A Method of On-line Monitoring for Vibration Table Bearings Based on VMD

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Abstract. Aiming at the problems that the bearing inside the sliding table of the shaker used for the dynamic test of spacecraft cannot be observed and the failure cannot be known at the initial stage, an online prediction method for bearing failure is proposed. In this paper, the acceleration sensor is selected as the monitoring medium of bearing motion state response, and the VMD (variational mode decomposition) is used as the analysis method of bearing acceleration response data to calculate the harmonic components of the bearing except the fundamental wave. Through the calculation results, the failure bearing can be intuitively interpreted.

1. Introduction
In aerospace, aviation, vehicle and other engineering fields, vibration test, as an effective means to test product reliability and dynamic strength, has been widely used in product performance assessment and dynamic strength appraisal. Vibration test equipment generally includes shaker, control system, measuring instrument and auxiliary equipment. As an important auxiliary equipment, sliding table is indispensable in vibration test, and its performance state also affects the test control effect and product response. If the sliding table suddenly breaks down during the test, the validity of product verification will be affected and the product will be damaged seriously. During a satellite vibration test in the United States, the bearing of the sliding table was damaged, resulting in severe structural damage. Three of the four solars were damaged, which was classified as A class A accident [1]. To avoid similar situations, it is essential to evaluate the condition of the slide before testing. In view of the problem of online monitoring and slider bearing state, this paper puts forward a kind of based on VMD (variational mode decomposition) of the embedded bearing acceleration state monitoring method, the purpose is to get the bearing status indicators, bearing danger ahead of time, to avoid bearing failure in the testing product loss, fill the shaker bearing more accurate state monitoring of blank.

2. Embedded bearing acceleration testing technology
2.1. Sliding table t-type bearing structure
The two key components of the sliding table are the slide plate and the hydrostatic bearing. The slide plate has high strength and stiffness. The upper surface is used for the installation of test pieces, while the lower surface is threaded with hydrostatic bearing lugs to generate horizontal vibration under the thrust action of the shaker. As shown in figure 1, under the normal working condition of the sliding table, the sliding plate can slide freely, the working curve is smooth and without burr, and the bearing
capacity can reach the maximum.

![Figure 1. Schematic diagram of relative position between slide and bearing](image)

2.2. Embedded installation of acceleration sensor
Since the bearings are located inside the sliding table and there are a large number of them, each bearing state cannot be checked by visual inspection, so sensors are used to monitor the working state of the bearings. The acceleration sensor should meet the following requirements:

- The size is smaller than the bearing clearance inside the sliding table;
- Protection meets oil and corrosion resistance;
- The range is more than 200g;
- High impact resistance;
- Type is IEPE piezoelectric sensor;
- The upper frequency response range is 10kHz.

The shaker bearings have two types: tile motion and shaft motion. To obtain dynamic signals, sensors should be installed on the moving parts of the bearing, and try to be close to the easily worn parts of the bearing to facilitate data acquisition. Considering that the vibration sensor will be soaked in lubricating oil for a long time, it is necessary to drill holes in the bearing and choose the screw connection mode. See the figure 2 for details.

![Figure 2. Physical picture of acceleration sensor installation on site](image)

3. Data processing method

3.1. Variational mode decomposition (VMD)

Variational modal decomposition (VMD) is a multi-scale non-recursive signal decomposition method which is suitable for the analysis of unsteady signals. This method transforms modal estimation into a variational problem, and determines the frequency center and bandwidth of each component by iteratively searching for the optimal solution of the variational model in the process of obtaining the decomposed components, so as to realize the effective separation of the frequency domain parts and components of the signal adaptively. The variational constraint problem can be expressed as

$$\min_{\{k_1, \cdots, k_K\}} \sum_{k=1}^{K} \left\| \arrow{c}{\delta(t) + \frac{j}{\pi t} \star u_i(t) e^{-j\omega_i t}} \right\|$$

(1)

In the formula, $u_i$ is the set of modal functions, $\omega_i, u_i$ is the set of central frequency, $\delta_i$ is the
heap function takes the partial derivative of “τ”, \( \delta(t) \) is unit impulse function, “j” is imaginary unit, “*” expresses convolution.

In order to solve the constrained optimization problem, the advantages of the second penalty term and Lagrange multiplier method are used in the implementation of the algorithm. Introduced the augmented Lagrangian function ζ, kicking direction multiplier method, a series of iterative optimization, find the ζ minimum value:

\[
\zeta([u_k], \{a_k\}, \lambda) = \min \sum_{k=1}^{K} \left[ \| \delta(t) + \frac{j}{\pi t} u_k(t) \|^{2} \right]^{1/2} + \left\| f(t) - \sum_{k=1}^{K} a_k u_k(t) \right\|^{2} + \left\langle \lambda(t), f(t) - \sum_{k=1}^{K} a_k u_k(t) \right\rangle
\]

In the formula, “a” is the bandwidth parameter, \( \lambda(t) \) is the lagrangian multiplier.

The modal components are iterated directly in the frequency domain, and finally the inverse Fourier transform to the time domain. The VMD method can overcome the shortcomings of modal aliasing and frequency effect that appear in the recursive decomposition algorithm such as empirical modal decomposition, and has good noise robustness and noise reduction effect. It has been applied in signal noise reduction, and its detailed theory is shown in references [2, 3]. Bearing damage may lead to motion stagnation, distortion of periodic acceleration signals, or superposition of high-frequency signals. Therefore, the VMD method can effectively separate the high frequency noise from the signal.

3.2 Application of VMD method in the field of bearing failure
VMD method is widely used in fault diagnosis of rolling bearings, fault features appear periodically in random signals in the form of pulses. It is difficult to obtain the fault characteristics of rolling bearing directly by the modal decomposition of the original vibration signal. Research has introduced the concept of spectral kurtosis, using VMD decomposed each order modal component (the intrinsic mode function, the IMF), and then calculate the corresponding component of the kurtosis value for its adaptive reconfiguration, then rapid spectral kurtosis analysis was carried out on the reconstructed signal, and band-pass filter design, according to the reconstructed signal is demodulated resonance after the line judge bearing failure[4]. For example, VMD parameters are optimized by means of the principle of minimum information entropy. Meanwhile, IMF where the minimum information entropy is located is obtained, and the envelope demodulation analysis is carried out on it to extract the characteristic frequency of bearing fault[5]. Or according to a kind of mean square error - Euclidean distance index selecting the IMF component containing abundant fault information for signal reconstruction, the reconstructed signal singular value decomposition for diagonal matrix singular values, combining the information entropy theory to calculate the diagonal matrix singular value of the entropy, using the singular value of entropy to distinguish between the size of the rolling bearing working state and fault type[6].

In the analysis of rolling bearing faults by VMD method, due to the large amount of original signal frequency information, the fault frequency will often be overlapped in the original signal, and too many or too few decomposition layers will lead to under decomposition or over-decomposition, resulting in modal aliasing. The application of spectrum kurtosis and information entropy is to obtain fault characteristic frequency accurately on the basis of VMD method.

3.3 Bearing state monitoring index
In the field of vibration test of aerospace products, the internal bearing of the sliding table is sliding bearing, and the resistance of the bearing movement after the formation of oil film comes from the liquid friction, so there is almost no noise generated when the healthy bearing moves. In addition, the vibration test of space products incudes sine sweep and steady-state random two kinds, in view of the limitations of VMD random vibration signal analysis, this paper uses the sine sweep test as sample data analysis, the bearing vibration response of oneness to ensure that the original signal fundamental frequency, is advantageous to the VMD process fault component extraction, and no need to make optimization method of VMD.

In the sine sweep frequency test, the bearing vibration response at the initial low frequency stage
contains fault characteristics. At this time, the fault characteristic frequency of friction caused by the fault of sliding bearing is much higher than the fundamental frequency of the normal vibration response of the bearing, while the vibration response signal of healthy bearing only exists after filtering out the noise interference. Therefore, the fault bearing can be accurately located only by screening out the response of other harmonic components besides the fundamental frequency signal. The decomposition layer number of 4 is sufficient in the VMD process below 10Hz.

The acceleration signals $x_i(t)$ of each bearing in a certain period of low frequency range are collected and intercepted. The data are decomposed into many modal sequences by variational modal decomposition like $u'_1(t), u'_2(t), \ldots, u'_n(t)$. $u'_i(t)$ is the time domain signal composed of the fundamental frequency of the original signal, other signals are the time domain signals corresponding to the residual harmonic frequency except the fundamental frequency. To facilitate the interpretation of the amplitude of harmonic components, the amplitude square of the original signal is separated from the amplitude square of $u'_i(t)$:

$$R_i(t) = x_i(t)^2 - u'_i(t)^2$$

(3)

“$t$” is the time range of intercept data, and the absolute value of variance of squares is taken to obtain the monitoring index of bearing status:

$$ENGR_i(t) = |R_i|$$

(4)

4. Test analysis

4.1. Test set

During the horizontal vibration test of a product with a mass of nearly 1 ton, the acceleration sensor monitoring the bearing state collected the response signal of abnormal bearing state. The equipment used in the test is the domestic 20-ton thrust electric vibration table, the size of the slide plate is 1.5m×1.5m, and a total of 16 bearings under the slide plate are distributed 4×4 uniformly. The test condition is 4~100Hz sine sweep frequency test, in which 4~8Hz is equal displacement input stage. In the frequency sweep process, burrs appear in the response curve of the bearing at the low frequency stage, which is most obvious when the vibration starts at 4Hz. Through preliminary interpretation, it is found that all the bearing responses have burrs, which is because the dry friction of the faulty bearing leads to the obstructed running of the sliding plate, and the other abnormal bearing responses are indirectly caused by the sliding plate. After further processing and analysis of the response data of each group, the fault bearing can be accurately located.

4.2. Data processing process

**Figure 3.** Typical acceleration time domain signal of bearing

Figure 3 shows the time-domain curve of typical bearing acceleration. Figure 3 (a) is the data collected
within a period of time after the sweep test reaches the initial position of the control spectrum; Figure 3 (b) is the data with certain changes in frequency and amplitude. The VMD method is suitable for the decomposition of unsteady signal, so the frequency of signal is allowed to have certain frequency conversion characteristics. Each bearing signal is decomposed, and the number of decomposition layer is 4. Figure 4 shows the curves of each layer after data decomposition of group a and group b. The first layer of data is the basic frequency waveform of the signal, and the second layer to the fourth layer are all high order frequency waveform. It can be seen that higher-order frequency waveform will appear “burr” at the corresponding position of peak and trough of the original signal.

![Figure 4. Data decomposition results of two groups](image)
(a)Data decomposition results of group a  
(b)Data decomposition results of group b

Calculate according to formula 3 and formula 4, and draw the index waterfall diagram (Figure 5.). It can be seen from the figure that the bearing No. 4 shows significant spikes in the intercept time range. It can be seen that the method proposed in this paper can effectively identify the bearing numbers in abnormal states.

![Figure 5. Bearing condition test results](image)
(a)Test results of group a  
(b)Test results of group b

4.3. Analysis instructions
After locating No. 4 bearing as a failure bearing through variational mode decomposition method, the
test personnel removed the horizontal slide plates of the vibration table and checked each bearing state one by one. Only No. 4 bearing showed wear. See the figure 6 for details.

**Figure 6. Physical drawing of bearing wear**

Due to the role of the bearing monitoring system, the fault bearing was found and positioned at the early stage of failure. The monitoring system effectively avoided the possibility of bearing problems worsening or even locking, and ensured the safety of test products.

5. Conclusion
As an effective evaluation method, the embedded acceleration monitoring method is suitable for fault diagnosis of multi-guide rail or multi-bearing sliding platform. A monitoring sensor is installed inside the sliding plate for each bearing in an embedded way, which can ensure the accuracy of bearing status indicator positioning. Status indicators evaluation to realize online synchronous calculation, after the own law, has the good real-time and intuitive, in the early stages of the abnormal state of bearing, effectively avoid shaker fault caused by damage to the product structure seriously, research is of great significance to the success of space products, and the production development of shaker has very good reference value.

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