Application of Cascaded Stochastic Resonance to Performance Evaluation of Aero-engine

Zhang Ying

College of Aeronautical Engineering, Civil Aviation University of China, Tianjin 300300, China

Liao Heng-Yu

9 Air Co. Ltd, Guangzhou 510470, China

Zhao Ge

State Grid Tianjin Electric Power Company, Tianjin 300010, China

Abstract
Analysis of the rotor system vibration can provide some bases for health evaluation, as an important part of the aero-engine health management. To promote the extraction accuracy of vibration information, cascaded bistable system was introduced into the investigation of the aero-engine high and low pressure rotors. The cascaded stochastic resonance proves to be the preprocessor for health evaluation, which weakens the high-frequency dithering of the waveform merged by noise and outlines the basic shape. The application to the four double-spool engines of an airplane has indicated the cascaded stochastic resonance technique is effective to reflecting the real vibration features of the aero-engine rotor systems, helping to estimate the condition of different aero-engines and sort them, especially while the vibration signals were mixed up easily with similar values.
Key words: AERO-ENGINE, HEALTH EVALUATION, VIBRATION, CASCADED BISTABLE SYSTEM, STOCHASTIC RESONANCE

1. Introduction

In the aviation field, the reliable operation of the aero-engine is a guarantee for flight safety, which is mainly decided by the health state of the engine. As the aviation maintenance transforms from hard time maintenance to health management, the health evaluation of the aero-engine has become an important part of the health management [1]. The civil aero-engine features a complex operation structure. It can easily run into various faults in the harsh working conditions, among which faults caused by vibration account for a large percentage [2]. The vibration fault of the rotor system can directly influence the functional accuracy, reliability and endurance of the engine. If the complete engine vibration goes beyond standards, it will seriously inhibit the qualification rate and increase the maintenance cost. Therefore, analysis of the rotor system vibration plays an important role in the health evaluation of the aero-engine.

The concept of "stochastic resonance" (SR) was first put forward in 1981 [3], after which typical SR theories represented by the adiabatic approximation [4] and linear response [5] have been established and the aperiodic SR [6], multi-dimensional SR [7] and twice sampling SR [8] have been gradually developed. They support and complete each other, leading to wide applications of the SR technique to the biomedical industry, the chemical reaction industry, the information communications industry, the electronic machinery industry, etc. [9] In recent years, the emergence of theories, such as SR recovery methods [10] and SR dynamics mechanism [11], have provided a new research idea to reveal the nonlinear phenomenon.

Currently, there are few applications of SR to the rotor vibration analysis of the aero-engine. Most applications are based on the enhancing effect of SR on weak signals to conduct test and characteristic extraction of rotor faults in the early period [12-13]. In terms of time domain test, cascaded bistable system [14] is found to be able to remove the high-frequency dithering and outline the waveform. This paper applies cascaded bistable system to analyze the vibration of the civil aero-engine, which serves as a preprocessor for the health evaluation of the engine vibration, and fully proves the validity and unique advantages of cascaded SR in extracting time-domain characteristics.

2. Cascaded bistable SR theory

2.1. Basic theory of bistable SR

In terms of weak signal detection, the nonlinear characteristics of the bistable system change the negative suppression of the noise on valid information in conventional handling. Based on its positive effect, Brown particles can be led to undergo a large-scale orderly transition between the bistable potential wells. The system output is rebuilt, resulting in the occurrence of SR. From the micro-level perspective, the process is controlled by Langevin equation [9]:

$$\dot{x} = ax - bx^3 + s(t) + n(t) \tag{1}$$

Where, the system output is the particle displacement, $x(t)$; $-(ax - bx^3)$ is the potential field force of the bistable system; $s(t)$ stands for the periodical driving force; $n(t)$ stands for the stochastic force, namely noise, and its intensity is D. Without external excitation, the bistable system potential function can be expressed below:

$$U(x) = -\frac{1}{2}ax^2 + \frac{1}{4}bx^4 \tag{2}$$

When $a > 0$, the bistable system is shown in Fig. 1. The system has two stable equilibrium points, namely $x = \pm\sqrt{a/b}$, and an unstable equilibrium point, $x = 0$.

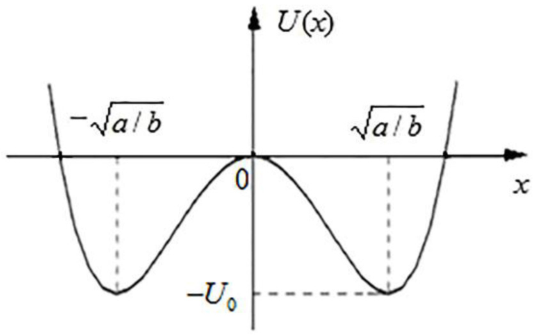


Figure 1. The feature curve of bistable system

Research [4-9] showed that changes of the characteristic parameters of noise, bistable system and driving signals, three elements of SR, can directly influence the system output. The three groups of parameters can be regarded as the generalized parameters. Noise-induced SR, parameter-tuning SR and twice sampling SR can be called the generalized SR for parameter adjustment. From the realization means, SR for parameter adjustment can be regarded as a process in which one element is changed to coordinate with the other two elements to achieve the optimal status of SR [15]. At the moment, the average jump frequency of particles (half of the Kramers rate) is equal to the frequency of the periodical driving force. Since the value of the Kramers rate can be changed through the adjustment of the noise intensity and the system parameter, and the twice sampling SR realizes the scaling down of the signal frequency [8]. Therefore, the generalized SR for parameter adjustment can reflect the different directions for the founding of the above frequency equation in essence.

In terms of the practical signal sample, the noise strength, D, cannot be randomly increased or decreased. Since the system parameters, b and the noise intensity D, make the same contribution during the construction process of system parameter output, the noise-induced SR can be regarded to be equal to the SR for parameter-tuning SR in some sense. When the noise intensity and the signal frequency are both larger than the small parameters, the twice sampling frequency and the system parameter adjustment can be adopted to achieve optimal matching of a new bistable system, new frequency and original noise strength [15].

2.2. Cascaded SR treatment method

Cascaded bistable system refers to that several bistable systems are connected in series. (See Fig. 2)

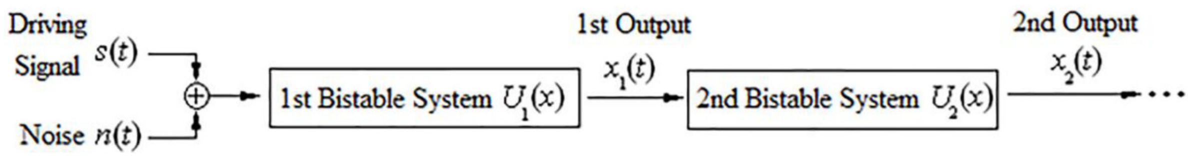


Figure 2. Constitution of Cascaded bistable system

Take the cascaded system consisting of two bistable systems for example. When the original input signal of is the sinusoidal signal $s(t) = A\sin(2\pi f_0 t)$, mixed with the Gaussian white noise, $n(t)$, the Langevin equation corresponding to the 1st and 2nd bistable system is:

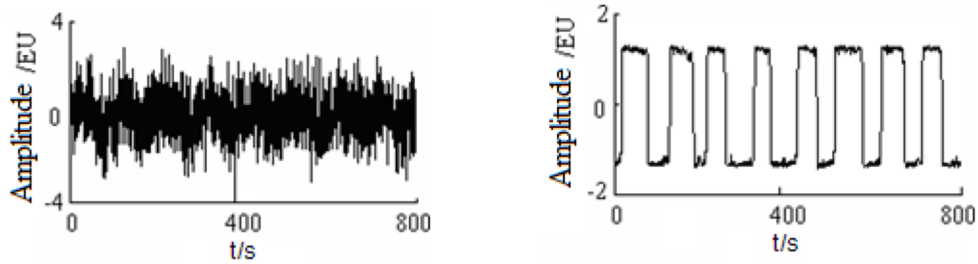
$$\dot{x}_1 = a_1 x_1 - b_1 x_1^3 + A\sin(2\pi f_0 t) + n(t) \quad (3)$$

$$\dot{x}_2 = a_2 x_2 - b_2 x_2^3 + x_1(t) \quad (4)$$

Where, a_1 and b_1, a_2 and b_2 are the system parameters of $U_1(x)$ and $U_2(x)$, corresponding. The output of 1st bistable system, $x_1(t)$, serves as the input of 2nd bistable system. Research [14] found that the periodical element and noise in $x_1(t)$ have undergone changes. The periodical element is approximate to the rectangular wave whose amplitude is enlarged. The input noise changes from the white spectrum to the color noise spectrum with Lorenz distribution. However, no matter noise input of certain amount belongs to which distribution; the noise will remain the same in terms of its total energy in any system. Therefore, when the cascaded bistable SR concentrates most noise energy on the low-frequency region, the energy of the high-frequency noise will be reduced absolutely, thus resulting in further reduction of the high-frequency amplitude. From the perspective of the time domain waveform, the cascaded bistable system transforms the signal by sharping changes beyond certain amplitude into the edge of rectangular waves, and filter he high-frequency small-amplitude vibration at the bottom and on the top of waves. The characteristic is obviously shown in the simulation calculation shown in Fig. 3.

3. Application of the cascaded SR technique to health evaluation of the aero-engine

Currently, the civil turbofan engine adopts the double-spool structure. The high-pressure compressor and the high-pressure turbine constitute the high-pressure rotor, while the low-pressure compressor containing the fan and the low-pressure turbine constitute the low-pressure rotor. The low-pressure rotor goes through the high-pressure rotor. The vibration caused by imbalanced rotor and other reasons is conveyed to the engine case through the bearing structure, and to the plane through the engine mounts. The vibration signals are collected through the vibration sensors installed on the case. During vibration analysis of the engine, some background signals with a larger energy and related to the rotation speed or other facts will disturb the health evaluation of the rotor system [13]. Cascade bistable system can be introduced into the vibration analysis of the aero-engine as a preprocessor of health evaluation. Based on its nonlinear low-pass filtering characteristic, the system continuously shift the high-frequency energy to the low-frequency energy through cascades of various stages to achieve the effect of removing high-frequency dithering and outlining the waveform profile. The method can be combined with the follow-up links after health evaluation and the other fault diagnosis methods to provide



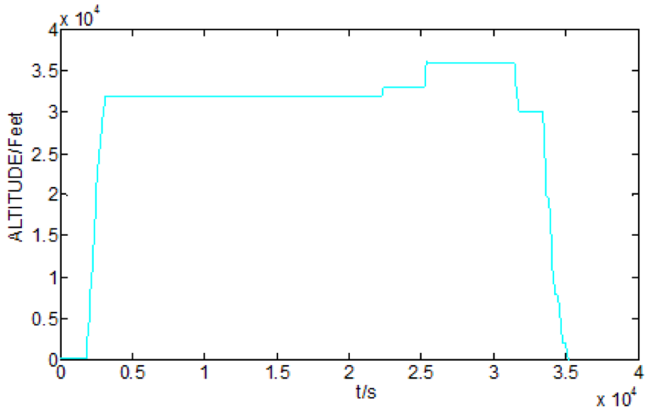
(a) Time domain waveform containing noise (b) Time domain waveform of the system output

Figure 3. Numerical simulation of the two-stage cascaded bistable SR

necessary bases for the aero-engine health management based on the vibration investigation.

Four sets of double spool engines of an airplane are taken as an example. The treatment objects is the vibration monitoring data of a flight. Fig. 4 is the flight altitude chart with the horizontal axis being time (t), the vertical coordinate being altitude and the unit being feet. The chart covers various flying periods of the plane, including taxing, taking off, climbing, cruising, descending, approaching and landing.

For the convenience of comparison, the low-pressure rotor and the high-pressure rotor vibration signals of the four engines are adopted as the input of the two-stage cascaded bistable system. Through the choice of the stable system parameters and the twice sampling frequency, a new system cooperation is achieved. Fig. 5 shows the original and output vibration signals of the low-pressure rotor system via cascaded SR. Where, $N1$ stands for the low-pressure rotor; VIB stands for the vibration value of the ro-



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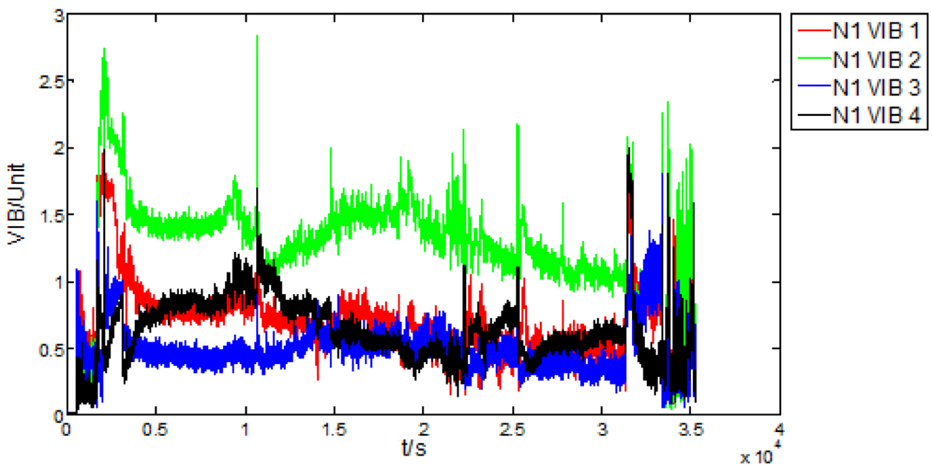
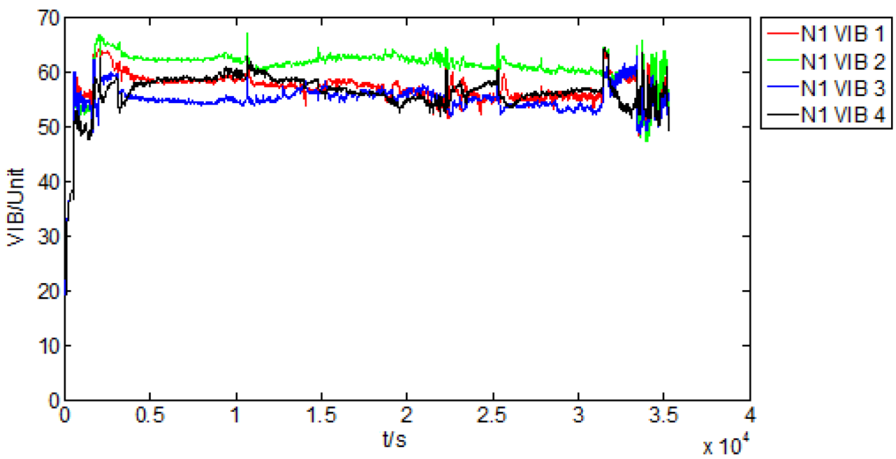


(a) Original waveform of the vibration signal



(b) Output waveform of the cascaded bistable system

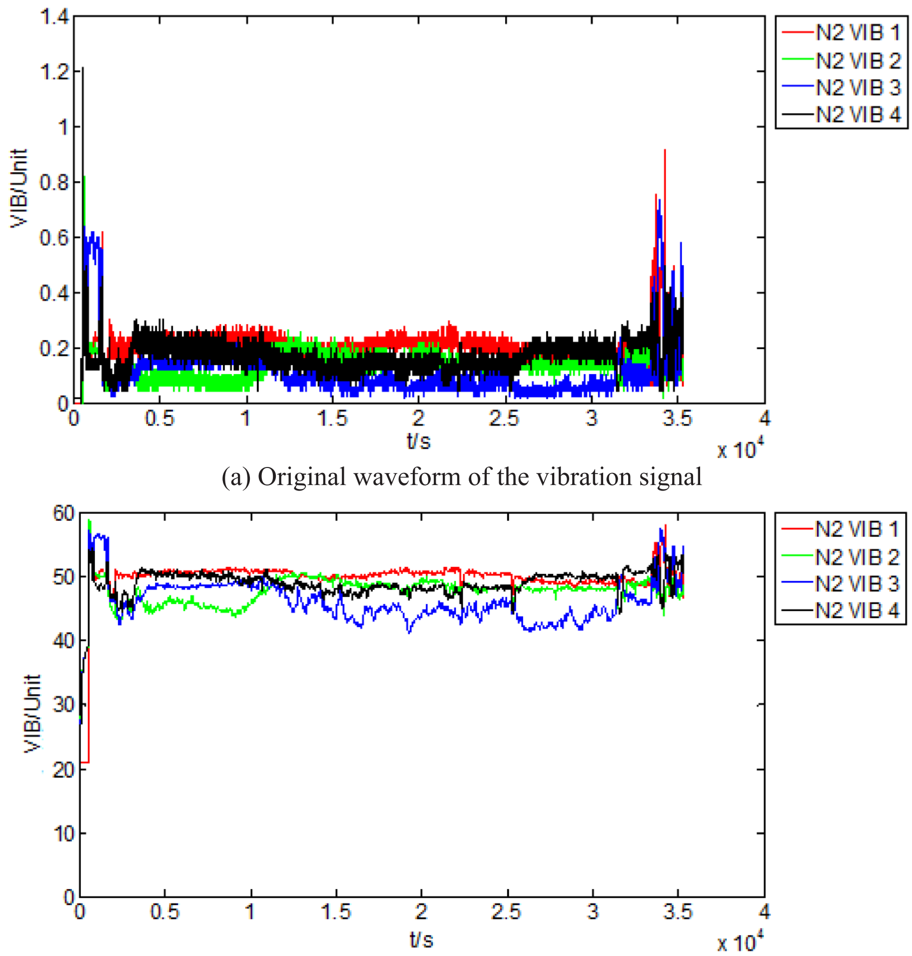
Figure 5. Cascaded SR results of the low-pressure rotor vibration signals of the four aero-engines

tor;1, 2, 3 and 4 stand for the first, the second, the third and the fourth aero-engine, counted from left to right. Therefore, $N1\ \ VIB\ 1$ stands for the vibration of the low-pressure rotor of Aero-engine 1. Here, the bistable system parameter is $a = b = 0.1 \times 10^{-4}$; the twice sampling frequency is $f_{sr} = 1\,\text{Hz}$; the number of data points is 35,309; the sampling time length is 35,309s.

In the contrast with Fig. 4, the four aero-engines vibrate dramatically in the period of taking off, climbing and descending. This coincides with the practical situation. From Fig. 5, it can be seen that the vibration values of the low-pressure rotor of Aero-engine 2 are obviously higher than that of the other three aero-engines. Before $1.5 \times 10^4 s$, the vibration values of the low-pressure rotor of Aero-engine 3 are obviously lower than that of Aero-engine 1 and Aero-engine 4. The vibration values of the low-pressure rotor of Aero-engine 1 and Aero-engine 4 are relatively close to each other. Since the noise level is low and the vibration of the low-pressure rotor of various engines differs, they can be told apart in the original vibration waveform. (See Fig. 5a) After the cascaded bistable system, the output results are shown in Fig. 5b. It can be seen that the amplitude value is enlarged; the high-frequency dithering is removed; the trend of the signal is more prominent; and the vibration difference of different engines is also more obvious.

When the vibration values of aero-engines do not differ greatly, the cascaded bistable system shows great advantages in outlining the profile of time domain waveform. This is verified through the vibration analysis of the high-pressure rotor system of the above four aero-engines. Fig. 6 shows the original waveform of the vibration signal of the high-pressure rotor and the output waveform of the cascaded bistable system. In Fig. 6, $N2$ stands for the high-pressure rotor; VIB stands for the vibration value of the rotor; $N2\ \ VIB\ \ 1$ stands for the vibration of the high-pressure rotor of Aero-engine 1. Relevant parameters of SR are selected as same as Fig. 5.

Through comparison of Fig. 5 and Fig. 6, it can be found that, under the same parameters, the vertical coordinate values of the high-pressure rotor are obviously lower than that of the low-pressure rotor both in terms of the original and the output signals after SR. The reason is that the high-pressure rotor is short in



(a) Original waveform of the vibration signal

(b) Output waveform of the cascaded bistable system

Figure 6. Cascaded SR results of the high-pressure rotor vibration signals of the four aero-engines

terms of its length, large in terms of its diameter and high in terms of its rigidity. Under general conditions, the longer and thinner low-pressure rotor can more easily be vibrated.

In Fig. 6 (a), the vibration values of the high-pressure rotor are close to each other. In the original time domain waveform, the vibration curves are almost overlapped, and hard to be told apart. It is impossible to compare the vibration situation of different engines. After the treatment of the cascaded bistable system, it can be seen that the vibration curve can distinguish the four aero-engines. On the whole, the vibration values of the high-pressure rotor of Aero-engine 1 are slightly higher than that of the remaining three aero-engines. Before 1.2×10^4s, the vibration values of Aero-engine 2 reach the minimum; the vibration values of Aero-engine 3 and Aero-engine 4 are close to each other. After 1.2×10^4s, the vibration values of the high-pressure rotor of Aero-engine 3 are smallest. Based on the comparison of Fig. 5 and Fig. 6, it can be seen that cascaded SR highlights the difference of the vibration situation of various aero-engines through the filtering of the high-frequency disturbance. According to the above analysis results, the long-term operation data are averaged on a flight basis so as to achieve analysis and ranking of aero-engines of different health states, and provide reference for further fault diagnosis.

4. Conclusions

Vibration monitoring is an important data source for health evaluation of the aero-engine. Due to structural design and other factors, the high-pressure and low-pressure rotor system of the double-spool engine have different vibration characteristics. Based on cascaded bistable SR, this paper conducts a vibration analysis of the high-pressure and low-pressure rotor system of four aero-engines of a plane under the same flying state, and achieve shaping of the original waveform, removal of the high-frequency dithering and highlight of the changing trend. The application fully verifies the validity of cascaded SR as a preprocessor of health evaluation. In particular, it can well assist in evaluating and ranking the health state of different aero-engines.

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An Optimal Feature Selection Method for the Classification of Ground Cover in Remote Sensing Images

Yu Yang

School of Automation Science and Electrical Engineering, Beihang University, Beijing, China

Hong Zheng

China Academy of Space Technology (CAST), Beijing, China

Chuanzhao Han

China Academy of Space Technology (CAST), Beijing, China

Abstract

Optimal feature selection is one of major problems associated with the design of classifiers for identifying ground cover in satellite remote sensing images. This paper proposes a novel method of optimization of feature selection, namely, Corrects and Errors Offset Each Other (CEOEO). The proposed method can resolve the close coupling that exists between the feature selection process and the classifier. First, our studies showed that the performance of feature combination mainly relies on the complementarity of the feature between correct and wrong recognition and does not relate to the performance of the classifier. Therefore, we built an optimal model of the feature subset