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Chinese Journal of Aeronautics 20(2007) 253-259
Chinese Journal of Aeronautics
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Research on Feature Extraction of Remnant Particles of Aerospace Relays

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Received 21 July 2006; accepted 5 February 2007

Abstract

The existence of remnant particles, which significantly reduce the reliability of relays, is a serious problem for aerospace relays. The traditional method for detecting remnant particles—particle impact noise detection (PIND)—can be used merely to detect the existence of the particle; it is not able to provide any information about the particles' material. However, information on the material of the particles is very helpful for analyzing the causes of remnants. By analyzing the output acoustic signals from a PIND tester, this paper proposes three feature extraction methods: unit energy average pulse durative time, shape parameter of signal power spectral density (PSD), and pulse linear predictive coding coefficient sequence. These methods allow identified remnants to be classified into four categories based on their material. Furthermore, we prove the validity of this new method by processing PIND signals from actual tests.

Keywords: feature extraction; aerospace relays; remnant particles; particle impact noise detection

1 Introduction

Aerospace relays are widely used in the national defense and aerospace systems, and their quality directly influences the performance of the aerospace sector as a whole. However, the effectiveness of most relays, especially domestic products, is restricted by poor production techniques that can leave remnants of scrap metal, wire pieces, tin dregs left over from the soldering process, as well as rosin and sealant. During operation of the aerospace relay system, outer vibration and concussion cause remnant particles to collide randomly. This can lead to false triggering of the relays, system inactivation, or even catastrophic system failure. So a solution for eliminating remnant particles from relays is urgently needed for aerospace development.

PIND is a test for detecting remnant particles that is commonly used by aerospace relay manufacturers worldwide before a relay system can leave the factory. It was made compulsory by military specifications MIL- STD-883E[1-2] and national specifications GJB65A- 91, and GJB2888-97 in China. The typical structure of a PIND test system is shown in Fig.1.

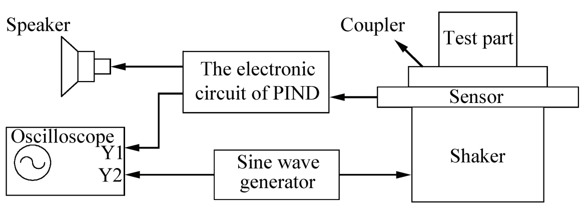

Fig.1 PIND test system specified by MIL-STD-883E_2020.7.

The PIND test is performed by placing the test part upon an acoustic sensor, which is mounted on top of a vibration shaker. The vibration shaker generates a series of mechanical vibrations, at specified

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Foundation item: China Science Technology and Industry Foundation for National Defense (FEBG 27100001)

frequencies, that agitate the restricted remnant particles. Because wave vibrations result in acoustic waves, the remnant particles then collide with the wall of the package at a specified frequency. These waves are converted into electrical signals by the transducer, and the operator can then determine whether remnant particles exist within the relay.

In the traditional PIND method, the operator judges the output signals either by watching the waveform on an oscilloscope or by listening to the sound from a speaker. However, this can cause failures to detect remnant particles or to register false alarms because of operator fatigue, negligence, and lack of experience[3]. Moreover, the PIND method can only detect the presence of remnant particles; it cannot provide detailed information such as material type, size, and weight of particles. This information would be very helpful for relay producers to find the causes of remnant particles and to make improvements in future designs.

After classifying the remnant particles into four categories, this paper proposes three feature extraction methods appropriate for each classification. Application indicates that the method is valid.

2 Characteristics of PIND Output Signals and Classification of Particles

There are three kinds of signals from the output of PIND testers: particle signals, component signals, and noise[4]. We focus on particle signals, and the working frequencies of particle signals ranging from 150 kHz to 160 kHz. A component signal is the sound generated by the movable components of a relay, such as armatures and springs, under external stimulation. Methods for distinguishing between the component signal and particle signal have been previously researched[4]. This paper mainly focuses on the feature extraction of particle signals under noise conditions, such as power source disturbances, environmental noise, and sensor noise.

After comparing the PIND output data from many common remnant particles, the particles have been classified into four categories:

A: metal particles with strong elasticity coefficient (such as tin dregs);

B: metal particles with weak elasticity coefficient (such as copper wire and ferromagnetic particles);

C: nonmetal particles with strong elasticity coefficient (such as rosin and glass scrap);

D: nonmetal particles with weak elasticity coefficient (such as rubber).

As proved by the experience of some relay producers, the physical characteristics of the 4 aforementioned categories are distinct, and therefore helpful for designers to locate the causes of remnant particles.

3 Preprocessing

Through FFT analysis of the original signal, the power spectral density distributes are mainly in 0-200 Hz and 150-160 kHz ranges[5]. Fig.2 and Fig.3 show the signal in the time domain and frequency domain, respectively.

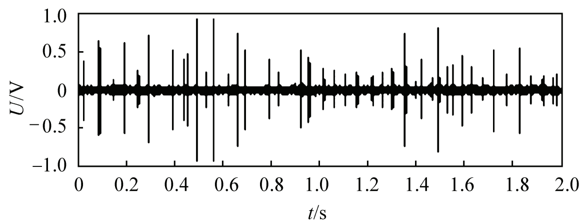

Fig.2 Waveform of PIND output sound signal.

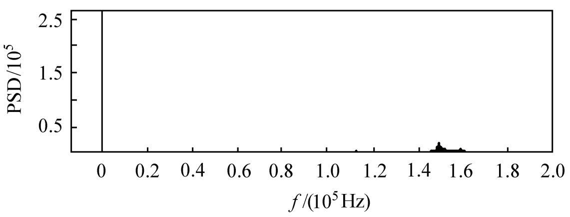

Fig.3 PSD of PIND output sound signal.

In the interval 0-200 Hz, the signal is composed of power source noise with 50 Hz and shaker noise with vibration frequency. However, in the interval 150-160 kHz the signal consists of sensor output; this is because of the collision between remnant particles and the shell of the relay. As information about the particles mainly comes from a sensor, a band-pass filter is used for original data processing. Many traditional methods with feature parameters in time domain (such as mean value, and standard deviation) and frequency-domain (such as harmonic component) have been tried. However, all of these parameters are very unstable—there exits a great difference even from the same relay under different test conditions. Furthermore, it is difficult to find the common character parameters for a specific sort of remnant. Consequently, it is difficult to extract the remnant particles directly, using the original signals results because of the instability of the feature parameters. Due to the complexity of relay structures and the independence of external vibrations, the impact time and initial velocity of collisions are almost random. The duration of every impact pulse is very short (a few milliseconds). The sum of them is only about 10% of the total sampling time, while the rest is the interval between pulses. Intervals with random lengths cause many unstable factors with traditional feature parameters, and weaken many characteristics of those impact pulses. Consequently, a new preprocessing method is proposed that removes the pulse interval before extracting the feature (as shown in Fig.4).

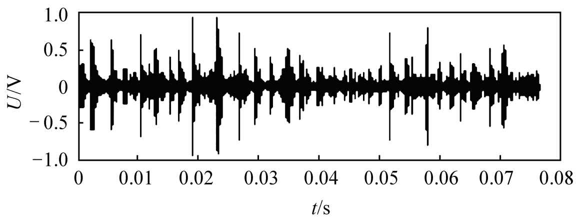

Fig.4 Waveform of signal without the interval background signal.

From the PIND output signal, it is obvious that the initial energy of a pulse increases rapidly until reaching the maximum. However, the attenuation process needs a long time. The “three thresholds detecting algorithm” is used for picking out the pulses in this paper. The basic principle is to divide the PIND output signal into many frames, with each frame about 10 μs in length. Then the energy of each frame is calculated and compared to the frame energy with a threshold T_h to find the body of the pulse. Finally, a search is made from the starting point forwards, as well as end point backwards from the body of pulse. This is done by recalculating the frame-energy with 5 μs step and comparing them with the lower thresholds T_{ls} and T_{le}. The suitable values of T_h, T_{ls} and T_{le} can be obtained through this experiment, $T_h=4\overline{V}$, $T_{ls}=\overline{V}$ and $T_{le}=\overline{V}$, where is the mean value of the sampling data. Fig.5 and Fig.6 show the extraction process.

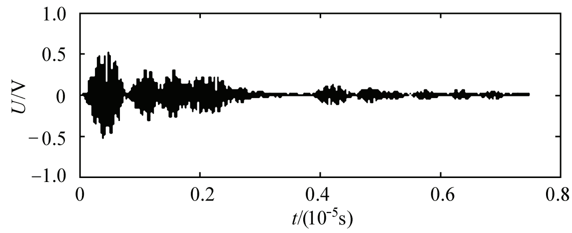

Fig.5 Waveform of PIND output signal pulse.

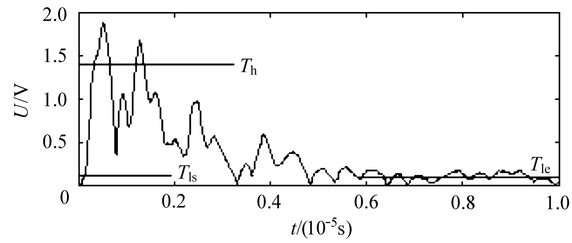

Fig.6 Start-end point detection method with three thresholds.

4 Definition of Feature Variable

4.1 Unit energy average pulse durative time

The durative time of a pulse is different among the various particles because of their diverse elasticity coefficients and unpredictable initial impact speed. The first feature variable is defined in Eq.(1) as the average durative time per energy.

$$\overline{t}_p = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{t_{pi}}{u_{RMS}}\right) \tag{1}$$

where N is the number of pulse in the total sampling time, t_{pi} is the durative time of ith pulse, u_{RMS} is the energy (the RMS amplitude) of the ith pulse.

Our experiment shows that $\overline{t}_p$ of particles from different classifications varies, and the sequence of four categories is: $t_{p-D} > t_{p-C} > t_{p-B} > t_{p-A}$. However, the range of each category is different for different relay structures. The detection thresholds for $\overline{t}_p$ are determined through experimentation, and Table 1 shows the ranges of model JQX-40MD relay for four kinds of particles.

Due to the structural complexity of aerospace relays and differences in particle materials, size, shape etc., it is difficult to find a certain feature variable to distinguish the material of particles. This paper proposes three different feature variables to facilitate that judgment.

Table 1 Detection thresholds for average durative time per rosin energy

Class of remainder	A	B	C	D
Detection thresholds range/(ms·V^{-1})	0-4.1	4.1-5.3	5.3-9.0	≥9.0

The average durative time per rosin energy has a direct relation with the elasticity coefficient of the particle material, and it thus reflects important information about the particles.

4.2 Shape parameter of signal power spectra density (PSD)

Analysis reveals that the PSD of the preprocessed PIND output signal mainly distributes in the 150-160 kHz range, and the PSD shape looks like a triangle. Fig.7 and Fig.8 represent the typical PSD output signals for tin dregs and rubber scrap.

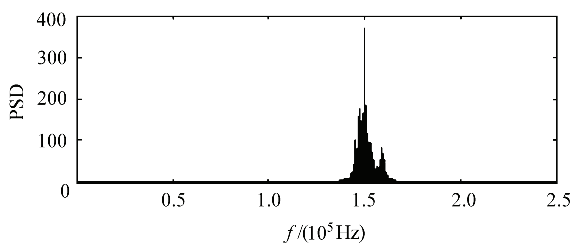

Fig.7 PSD of PIND output sound signal for tin particles.

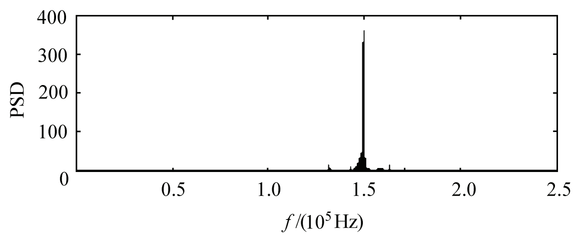

Fig.8 PSD of PIND output sound signal for rubber particles.

It is obvious that the shape of various particles is different. For example, the shape of metal particles is plump and looks like a pear, and the shape of non-metal particles is thin and sharp, similar in appearance to an upside-down cane. In order to describe this feature, the author defines the shape parameter of signal PSD, which is the ratio of S_1 and S_0. The area of the PSD in the frequency axis range 145-165 kHz is S_1, and the area of triangle formed by the segment frequency axis range 145-165 kHz is S_0.

The shape parameter of signal PSD is as follows

$$\eta = \frac{S_1}{S_0} \tag{2}$$

The experiment shows that the parameter η is insensitive to a particles' mass, vibration acceleration, speed, and structure of the relay. However, it is only effective to distinguish between metal (Class A, Class B) and non-metal (Class C, Class D) particles. The detection threshold achieved by experiment is:

metal particles: $\eta \geqslant 0.1$

non-metal particles: $\eta < 0.1$

The shape parameter of a signal is a function of the ratio between main frequency section and other harmonics. It is simple, but robust, under many conditions of PIND and has the reliability required for different relay of structures.

4.3 Pulse linear predictive coding coefficient sequence

Linear prediction is a parameter estimate method based on autoregressive (AR) model. Suppose the target signal arrays correlate with each other, the signal can be estimated with the output of a full poles linear model (as shown in Eq.(3) and Fig.9). White noise input, and the least RMS rule are often used for this estimation[6].

$$H(z) = \frac{G}{1 - a_1 z^{-1} - a_2 z^{-2} \cdots - a_m z^{-m}} \tag{3}$$

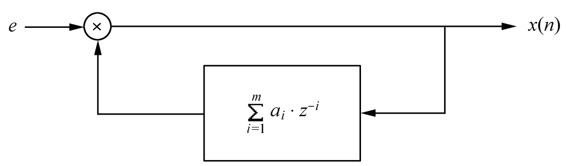

Fig.9 Model of the full-poles system for linear predictor coefficients analysis.

In this paper, the output signal (impact pulse) can be considered as a determinate signal, and within the scope of one pulse every sample point can be estimated with linear combinations of the former sample values. This relationship can be illustrated with Eq.(4).

$$x(n)=\sum_{i=1}^{m} a_i \cdot x(n-i) \tag{4}$$

where $x(n)$ is the sample point of signal in time n, $x(n-i)$ is the former sample values of $x(n)$, a_i is the coefficient of linear combinations.

There is no precise method to calculate the rank of a coefficient array. One common method, with a minimum amount of error, is to find the appropriate rank through ransack[7]. This paper utilizes the LPC array as a character value for classification purposes, not for reconstruction, so the level of precision does not need to be too high.

Some experiments were carried out with different rank of LPC array. These results indicate that the values of coefficients in rank 9 or higher are very small, so rank 8 is selected as the optimal rank. In the calculation method for LPC array, auto-correlation equations and Levinson-Durbin[8] recursion algorithm are used.

Adequate amounts of arrays are required to accomplish a precise classification. There are many pulses in the sampling time, and each pulse can be expressed by a LPC array. By applying weight calculations to each pulse energy (the RMS amplitude), the mean LPC array can be obtained as

$$\{\hat{a}\}=\frac{1}{m}\sum_{i=1}^{m} A_i \cdot \{a_i\} \tag{5}$$

where $\{\hat{a}\}$ is the weighted mean LPC array in total sampling time, $\{a_i\}$ is the LPC of the No.i pulse, A_i is the RMS amplitude of No.i pulse, m is the number of pulse in the sampling time.

In order to obtain the relationship between different LPC arrays and different remnant particles, this paper carried out PIND tests. The LPC arrays were classified into four kinds of same mass particles (rubber, tin, copper line and rosin), same vibration acceleration, and different vibration frequencies. The LPC arrays are obtained in different vibration frequency (20-120 Hz with frequency step of 10 Hz), which are shown from Fig.10 to Fig.13.

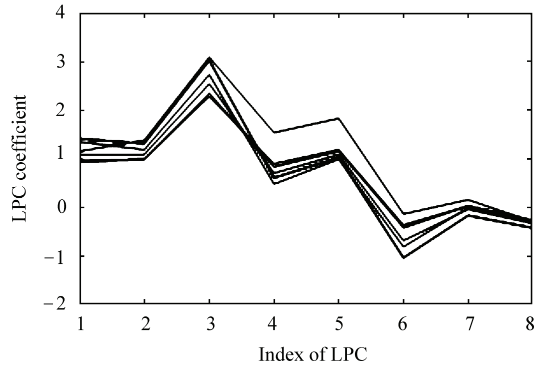

Fig.10 LPC array chart from PIND output signal with rubber particles under different frequencies.

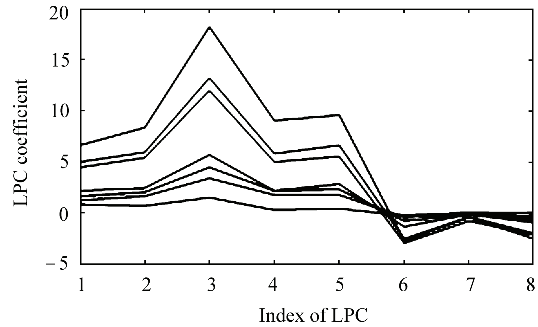

Fig.11 LPC arrays chart from PIND output signal with tin particles under different frequencies.

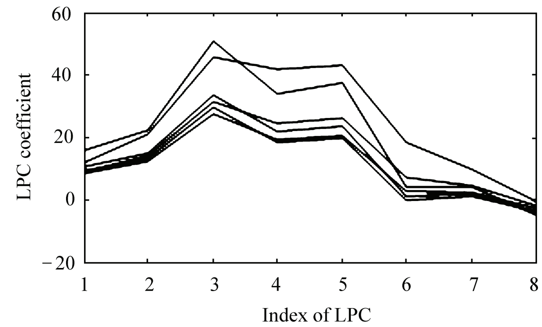

Fig.12 LPC arrays chart from PIND output signal with copper line under different frequencies.

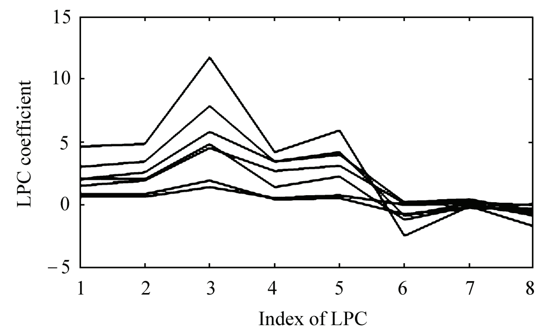

Fig.13 LPC arrays chart from PIND output signal with rosin particles under different frequencies.

The two frequencies with the shortest distance of the average LPC array are fixed for each kind of particle, making them good characters for analysis. The results achieved from the experiment are shown as follows (the following are vibration frequencies for the 4 different classifications of remnants):

A: LPC arrays in 50 Hz and 60 Hz have the shortest distance;

B: LPC arrays in 90 Hz and 100 Hz have the shortest distance;

C: LPC arrays in 60 Hz and 100 Hz have the shortest distance;

D: LPC arrays in 50 Hz and 100 Hz have the shortest distance.

It is easy to classify the remnant particles by PIND tests with the four special vibration frequencies (50, 60, 90 and 100 Hz). The distance of LPC arrays, under different vibration frequencies stands for the sensitivity of particles to the external condition.

4.4 Synthesis of multiple feature variables

Due to the complexity of PIND output signal, three of the feature variables above need to be considered together to make a comprehensive and effective judgment. In this paper, a grading method is used to accomplish synthesis of the three variables, and marks are assigned as follows: average durative time per energy: 25; shape parameter of signal PSD: 25; LPC array: 50. Based on this method, the total marks of each category are obtained, and the category with the top mark used to determine classification. The credence of this kind of judgment is

mark <50: invalid

50≤mark <100: relatively effective

mark =100: effective

5 Applications

In order to prove the validity of this method, the PIND test was carried out on 25 Model JQX-40MD aerospace relays. Each relay had some special remnant particles remaining inside, including metals (tin, copper wire, and iron scrap) and non-metals (rubber, rosin, and chip shell). The mass of the particles in each relay was around 0.1 mg.

The condition of the PIND test is:

impulse: 200 g, 3 times

vibration: 20 g, 50 Hz, 5 s

impulse: 200 g, 1 time

vibration: 20 g, 60 Hz, 5 s

impulse: 200 g, 1 time

vibration: 20 g, 90 Hz, 5 s

impulse: 200 g, 1 time

vibration: 20 g, 100 Hz, 5 s

The results of these tests are shown in Tables 2-5, which verify that the effectiveness rate exceeds 80%.

Table 2 PIND test result of relays with tin particles

Average durative time per energy/ $(s\cdot V^{-1})$	Shape parameter of signal PSD	Frequencies for LPC array with minimum distance	Mark and result
2.26	0.130	50,60 Hz	A (100)
3.43	0.152	50,60 Hz	A (100)
2.58	0.221	50,60 Hz	A (100)
1.04	0.099	50,90 Hz	Invalidate（25）
6.22	0.110	50,60 Hz	A (75)
3.58	0.052	50,100 Hz	D (75)
4.10	0.103	50,60 Hz	A (75)
6.02	0.156	50,60 Hz	A (100)

Table 3 PIND test result of relays with copper lines

Average durative time per energy/ $s\cdot V^{-1}$	Shape parameter of signal PSD	Frequencies for LPC array with minimum distance	Mark and result
4.25	0.502	90,100 Hz	B (100)
4.61	0.112	60,100 Hz	Invalidate(50)
5.23	0.331	50,60 Hz	Invalidate (50)
5.49	0.201	90,100 Hz	B (75)
3.55	0.105	90,100 Hz	A (75)
5.11	0.117	90,100 Hz	B (100)
2.34	0.056	90,100 Hz	Invalidate (50)
5.29	0.042	90,100 Hz	B (75)

Table 4 PIND test result of relays with rosin particles

Average durative time per energy/ $(s\cdot V^{-1})$	Shape parameter of signal PSD	Frequencies for LPC array with minimum distance	Mark and result
6.22	0.041	60,100 Hz	C(100)
5.50	0.033	60,100 Hz	C(100)
5.31	0.076	50,100 Hz	Invalidate (50)
6.01	0.093	60,100 Hz	C(100)
7.21	0.067	90,100 Hz	Invalidate(50)
7.45	0.121	60,100 Hz	C(100)
2.58	0.080	60,90 Hz	Invalidate (50)
3.01	0.054	60,100 Hz	C(100)

Table 5 PIND test result of relays with rubber particles

Average durative time per energy/ ($s\cdot V^{-1}$)	Shape parameter of signal PSD	Frequencies for LPC array with minimum distance	Mark and result
9.11	0.060	50,100 Hz	D(100)
10.25	0.067	50,100 Hz	D(100)
11.20	0.134	50,100 Hz	D(75)
8.01	0.091	50,100 Hz	D(100)
10.65	0.084	50,100 Hz	D(100)
9.21	0.049	60,100 Hz	Invalidate (50)
9.54	0.125	50,100 Hz	D(100)
7.01	0.059	50,100 Hz	D(75)

6 Conclusions

Through classifying common remnant particles into four categories based on output sound signals in a PIND tester, three feature extraction methods were proposed, and some valuable conclusions gained.

(1) The preprocessing method of eliminating pulse intervals is helpful for increasing stability of the feature variables.

(2) Unit energy average pulse durative time is valuable for classifying remnants into four groups, but the thresholds need to be individually set for different relay structures.

(3) Shape parameter of signal PSD is helpful to distinguish metal and nonmetal particles, and it is effective under different test conditions.

(4) Pulse linear predictive coding coefficient sequences are a good feature for classification, but much more calculation is needed to make their use precise.

(5) The mark-grading method of synthesis is a kind of linear weighted method for variables. It is simple and practical to use, and has a high level of precision. Consequently some other complex synthesis methods like artificial neural network (ANN) are suggested.

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