuracy, so it has been widely used since it was proposed.

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However, the decimation of ZFFT must consume a lot of original sampling data to decrease the sample rate. Clearly, this method is not suitable for the refinement analysis of the transient signal and length limited signal.

Zero-padding FFT represents a solution used to decrease the frequency distance between bins, it involves lengthening the signal sequence by adding zeroes at the end of time samples before DFT calculation. However, computing a full zero padded DFT can be wasteful. To overcome the high computation problem, some modified algorithms have been proposed [23]. At the same time, since the DFT algorithm requires that the sequence length be a power of 2, the length of the zero-padded sequence must be a power of 2 as well, which means the multiple of the spectral refinement is not arbitrary, but the power of 2.

The principle of the Fourier transform continuous zoom based method is similar to that of the Chirp Z-transform [24]. It achieves a spectrum of extremely high accuracy by continuous zooming of the concerned frequency segment concerned.

In this paper, a micro frequency-shift based algorithm for zoomed spectral analysis (MFS-FFT) is proposed and applied to the spectral analysis of milling vibration measurement. Spindle speed ramp-up milling tests are a novel experimental approach for chatter stability detection [25]. This milling experiment has been carried out in order to verify the proposed algorithm. The proposed algorithm can zoom the sampled signal spectrum along the entire frequency axis, rather than zoom a portion of the whole spectrum at one time, and the algorithm can implement arbitrary multiple refinement for an initial spectrum. In this algorithm, the spectral refinement which is very different from the traditional algorithms, such as ZFFT, CZT, zero-padding FFT, is realized by a certain times of micro frequency-shift of sampling data. Guangming Dong and Jin Chen applied a similar frequency-shift bispectrum method to rolling element bearing diagnosis and attained remarkable results [26]. Here, the "micro frequency-shift" is named because the amount of frequency shift is very small (smaller than the frequency resolution) compared to the conventional amplitude modulation methods. The name is inspired by "Micro Doppler Effect" [27].

2. The micro frequency-shift based method

2.1. Theoretical basis of the proposed method

Signals in engineering practice are usually non-periodic, and they are converted into discrete non-periodic sequences by A/D conversion. The general non-periodic sequences can be represented by a Fourier integral of the form

$$x[n] = \frac{1}{2\pi}\int_{-\pi}^{\pi} X(e^{j\omega})e^{j\omega n}d\omega, \tag{1}$$

where

$$X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} x[n]e^{-j\omega n}. \tag{2}$$

In generally, Eq. (2) is referred to as the discrete-time Fourier transform (DTFT). Fourier transform $X(e^{j\omega})$ is called the spectrum of $x[n]$, which is a function of a continuous variable (the period is 2π). In applications and algorithms based on explicit evaluation of the Fourier transform, it is ideally the discrete-time Fourier transform (DTFT), because computers can handle a limited amount of data, and discrete time sequences must be truncated using window function. The actually computable algorithm of Fourier analysis of finite-length sequences is DFT. Considering a finite-length sequence $x[n]$ of length N samples such that $x[n] = 0$ outside the range $0 \leqslant n \leqslant N-1$, its DFT analysis equation is written as follows:

$$X[k] = \sum_{n=0}^{N-1} x[n]e^{-jk(2\pi/N)n}. \tag{3}$$

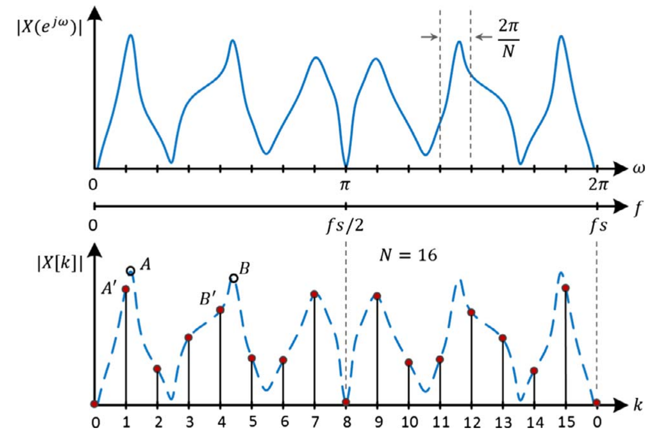

Fig. 1. Schematic diagram of DFT spectral sampling.

The DFT $X(k)$ is itself a sequence rather than a function of a continuous variable, and it corresponds to N samples, equally spaced in frequency $[0,2\pi]$ of the DTFT $X(e^{j\omega})$ of the signal. The discrete-time sampled frequencies $\omega_k = 2\pi k/N$, $k = 0,1,\cdots,N-1$, that is:

$$X[k] = X(e^{j\omega})|_{\omega=2\pi k/N}. \tag{4}$$

In general, the locations of peaks in the DFT values do not necessarily coincide with exact frequency locations of the peaks in the DTFT, since the true spectrum peaks can lie between spectrum samples. In Fig. 1, the true spectrum peaks A lies between sample 1 and sample 2, and the true spectrum peaks B lie between sample 4 and sample 5. It is as if the DFT spectrum is seen through $(N + 1)$ picket fences and only the parts in the N gaps are obtained. This phenomenon is known as the picket fence effect (PFE). The width of one picket fence (sampling interval) is called frequency resolution Δf ($\Delta f = fs/N$, fs is sampling rate, N is the point number of DFT).

In addition, the windowed truncation introduced by DFT also result in reduced resolution and leakage. Especially when the signal has some relatively close harmonics, serious spectral interaction will occur leading to the inability to distinguish harmonic components. However, thanks to the existence of spectrum leakage, even though the harmonic frequency doesn't coincide with the sampling frequency location, we can get an approximation of the harmonic. In Fig. 1, although the accurate peaks are not sampled at frequencies A and B, DFT samples their approximations. In this sense, the spectrum leakage error is not entirely detrimental. Otherwise, the picket fence error would be unacceptable.

2.2. Principle of the micro frequency-shift spectrum zoom method

Spectral sampling result in the obtained DFT spectrum is just the N-points discrete value of the signal spectrum rather than the full spectral characteristic. When the sampling rate and the point number of the sequence involved in DFT is fixed, the frequency sampling interval is fixed. This means that the amount of spectral information obtained is also fixed. But if the spectrum is properly shifted, the new location of the initial spectrum, which was blocked originally by the picket fence can be sampled. In Fig. 2, point A and point B are two peak points, but they are not sampled originally due to the spectral sampling. After the spectrum was shifted $0.5\Delta f$ to the left, the two peaks are sampled accurately. This is much like a scene in life, when seeing something through a picket fence, if properly changing the perspective to the left or right, we can see the scenery that was originally blocked.

Based on the above analysis, if the time domain signal was done frequency shifting properly before the FFT, some original blocked information of the spectrum can be obtained. Here, first the signal underwent micro frequency shifting followed by FFT and was called the micro frequency-shifted spectrum. Further, if the signal underwent micro frequency shift many times in range $\pm$ $0.5\Delta f$, much unknown