應用平均頻譜峰度於模態振動訊號進行軸承損壞診斷

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摘 要

在本研究中，提出振動模態之平均頻譜峰度演算法，可有效應用於軸承損壞診斷分析。首先以小波包絡函數擷取軸承振動模態，再藉由平均頻譜峰度分析演算法，最後可獲致頻譜峰度視窗長度對頻譜峰度值之二維圖。由理論分析可發現，對正常軸承之頻譜峰度值小於 3，近似隨機訊號之峰度值；然而，對損壞軸承之頻譜峰度值則大於 3，其二維圖呈現具山峰形狀之尖峰現象，其山峰形狀之中心值，可轉換對應其軸承損壞型式之特徵頻率，藉此可用以確認損壞軸承元件。

關鍵詞：軸承損壞、小波包絡函數、頻譜峰度、模態振動

Applying the Mean Spectral Kurtosis to a Mode Vibration for the Bearing Defect Diagnosis

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Abstract

This paper proposes that a mean spectral kurtosis analysis algorithm can be effectively applied to mode vibration for bearing defect diagnosis. First, the wavelet enveloping function is used to derive a mode vibration of bearing. Then, the mean spectral kurtosis analysis algorithm is applied to the mode vibration. Finally, the two dimensional diagram of window length vs. mean spectral kurtosis could be derived. The theoretical study shows that for normal bearing the mean spectral kurtosis is lower than 3 in the diagram, which is similar to the kurtosis of a random signal. On the other hand, for defect bearing the mean spectral kurtosis is higher than 3 in the diagram, which takes the shape of a pointed mountain peak and corresponds to the characteristics of bearing defect. Accordingly, the mean spectral kurtosis analysis algorithm could also identify the defect type of a bearing system.

Keywords: Bearing Defect, Wavelet Enveloping Function, Spectral Kurtosis, Mode Vibration

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I. Introduction

Bearing defect diagnosis, based on vibration analysis, has been widely adopted in many rotating machines. The detection of bearing defect is usually implemented by identifying the bearing characteristic frequencies from the measured vibration. However, the vibration signal of initial-defect bearing is easily corrupted by the environment noise, which makes the bearing characteristic frequencies difficult to be investigated. To effectively diagnose defect occurring in a bearing, a variety of signal processing methods have been developed [1–8].

In general, the raw spectrum of bearing vibration is dominated by the resonance frequencies excited by the bearing defect, and containing little diagnostic information. Whereas the envelope spectrum, derived from the amplitude demodulation of vibration signal, contains the required information about the repetition frequency of defect impacts to diagnose the running condition of a bearing. In the frequency domain analysis methods, the high frequency resonance technique is usually applied to demodulate the vibration signal and, thus, the demodulated spectrum could show a pattern of the defect characteristic frequency with equal spaced side band [1–4]. In the case of analyzing a high-frequency resonance, the high frequency resonance technique takes advantage of providing a low-frequency demodulated signal with a high signal-to-noise ratio.

Spectral kurtosis is a statistical evaluation for investigating how the impulse response of a signal varies with frequency. When the rolling components of a bearing strike the bearing defect, a series of impulse responses at the resonance frequencies are excited. The spectral kurtosis is potentially useful for evaluating the bearing defect at the resonance frequencies excited, and proved to possibly detect the frequency bands with the impulsiveness excited by defects of the bearing components [5–9]. Wang et al. Lei *et al.* [7] applied a wavelet packet transform at different depths to evaluate the enhanced Kurtogram for determining the location of resonant frequency bands. Therefore, the envelope spectrum can be derived from the selected resonant frequency band and, then, be used to determine the type of fault by identifying its characteristic frequency. Jia *et al.* [8] use the ability of MCKD in indicating the periodic fault transients and the ability of spectral kurtosis in locating these transients in the frequency domain to evaluate the filtered signals for deriving the envelope with maximum kurtosis. Thus, the envelope spectrum with an optimal frequency band is obtained for diagnosing bearing defect.

In this paper, the mean spectral kurtosis analysis algorithm for a single mode of bearing vibration is proposed to apply in the bearing defect diagnosis. First, the wavelet enveloping function uses to derive a mode vibration of bearing. In practice, the procedure of wavelet enveloping function could be implemented in the real time. A designated passband for the function parameter is applied to filter out the vibration signal around a selected high-frequency band with the center at a chosen resonant frequency of the bearing system. It takes advantage of avoiding the interference of low-frequency noise transmitting from the environment, and enhancing the signal-to-noise ratio. Secondly, the mean spectral kurtosis analysis algorithm can apply to the mode vibration. The algorithm harnesses the ability of band-passed vibration in highlighting the periodic fault transients and the ability of mean spectral kurtosis in locating the defect frequency with the window length. Finally, the two dimensional diagram of window length vs. mean spectral kurtosis could be derived. It is shown that for normal bearing the mean spectral kurtosis is lower than 3 in the diagram, and similar to the kurtosis of a random signal. On the other hand, for defect bearing the mean spectral kurtosis is higher than 3 in the diagram, and a mountain shape of peaks is shown and can be corresponded to the characteristics of bearing defect. Accordingly, the mean spectral kurtosis analysis algorithm could also identify the defect type of a bearing system.

II. Theoretical Study

In the signal processing of bearing vibration, time scale and the corresponding energy distribution are two most important approach for studying the characteristics of vibration signal. In practice, the procedure of wavelet enveloping function could be implemented in the real time, and is a signal processing method in time scale. A designated band-pass for the function parameter is applied to filter out the vibration signal around a selected high-frequency band with the center at a chosen resonant frequency of the bearing system. It takes advantage of avoiding the interference of low-frequency noise transmitting from the environment. Furthermore, the energy distribution can enhance the signal-to-noise ratio. In this paper, the mean spectral kurtosis analysis algorithm for a single mode of bearing vibration is proposed to apply to the bearing defect diagnosis. The algorithm harnesses the ability of band-passed vibration in highlighting the periodic fault transients and the ability of mean spectral kurtosis in locating the defect frequency with the window length. According to the theoretical study, it is shown that for normal bearing the mean spectral kurtosis is lower than 3 in the diagram, and similar to the kurtosis of a random signal. On the other hand, for defect bearing the spectral kurtosis is higher than 3 in the diagram, and a mountain shape of peaks is shown and can be corresponded to the characteristics of bearing defect. Accordingly, the mean spectral kurtosis analysis algorithm could also identify the defect type of a bearing system.

In the following, the wavelet enveloping function for deriving a mode vibration of bearing is first studied in Section 1. Then, in Section2 the mean spectral kurtosis analysis algorithm will apply to a single mode of bearing vibration, and the two dimensional diagram of window length vs. mean spectral kurtosis could be derived. Accordingly, the running condition of bearing vibration can be diagnosed.

1. Band-passed Signal with Wavelet Enveloping Function

A wavelet enveloping function $g_{a,\tau}(t)$ of analysis wavelet can be written as [3]

$$g_{a,\tau}(t) = \frac{\sqrt{a}}{j\ \pi(t-\tau)}\left(e^{-\frac{1}{2}(\frac{t-\tau}{a})^2 + j2\pi\ \frac{f_L}{a}(t-\tau)} - e^{-\frac{1}{2}(\frac{t-\tau}{a})^2 + j2\pi\ \frac{f_H}{a}(t-\tau)}\right) \tag{1}$$

where f_L and f_H denote the low cut-off frequency and the high cut-off frequency in the frequency domain, respectively. Thus, the wavelet transform is a linear transformation that can decompose a signal $x(t)\in L^2(R)$ into the elementary functions $g_{a,\tau}(t)$ and can be defined as the convolution of two functions

$$W_g(a,\tau) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} x(t)\, g^*_{a,\tau}(t)\, dt \tag{2}$$

where $g^*_{a,\tau}(t)$ is the complex conjugate of $g_{a,\tau}(t)$.

By taking the real-part value of $W_g(a,\tau)$, the band-passed signal of a vibration can be derived. The filtering passband and steepness at cut-off frequencies for $g^*_{a,\tau}(t)$ could be easily designated by setting parameters f_L, f_H and a [3].

2. Mean Spectral Kurtosis Analysis Algorithm for Mode Vibration

The spectral kurtosis Analysis is defined in terms of the Short Time Fourier Transform (STFT) which can derive a time/frequency diagram of a signal [1–4]. By shifting a short time window, such as hanning window, along the signal in overlapping steps the STFT can construct a 3 dimensional diagram to show the spectra for short-time intervals. Accordingly, the kurtosis at each frequency along the time-interval direction is then calculated to derive the spectral kurtosis property in a 2 dimensional diagram of frequency vs. spectral kurtosis. Based on the spectral kurtosis analysis, the spectral kurtosis is about 2, lower than 3, for the normal bearing. On the other hand, the spectral kurtosis can be much higher than 3, but vary in a wide range and decrease with increasing running speed of bearing, for the defect bearing. In addition, the defect component in the bearing is difficult to figure out.

In the paper, a mean spectral kurtosis analysis algorithm for a single mode of bearing vibration is proposed to improve the problems of the spectral kurtosis varying in a wide rage and the difficulty of figuring out the damaged component for the defect bearing. Because the calculated spectral kurtosis would depend on the choice of analysis parameters, in particular the window length. The window length gives a balance between separating the individual bursts and encompassing them within the window. The algorithm harnesses the ability of band-passed vibration in highlighting the periodic fault transients and the ability of spectral kurtosis in locating the defect frequency with the window length. The proposed algorithm is described as follows.

(1) Obtain an original vibration signal $x(t)$ of the bearings and band-pass it by the wavelet enveloping function to derive a mode vibration.

(2) Determine the window length to cover the range of bearing defect characteristics in the frequency $F_L< F_{Defect}< F_H$. Accordingly, the range of window length W can be in the range
$(F_S/F_H)< W< (F_S/F_L)$,
where F_S is the sampling rate.

(3) Apply the spectral kurtosis analysis with window length W to analyze the mode vibration derived in step (1). Accordingly, a 2 dimensional diagram of frequency vs. spectral kurtosis can be obtained. The mean spectral kurtosis, SK_{mean}, can use to correspond to the individual bursts in the window length, and a window length and mean kurtosis pair, (W, SK_{mean}), can be obtained.

(4) Repeat the calculation in step (3) with increasing the window length from (F_S/F_H) to (F_S/F_L). Accordingly, a mean spectral kurtosis diagram of window length vs. mean spectral kurtosis can be obtained.

(5) Detect the fault characteristic frequency in the spectral kurtosis diagram and diagnose the fault types. For a normal bearing, there is no peak shown, and the spectral kurtosis is about 3. On the other hand, for a defect bearing there would be a mountain shape of peaks shown with corresponding to the bearing defect characteristics. The defect frequency, F_D, can be derived from
$F_D=F_S/W_{peak}$,
where W_{peak} is the window length at the center of the mountain shape in the mean spectral kurtosis diagram.

As shown in Step (2), the window length for bearing defect at frequency F_{Defect} can be $W=F_S / F_{Defect}$. In practice, the STFT for the vibration in this window period will show clear peaks at the defect frequency and its harmonics. Therefore, the kurtosis for the STFT can be high. On the other hand, with an increase of the window length can decrease the kurtosis for the STFT. Accordingly, for a defect bearing a mountain shape of peaks can be shown in the mean spectral kurtosis diagram and corresponded to the characteristic frequency of bearing defect.

III. Experimental Study

In this section, the applications of the above algorithm to the vibration signals of tapered roller bearings (SKF type 32208) are investigated. The electrical-discharge machining method is applied to produce artificial defect on the surface of bearing components which are roller and inner race. The defect sizes are described in the Table 1 and the description of the test rig is shown in Figure 2. The vibration signals are measured on the housing of the test bearing by mounting an accelerometer with the sensitivity 10.41 mV/g. The measured direction is radial to the shaft in the horizontal. The tested bearings run at 1000 and 2000 rpm, and the characteristic frequencies of tested bearings for roller and inner race are 97.3 Hz and 131.9 Hz, respectively.

In the investigation of bearing vibration, there are 20 times of sampling data, with time period 1 second at the sampling rate 100kHz, to apply to the proposed algorithm. Figures 2 and 3 show the studies of test bearings at running speed 1000 rpm, and Figure 4 shows at running speed 2000 rpm. According to the vibration spectra, as shown in Figure 2(a), Figure 3(a) and Figure 4(a), of bearing vibration there are four vibration modes for applying in the experimental study. In addition, it is shown that the bandwidth demodulated directly determines the highest frequency in the resulting envelope spectrum and will be sufficient to diagnose any defect type, if it is at least four times the inner race fault frequency [5,6]. Therefore, in the experiment study the passband width 1.5kHz is designated, and the highest frequencies of the vibration modes are found at 1500Hz, 3100Hz, 4200Hz and 8900Hz, respectively.

Table 1 Defect sizes of defect bearings

Defect type	Defect size (length x width x depth)
Roller defect	16 mm x 0.15 mm x 0.1 mm
Inner-race defect	18.5 mm x 0.15 mm x 0.1 mm

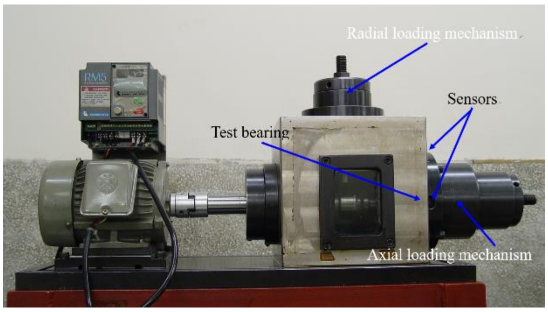

Fig.1 Schematic of the test rig

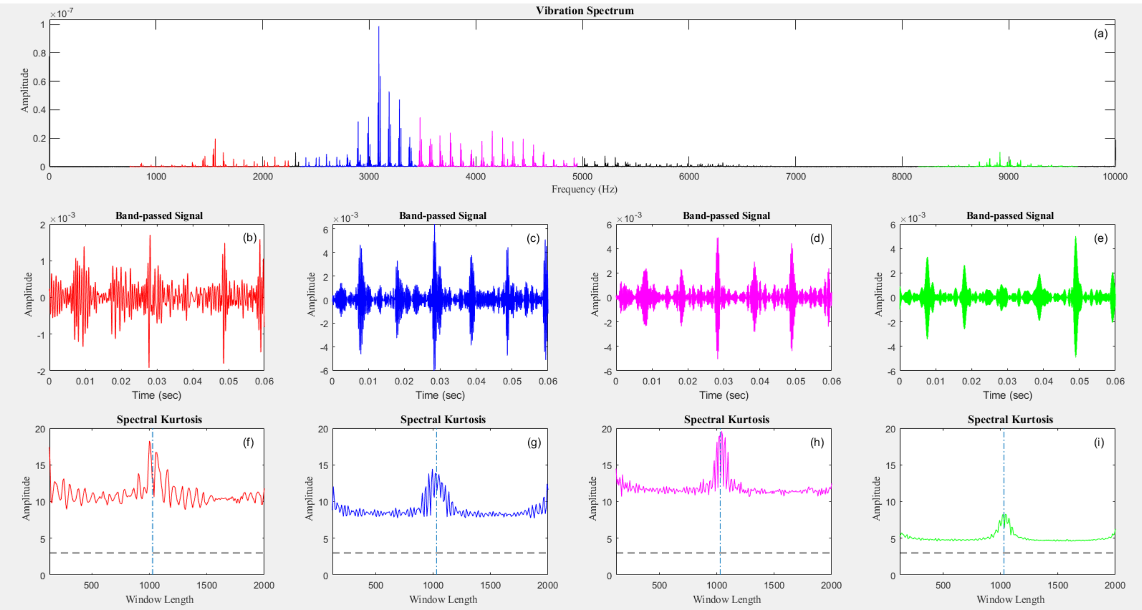

Fig.2 Mean spectral kurtosis analysis for roller defect bearing running at 1000 rpm

Figure 2 shows the analysis result of mean spectral kurtosis for the roller defect bearing running at 1000 rpm. According to the mean spectral kurtosis analysis algorithm, the wavelet enveloping function with designating four different passband is applied to the bearing vibration. The band-passed vibrations with the center frequency at 1500Hz, 3100Hz, 4200Hz and 8900Hz corresponding to the four vibration mode are shown in Figures 2(b)–(e), respectively. In general, the characteristic frequency of bearing vibration can be in the range from 50Hz to 1kHz for most application of bearing running speed. For covering the frequency band of bearing characteristics, the range of window length W can be in the range from 100 to 2000 sampling points. Therefore, the spectral kurtosis diagram of window length vs. mean spectral kurtosis for the band-passed vibrations can be obtained, as shown in Figures 2(f)–(i), respectively.

In Figure 2(f)–(i), the mean spectral kurtosis is above the dash line of being the amplitude 3. In addition, the dash-dot lines in these four figures indicate the center of the mountain shape at the window length W=1026, which is corresponding to the characteristic frequency of roller defect at 97.3Hz. On the other hand, Figure 3 shows the analysis result of mean spectral kurtosis for a normal bearing running at 1000 rpm. In Figure 3(f)–(i), the mean spectral kurtosis shows almost a straight line, with no mountain shape found, and is lower than the dash line of being the amplitude 3. Therefore, the threshold value of the mean spectral kurtosis for a bearing defect can be 3, and the mountain shape of peaks can indicate the defect type of running bearing.

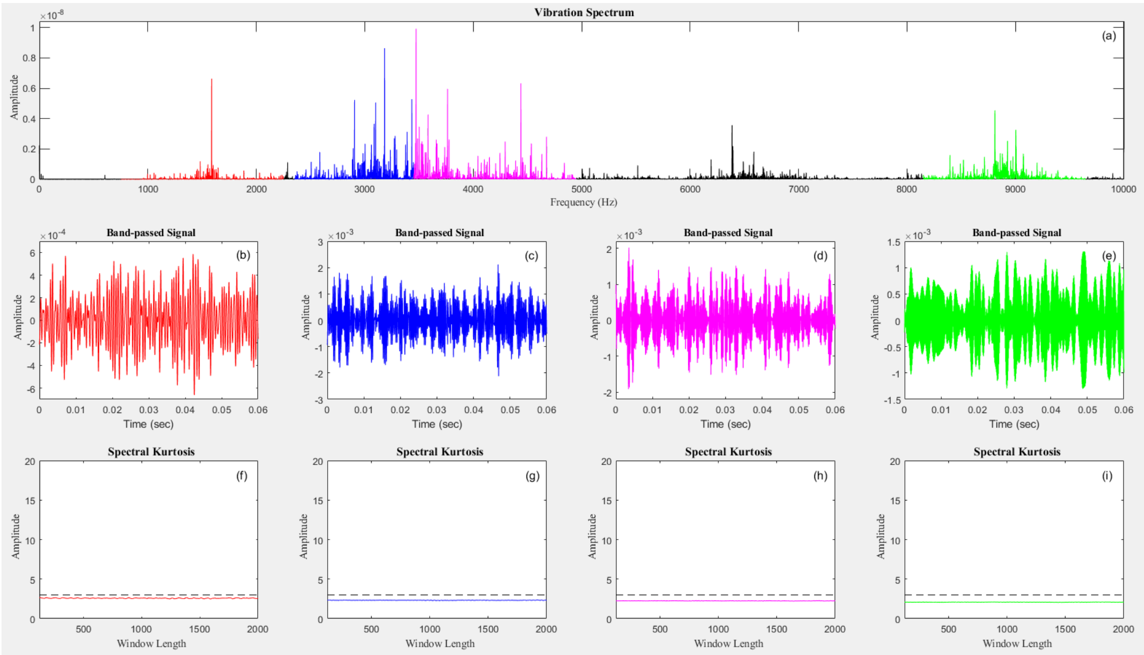

Fig.3 Mean spectral kurtosis analysis for normal bearing running at 1000 rpm

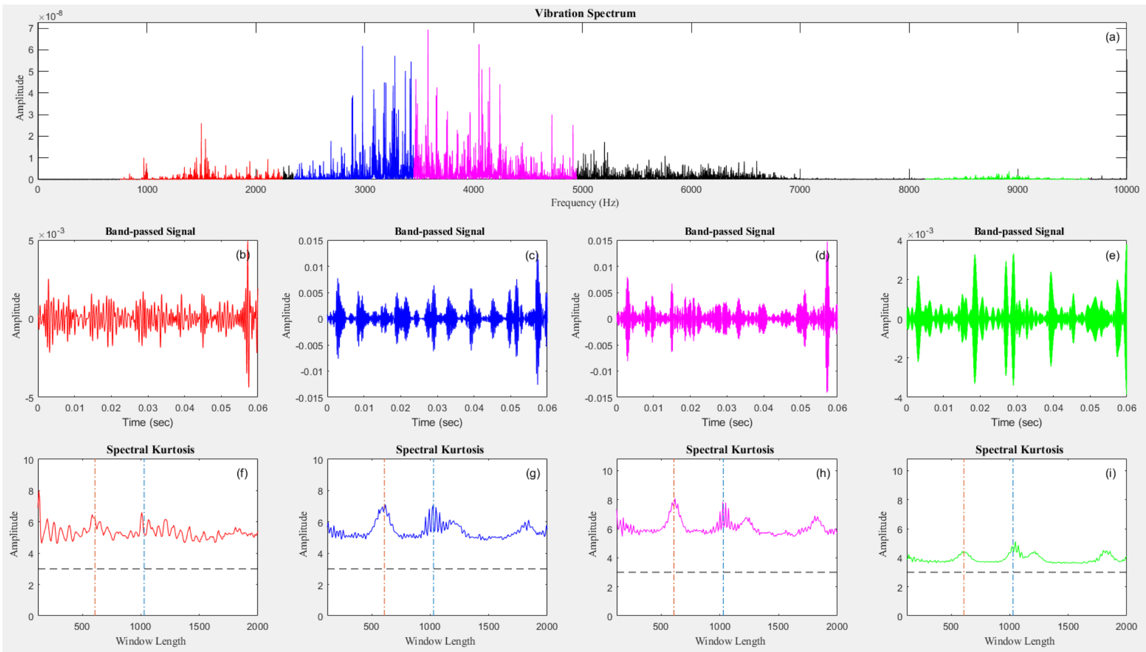

Fig.4 Mean spectral kurtosis analysis for roller and inner-race defect bearing running at 1000 rpm

Figure 4 shows the analysis result of mean spectral kurtosis for the roller and inner-race defect bearing running at 1000 rpm. In Figures 4(f)–(i), the mean spectral kurtosis is above the dash line of being the amplitude 3. However, in comparison with Figure 2 it is found that the base line of mean spectral kurtosis becomes lower. In addition, there are two dash-dot lines in every spectral kurtosis diagram. These two lines indicate the center of the mountain shape of peaks at the window length W=606 and W=1026, which is corresponding to the characteristic frequencies of inner-race defect at 164.7Hz and roller defect at 97.3Hz, respectively. It should be noted that there are another two mountain shape of peaks with center at the window length W=1212 and W=1818, respectively, which are the harmonics of the window length W=606.

IV. Conclusion

In the signal processing of bearing vibration, time scale and the corresponding energy distribution are two most important approach for studying the characteristics of vibration signal. In practice, the procedure of wavelet enveloping function could be implemented in the real time, and is a signal processing method in time scale. A designated passband for the function parameter is applied to filter out the vibration signal around a selected high-frequency band with the center at a chosen resonant frequency of the bearing system. It takes advantage of avoiding the interference of low-frequency noise transmitting from the environment. Furthermore, the energy distribution can enhance the signal-to-noise ratio.

The limitation of spectral kurtosis for the defect bearing is varying in a wide range and decrease with increasing running speed of bearing. In addition, the defect component in the bearing is difficult to figure out. In this paper, the mean spectral kurtosis analysis algorithm for a single mode of bearing vibration is proposed and proved effectively to apply in the bearing defect diagnosis. The algorithm harnesses the ability of band-passed vibration in highlighting the periodic fault transients and the ability of mean spectral kurtosis in locating the defect frequency with the window length.

According to the theoretical and experimental studies, it is shown that for normal bearing the mean spectral kurtosis is lower than 3 in the diagram, and similar to the kurtosis of a random signal. On the other hand, for defect bearing the mean spectral kurtosis is higher than 3 in the diagram, and a mountain shape of peaks is shown and can be corresponded to the characteristics of bearing defect. Accordingly, the mean spectral kurtosis analysis algorithm could also identify the defect type of a bearing system. This is of great practical significance for the signal processing method of spectral kurtosis in the bearing defect diagnosis. However, it should be noted that the spectral kurtosis would essentially be decrease with the increase of running speed. Thus, with the increase of running speed the spectral kurtosis will be lower and the mountain shape more blurred.

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