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A new transmission gearboxes fault diagnosis system based on Bistable Stochastic Resonance

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ABSTRACT

This paper proposed a new transmission gearboxes fault diagnosis system and introduced motor current signal analysis to drive gearbox fault diagnosis, use stochastic resonance theory and DTW algorithm to introduce fault signal processing and fault analysis. Discuss the possibility of system programming based on mixed language programming for VC++and MATLAB. Demonstrated a new method for the special conditions of gearbox fault diagnosis system. Predictable, it has great value in the future fault diagnosis.

Keywords: Diagnosis system; Fault diagnosis; Dynamic time warping; Stochastic resonance

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INTRODUCTION

Gearbox as an essential common components for connecting and power transmission in the machinery and equipment , get widely used in aircraft, electric locomotive, ship, automobile, wind power generation equipment etc. It has an important impact on dynamic performance of the machine, so it is significant that accurate monitoring of gear fault.

At present, it is the mainstream monitoring methods based on vibration monitoring for such machines and has also made good progress in vibration signal acquisition and processing after several generations of scholars' research, but at the some actual field many of equipment difficult to close or the reasons of special operating conditions makes vibration diagnosis difficult to implement[1]. How to improve the existing gearbox fault monitoring system diagnostic accuracy, timeliness and adaptability under variable conditions to make it better be used in actual production is an interesting topic. For this reason, this paper combines the theory of stochastic resonance, DTW algorithm and current analysis put forward a fault diagnosis system of the transmission gearboxes.

2. Bistable system stochastic resonance

Stochastic resonance was put forward by Italy Benzi in 1981 for the interpretation of recursive glacial cycle. After that the same principle applied in a wide variety of systems. This theory explains the concept : weak periodic signal that lost in the background noise through a non-linear systems , nonlinear systems, signals and noise reaches a certain match , background noise enhance weak periodic signal transmission , make the output SNR enhancement [2], the classic model of stochastic resonance in Figure 1 Shown in.

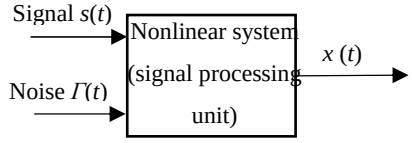

Figure 1 the general structure of stochastic resonance

Bistable systems in physics, chemistry and all the natural sciences have a wide range of applications [3], the paper's stochastic resonance is also based on this system. Langevin equation with double-well potential is the most representative of the bistable nonlinear system and its mathematical model is

$$X = ax(t) - bx(t)^3 + u(t) + \Gamma(t) \quad (1)$$

The model describes a particle at the same time be motivated force u (t) and noise Γ (t), as in Figure 2 shows drive in the symmetric double-well potential. System has two of the same potential well and a potential barrier, well bottom located at $\pm\sqrt{a/b}$ and barrier height is $\Delta U = a^2/4b$。

X is system output a, b is greater than 0 for non-linear system parameters. When $u(t) = A\cos(\omega t + h)$,input force is the external modulation signals driven by Gaussian noise signal, A is signal amplitude, ω is frequency modulation signal; Γ(t) represent the Gaussian white noise, and meet the statistical mean and autocorrelation functions as follows:

$$\begin{cases} < \Gamma(t) >= 0 \\ < \Gamma(t)\Gamma(t+\tau) >= 2D\delta(\tau) \end{cases}$$

D is noise strength, τ is the delay time. δ is the impact function [4].

When there is no modulation and noise effects, particle in one of two potential well, it was determined by the initial state. When A>0, a potential well driven by signals, periodic changes occurs with the frequency ω. When A<Ac ($A_c = \sqrt{4a^3/(27b)}$), only within a trap a particle localized at the same frequency to periodic motion. However, when after the introduction of noise, even when A≤ A_C, particles can also trap from the original jump into another trap. External input into periodic change, effectively synchronize the switching caused by noise, thus making the small component in system output x (t) has been strengthened, thus improved output SNR.

The key of Stochastic Resonance is the system to achieve a better match between signal and noise. At the time of signal detection, general signal's size cannot be changed, can be changed only is system parameters and intensity of noise. System parameters a directly determine a system output can reach how the highest transition frequency, its value more than signal frequency two orders of magnitude. Value of parameter a, b determines the potential barrier height , when determines the parameter a, b, noise intensity value D can be experimentally determined , when the signal and noise cooperative energy can overcome barrier blocking , stochastic resonance system reached status.

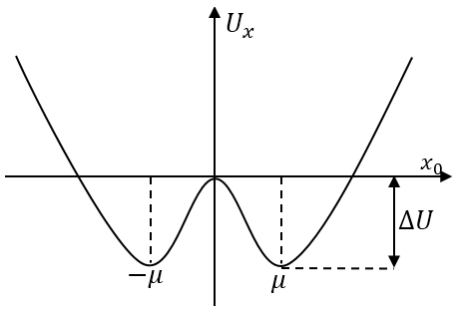

Figure 2 a symmetric double-well potential diagram

After determine the parameters of bistable systems, we have available four-order Runge Kutta numerical calculation method [5], discrete and numerical solve formula (1) we can obtain output signal which through SR. The formula is

$$\begin{cases} y_{n+1} = y_n + \dfrac{h}{6}(K_1 + 2K_2 + 2K_3 + K_4) \\ K_1 = f(x_n, y_n) \\ K_2 = f\left(x_n + \dfrac{h}{2}, y_n + K_1\right) \\ K_3 = f\left(x_n + \dfrac{h}{2}, y_n + K_2\right) \\ K_4 = f(x_n + h, y_n + hK_3) \end{cases}$$

3. DTW principle

Dynamic time warping is a classic optimization problem, which uses time warping functions that satisfy certain criteria w (n) describes the time relation between the test and reference templates. The algorithm is based on dynamic programming (DP) ideas, solve the problem of template matching signal varies, in short, is to establish an adjacency matrix, and find the shortest path.

Assume that time series of Q and C, their lengths are n and m, a sequence as a reference template, a sequence as a test template, the value of each point in the sequence is the eigenvalues of the characteristic signal every frame.

Assume that two time series are expressed as
Q :{ q_1, q_2... q_i... q_n}
C :{ c_1, c_2... c_j... c_m}

If n=m and then there is much more convenient, we can direct calculate the distance between two sequences, $D_{EUC}(Q, C) = \sqrt{\sum_{i=1}^{n}(q_i - c_i)^2}$。 But if n is not equal to m we need to align our calculations.

In order to achieve alignment, construct a n×m matrix networks with matrix elements (i, j) to denote qi and cj. Use d(qi, cj) to represent local distances between qi and cj. Local distance using Euclidean distance, that is, d (qi, cj) = $(qi-cj)^2$. DP algorithm can be attributed to find a path through the number of lattice points in this grid, the path through the lattice is the two of a sequence alignment point calculation.

If a structured path W is the minimum of all elements on the path, the minimum value is the DTW Distances between Q and C [6], let W the first k element is $W(k)=(i, j)_k$, then the DTW Distance is :

$$DTW(Q, C) = \min\left[\frac{1}{K}\sum_{i=1}^{K} w_i\right]$$

The denominator of K is mainly used to regular path for different length compensation.

In practical applications also need to limit the winding path of walking areas. To facilitate the matrix processing , should limit the swings of curved path close to the diagonal sides of the distance matrix , therefore , without considering the subset of regions outside the distance similarity call this curved path factor for bending window. Bent window settings for two main reasons: (1) can accelerate the speed of dynamic time warping algorithm; (2) to prevent the emergence of morbid curved paths in logic. In the analysis of time series, the time factor is very important, a big time offset is moot, and it should be ignored from a logical point of view.

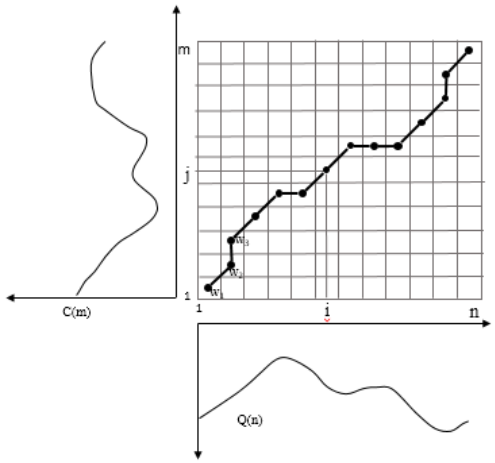

Figure 3 DTW algorithm diagram

Set point (i, j) on the best path , then from point (1,1) to (i ,j),the subpath is also a local optimum , that is to say the optimal path from the point (1,1) to the point (n, m) can be obtained by recursive search the optimal solution between the time (1,1) and the end (n, m),namely:

$S(1, 1) = d(q_1, c_1)$
$S=d(qi, cj)+\min\{S(i-1,j),S(i-1,j-1),S(i,j-1)\}$

Final Time Series curved path minimum accumulated value S (n, m). Along the curved path backwards by a minimum cumulative value from S (n, m) to the start point S (1, 1), we can find the entire curved path [7].

4. Gearbox fault diagnosis system

Machine fault diagnosis system usually includes four aspects of the content, data acquisition, data processing, fault analysis, and finally the human-computer interaction in software system, as Figure 4 shows.

4.1 Signal acquisition

Signal acquisition is the processes which use the sensor converting the electricity of mechanical into analyzable signal.

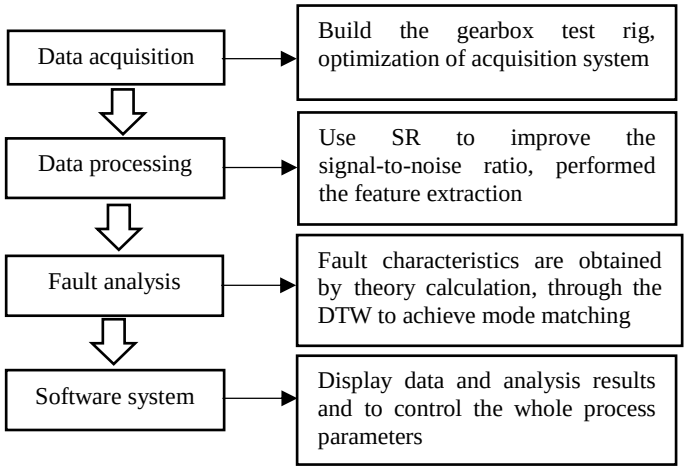

Figure 4 mechanical fault diagnosis procedures

Vibration signal detection methods we have already mentioned in the introduction of inoperability in some conditions, but gear box motor current is easily measured, and is a form of output shaft torque of the motor [8].

Motor current signal analysis, referred to MCSA, is the use of stator current signal analysis point, to study the relation between its characteristic and fault. This approach not only lower costs but also can realize remote monitoring, more favorable is the signals in addition to the normal functioning of information, also includes

operating information, so you can establish precise and reliable load model for condition monitoring. Now this method is more and more mature and widely applied in fault diagnosis of motor. Through research it was discovered that this method can also be applied to the motor dragging equipment, and has made some progress in practice.
Using a current transformer on current signal acquisition, after sampling circuit and A/D converter finally completion of the current signal sampling.

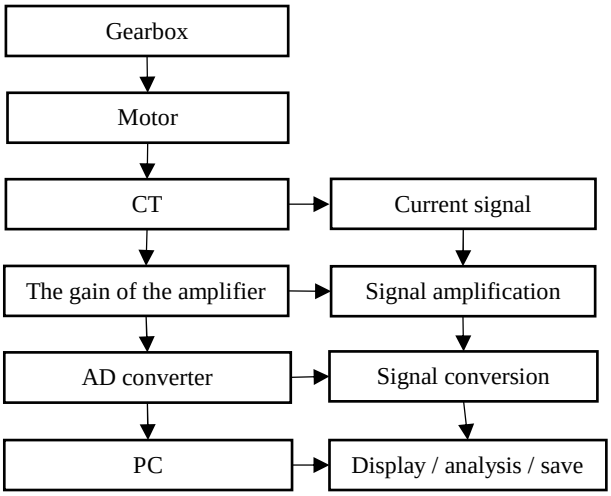

Figure 5 a schematic diagram of test bench

4.2 Data processing
Every coin has two sides, and current method of fault signal is weak and masked by much 50Hz power supply signals and random noises, so we requires the efficient signal processing method to extracting weak signal.

De-noising methods are filtering hardware and software filtering methods. However, early fault performance in stator current in the mostly is non-steady-state or mutations in weak signal, whether hardware or software-based filtering Fourier transform filtering method, will result in a certain extent damage in signal inevitable when make a suppression of noise. Even may because background of complex strong noise and led weak signal that frequency close to noise cannot detection, so traditional signal detection and processing technology cannot meet our requirements.

In fact, noise is not always slow down system performance, under certain conditions, noise can also help signal detection .In some nonlinear systems, input a certain amount of noise will improve system response quality, such as increasing the signal to noise ratio. This is known as stochastic resonance (SR). With nonlinear theory of weak signal detection in strong noise background development and application, stochastic resonance has been applied in a variety of signal processing issues and achieved good results.

After testing comparing Fourier transform, Wavelet transform and based on single marked degrees index method cannot right classified gearboxes' vibration signal which have similar fault mode, but the method based on stochastic resonance can let different fault of features information displayed in spectrum figure effective. This fully shows that stochastic resonance method are very sensitive to the change state of gearbox fault .It can improve recognition precision and distinguish very similar of fault mode, thus suitable as fault features detection method of gear box current signal.

In order to better analyze the signals, and to facilitate next fault identification, signal through stochastic resonance system, then FFT spectrum analysis processing implementation, in order to identify the fault feature.

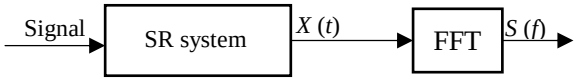

Figure 6 data processing structure diagrams

4.3 Fault analysis
Theoretical fault feature can be obtained through theoretical calculation, and through systematic training on fault feature to creating reference templates, through DTW pattern matching algorithm

(1) Fault feature analysis
Gearbox fault occurred on the gears and roller bearings (gear for 60%, bearings for 19%), therefore, research on gearbox fault also focused on the gears and roller bearings [9].

Rolling bearing is the box bearing unit, in addition to high speed, heavy load, and conditions are abominable. In ball bearing, fault 90% occurs on the inner ring and the outer ring, the other faults occurred on the roller, there is little fault of cage [10]. For gear, because of their manufacturing errors, poor maintenance, may cause the gear to fail, a common gear failure is mainly pitting corrosion, flaking, plastic flow, as well as tooth root cracking, even tooth breakage, etc. Fault ratio as shown in table 1 below.

When analyzing the fault characteristics, the experience of vibration signal detection used in current signal detection. According to the frequency of vibration fault current signal, current fault frequency can be derived.

Table 1 percentage of gear faults

Broken teeth	Pitting corrosion	Scratches	Wear	Other
41	31	10	10	8

Bearing fault has a unique set of frequency, which can identify bearing problems. These frequency peaks in the current spectrum indicate bearing fault (inner ring, outer ring, rolling elements and cage), we through the peak amplitude to evaluate the degree of deterioration under.

Outer fault frequencies:

$$f_{OD} = \frac{n}{2} f_{rm}(1 - \frac{BD}{PD}cos\phi)$$

Inner fault frequency:

$$f_{ID} = \frac{n}{2} f_{rm}(1 + \frac{BD}{PD}cos\phi)$$

Rolling element fault frequency:

$$f_{BD} = \frac{PD}{2BD} f_{rm}(1 - (\frac{BD}{PD})^2 cos^2\phi)$$

Cage fault frequency:

$$f_{CD} = \frac{1}{2} f_{rm}(1 - \frac{BD}{PD}cos\phi)$$

Among them, the f_{rm} is frequency for motors, n is the number of rolling elements,BD and PD is the rolling element diameter and pitch diameter of the bearing, Φ is the contact angle of the rolling elements [11].

The meshing vibration of the gear transmission system is inevitable. In the operation of gears, the two gears meshing with each other, the load distribution is changing, it can cause rigidity of gear changes, causing vibration of gears, and this vibration is known as meshing vibration. When the gear is defective, meshing vibration frequencies and their harmonic components can be especially prominent, thus monitoring meshing frequency for gear fault diagnosis is very important. The formula is as follows:

$$f_z = Z\frac{N}{60}$$

Where Z is the number of gear teeth, N is the corresponding gear speed [12].
Fault analysis of gear can also through sideband analysis, spectral analysis, and so on.

With the vibration frequency, based on $CF = f_1 \pm mf_v$, m=1, 2, 3... Calculate the characteristic frequency of currents. f_1 is the supply frequency, f_v is vibrational frequencies calculated in above formula.

(2) Fault pattern matching
Gearbox fault diagnosis technology is a complex technology, gearbox fault diagnosis' core is the pattern recognition, namely to find fault while the fault classification [13].

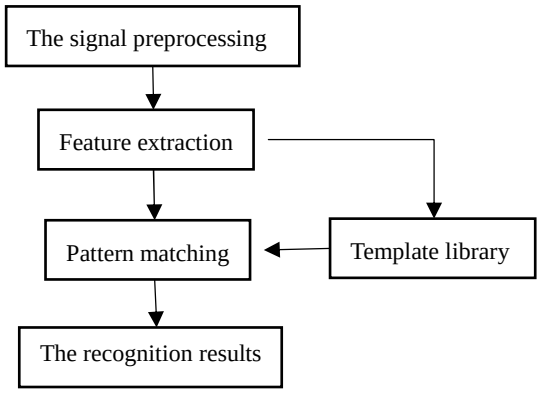

Figure 7 pattern recognition principle diagrams

Pattern recognition have many ways, including DTW technology, it was first applied to the field of automatic speech recognition, to handle different speed impact on the speech recognition, has the characteristics of simple and efficient. Using DTW distance as a similarity measure can take full advantage of different status signals during the operation of the gearbox, achieve the quantitative diagnosis of engine gearbox fault, and can overcome the problem of phase difference between time series.

In order to achieve a quantitative fault diagnosis, can depending on the gearbox performance of specific circumstances, in accordance with a certain interval, the fault is subdivided into equal intervals or different intervals of reference samples. For example, gear pitting fault in accordance with different, divided into the 2%,3%,4% and 5%and so on ; For higher diagnostic accuracy, of course, can be subdivided into more fault modes. Template databases are usually obtained by mathematical model of experimental data and theoretical calculations.

4.4 Software systems design
The system has completed a half after theoretical support for the fault diagnosis of gearbox, but for practical production we also need to embed theoretical algorithm into the software system. Already introduced the realization of algorithm theory system, but we also need to implement in software visualization of data to visually observe gearbox running condition.

The software system in addition to data acquisition, fault detection subsystem also contain management subsystem, the system has three main functions: parameter setting, historical data query, statistical reports and print. The parameter setting is responsible for all the parameters of the system, and to adjust to changing conditions. Historical data query and statistical reports and print module belongs to the output system, provides the convenience for the user.

Software system previously deposited in a conventional gear box fault model, and supports the user re training fault characteristics in the use process based on actual condition so that more accurate in fault matching. Software system let current signal of CT acquisition through stochastic resonance, and then after the DTW matching algorithm and fault model established in advance. After determine the fault type, system will return fault type to the user and provide corresponding solutions.

In the system should not only store experience in data form but also let the operator involved, in some fault diagnosis occasions people has not alternative status, therefore using two kinds of diagnostic methods in human-computer interaction link, one is system for the real-time detection of gearbox in the work, proposed alarm and fault recommends to operator, another is the operator find suspicious phenomenon according to the site and collect data observation, more targeted to detect the fault diagnosis system and guide the judged results.

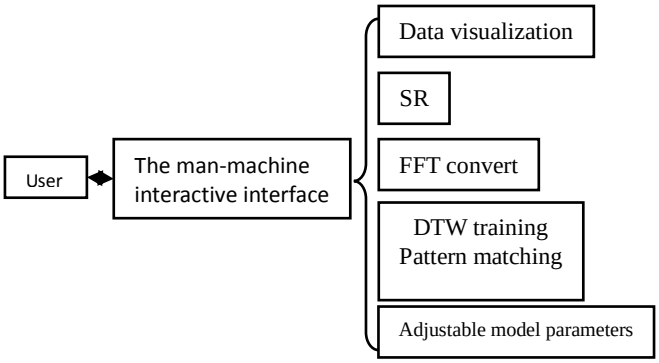

Figure 8 software function block diagram

So in the design of software system, we should not only consider convenient implementation of the algorithm and real-time processing of large volumes of data but also consider the hardware and software compatibility and robustness of the whole system .DTW algorithm is an algorithm which calculate the minimum distance constantly to implement pattern matching, in training and matching process involves a lot of matrix operations, and MATLAB has excellent performance in matrix operations, so we can consider use MATLAB to develop program of the system. Because MATLAB is based on explanatory language, its implementation is inefficient. But because C++ can generate executable files, enhance its portability, easy on another computer running. So we should study C++ and MATLAB language's interface implementation method, use idea of mixed-language programming to achieve the development of system software for fault diagnosis. Rapid development tools C++Builder can be used in program design; it can design interface and realize subroutine calls [14].

MATLAB with a powerful toolbox, its performance is very complete and stable, and offers a wealth of C/C++ math library, which can be used similar to MATLAB language syntax to write C++ programs, it is very convenient, although the speed still slowly than regular C/C++ program , but it is worth for the development of high efficiency and reliability. This method of mixed-language programming has been studied and used by a large number of scholars. It belongs to relatively mature methods, and easy to implement. So ultimately adopted this mixed program completed the design of the software system.

CONCLUSION

Gearbox drive motor’s stator current signal is an easily measured signal, using the gearbox fault diagnosis system is not only low cost but also suit for remote monitoring, according to the Motor Current Signal Analysis in practical application of machinery fault detection, Stochastic Resonance theory in modern signal processing techniques are widely used to improve signal to noise ratio, Dynamic time warping algorithm is simple and efficient of the pattern identified by computing the minimum distance between the template, combined with the Stochastic Resonance theory and dynamic time warping algorithm as the basic theory of fault diagnosis, in the use MATLAB algorithms library on the development environment VC++ into mix programming and to realize the development of fault diagnosis software.

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