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## Study on Damping Characteristics of Tilting-Pad Gas Seals Based On Random Decrement Method

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# Study on Damping Characteristics of Tilting-Pad Gas Seals Based On Random Decrement Method

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**Abstract.** The influence of the airflow excitation force on the damping characteristics of the seals is an important index to evaluate the stability of seals. In order to verify the stability of the tilting-pad seals proposed by author, in this paper, an impact test is used to test the damping characteristics of the cylinder installed with tilting-pad seals and fixed-pad seals respectively. The multiple hammering signals are processed by the random reduction method to minimize the environmental and anthropogenic interference. Finally, a comparison has been carried out between these two seals under the same experimental conditions, and the result shows that the absolute damping factors of these two seals both decrease with the increase of rotor speed. However, the absolute damping factor of tilting-pad seals is bigger than that of fixed-pad seals, which indicates that the stability of tilting-pad seals is higher than that of fixed-pad seals.

## 1. Introduction

A new kind of gas seal named tilting-pad seal was proposed [1]. In order to verify the performance of tilting-pad seal, comparative test of fixed-pad seal and tilting-pad seal has been carried out. It is well known that the damping characteristic of the cylinder installed seals is an important index to evaluate the stability of seals. The damping characteristics are compared by analyzing the logarithmic attenuation rate of the cylinder installed these two kinds of seals respectively. The common methods of damping characteristic test include half-power bandwidth method and logarithmic attenuation rate method. The latter can be carried out by hammering test, because this test is simpler and more useful. But in the actual testing process of cylinder damping characteristics, because the rotor is in rotational state, there are many kinds of interference factors such as motor interference, pneumatic noise, dynamic impact on the test environment, so that the measured cylinder attenuation response waveform will contain a wealth of broadband noise. Moreover, because the strength and direction of each hammering test depends entirely on the experience of the experimenter, it is difficult to reach the ideal state. If only a single attenuation signal is selected to filter the damping coefficient of the cylinder, the error will be very large. In order to eliminate the uncertainty of the data obtained from the single hammering test and to make the identified cylinder damping characteristics more accurate, this paper introduces the random decrement method (RDM) to deal with the original attenuation waveform of the multiple cylinder hammering tests.



## 2. Analysis Algorithm

RMD is mainly used to eliminate or reduce the random components from many stationary response samples of the linear vibration system by means of average and mathematical statistics to obtain the free response signal under certain initial excitation. The main idea is to distinguish the deterministic vibration signal from the random vibration signal in the measured vibration response signal, by using the property that the mean value of stationary random signal is zero to separate the deterministic signal from the random signal. Finally, an accurate free attenuation vibration signal is obtained. The details are as follows.

For a linear system, the forced vibration response of a given measuring point under arbitrary excitation can be expressed as,

$$y(t) = y(0)D(t) + \dot{y}(0)V(t) + \int_0^t h(t-\tau)f(\tau)d\tau \quad (1)$$

$D(t)$  is the free vibration response of the system with initial displacement 1 and initial velocity 0.  $V(t)$  is the free vibration response of the system with initial displacement 0 and initial velocity 1.  $y(0)$  and  $\dot{y}(0)$  represent the initial displacement and initial velocity respectively.  $h(t)$  is the function of system vibration under unit impulse.  $f(t)$  represents external excitation. Selecting an appropriate constant  $A$  to intercept a structural measured random vibration response signal  $y(t)$ , a series of different intersection points  $t_i$  ( $i=1, 2, N$ ) can be obtained. The response  $y(t-t_i)$  from the  $t_i$  moment can be regarded as a linear superposition of three parts, that is, the free vibration response caused by the initial displacement of the  $t_i$  moment, the free vibration response caused by the initial velocity of the  $t_i$  moment and the forced vibration response caused by the random excitation of the  $f(t)$  beginning at the  $t_i$  moment. The formula is as follows,

$$y(t-t_i) = y(t_i)D(t-t_i) + \dot{y}(t_i)V(t-t_i) + \int_{t_i}^t h(t-\tau)f(\tau)d\tau \quad (2)$$

Since the excitation  $f(t)$  is stationary and the starting point of time does not affect its random properties, a series of time starting points ( $t_i$ ) of  $y(t-t_i)$  can be moved to the coordinate origin. And the subsample function  $x_i(t)$  ( $i=1, 2, \dots, N$ ) of a series of random processes can be obtained as,

The statistical average of the above formula is obtained as,

$$x_i(t) = AD(t) + \dot{y}(t_i)V(t) + \int_0^t h(t-\tau)f(\tau)d\tau \quad (3)$$

$$\begin{aligned} x(t) &= \frac{1}{N} \sum_{i=1}^N x_i(t) \approx E[AD(t) + \dot{y}(t_i)V(t) + \int_0^t h(t-\tau)f(\tau)d\tau] \\ &\approx AD(t) + E[\dot{y}(t_i)]V(t) + \int_0^t h(t-\tau)E[f(\tau)]d\tau \end{aligned} \quad (4)$$

Since the mean value of excitation  $f(t)$  is 0, also the system vibration response  $y(t)$  and  $\dot{y}(t)$  both are stationary random vibration with a mean value of 0, that is,  $E[f(t)]=0$ ,  $E[\dot{y}(t_i)]=0$ , The equation (4) can be simplified to,

$$x(t) \approx AD(t) \quad (5)$$

The free vibration response with the initial displacement of  $A$  and the initial velocity of 0 is obtained. Using the obtained free vibration response as the input data, the dynamic parameters of the measured system can be obtained by time domain identification of modal parameters.

### 3. Damping Characteristic Test Method

In this paper, a method of logarithmic attenuation rate is used to determine the damping characteristics of cylinder installed seals, which is a common time domain method. The cylinder is regarded as a single degree of freedom system, and the damping free response formula of the system is as follows,

$$X = Ae^{-\zeta\omega t} \cos(\sqrt{1-\zeta^2}\omega t + \phi) \quad (6)$$

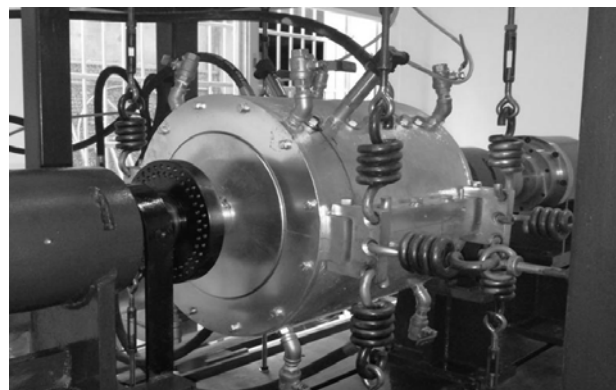
In the equation,  $e$  is the base of natural logarithm,  $\zeta$  is the damping factor. For the attenuation response, the factor  $\zeta$  is negative and the greater the absolute value is, the faster the attenuation is, it is illustrate that the system have higher stability.

First, the original waveform of the multiple attenuation response of the cylinder was measured by hammering the cylinder several times from vertical and horizontal directions. Secondly, since each hammering test is performed manually, it is difficult to ensure that the force and direction of the stroke are exactly the same. The multiple attenuation waveforms are processed by RDM, and a more accurate single attenuation waveform is obtained. Finally, a suitable region of the attenuation signal is intercepted and fitted by the equation (6), the damping characteristics of the cylinder are obtained by fitting calculation.

The force signal of each stroke is picked up by CL-YD-305A force hammer as the figure 1 show. And the  $x$  and  $y$  vibration response signals of the cylinder are obtained by the velocity sensors, which are attached to the horizontal and vertical directions of the cylinder. The sampling frequency is 10 kHz, and each sampling time is 10 S. The rotor speed range 0 ~ 3000rpm, the inlet air pressure range 0~0.6 MPa. The cylinder photo of test rig is shown in Figure 2.



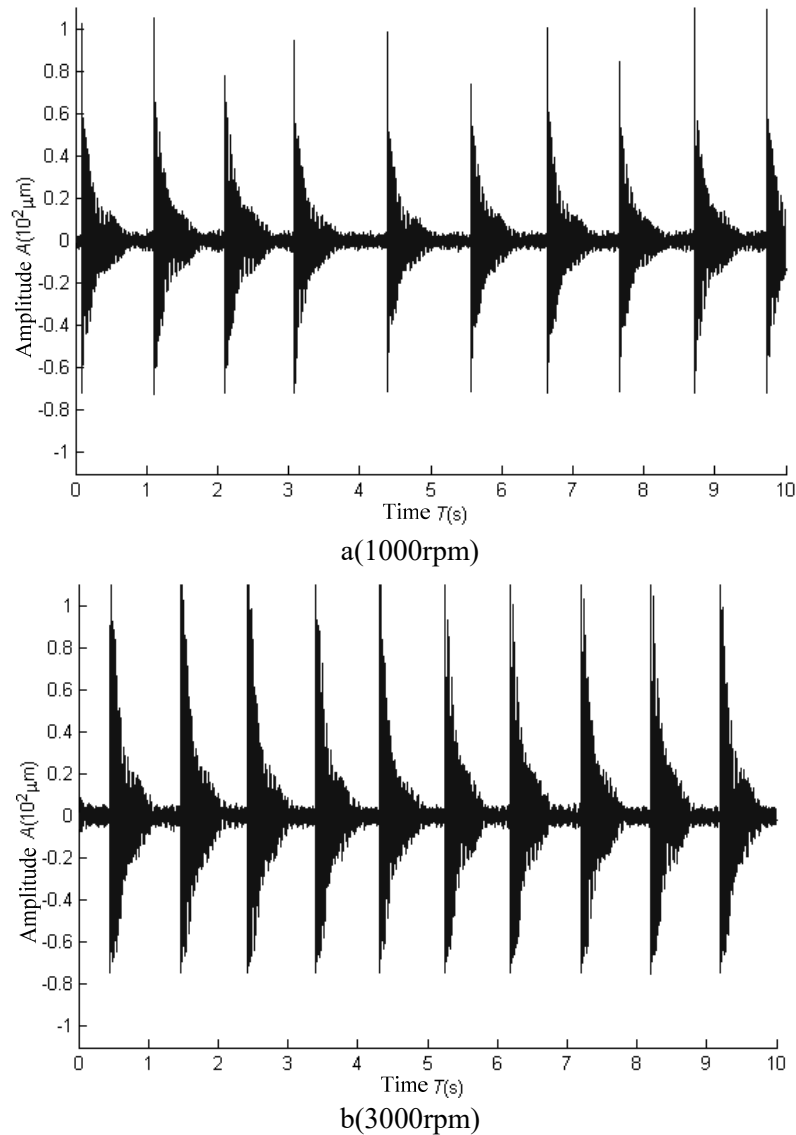
**Figure 1.** CL-YD-305A force hammer



**Figure 2.** Cylinder of Test Rig

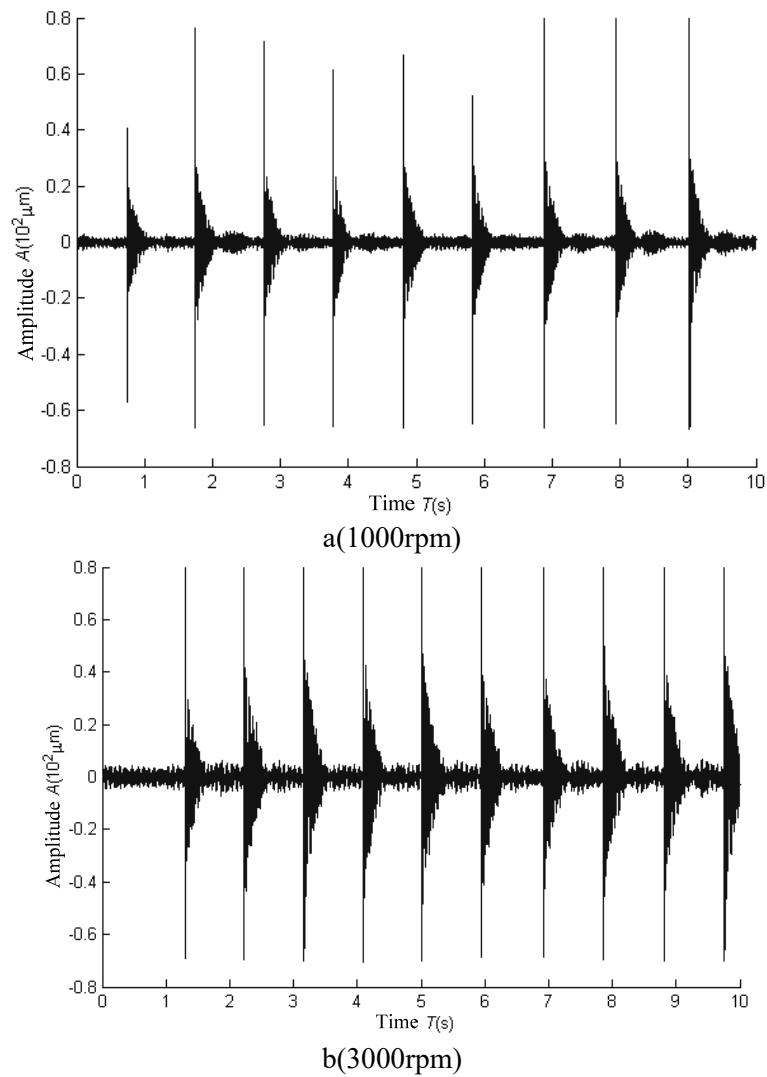
## 4. Test Results Analysis

### 4.1. Comparison of Original Attenuation Waveform of Two Kinds of Gas Seal



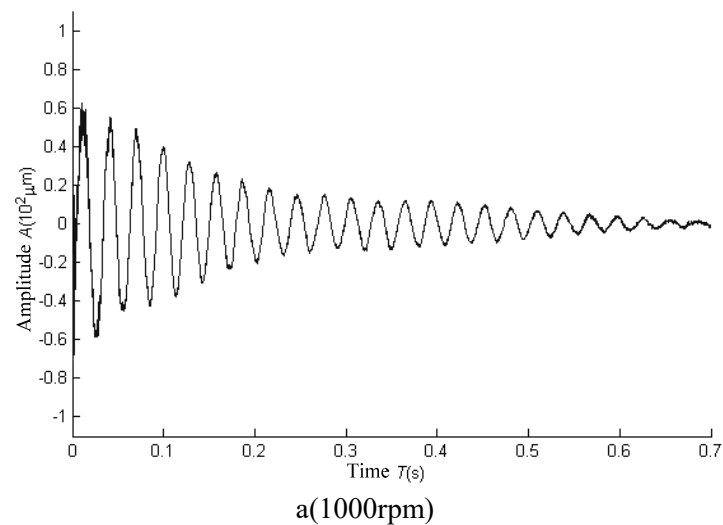
**Figure 3.** Original Waveform of Hammering Test for Fixed Seal Cylinder

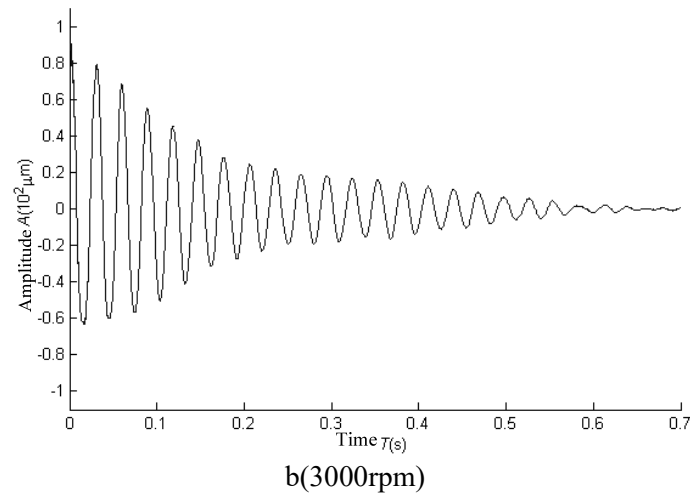
Comparative tests of fixed-pad seals and tilting-pad seals were carried out under the following conditions: the inlet pressure is kept at 0.5 MPa, the outlet pressure is 0.1 MPa, the rotor eccentricity is 0, and the rotor speed is from 1000rpm to 3000rpm, respectively. The Figure 3 shows the original waveform of hammering test for cylinder installed the fixed-pad seals, and the Figure 4 shows the similar result for cylinder installed the tilting-pad seals. From these diagrams, obvious attenuation waveforms can be seen, but careful observation shows that the noise signal between the two pulse signals is obvious, and the size of the noise signal cannot be ignored. It is difficult to keep the signal clean at the moment of hammer dropping when single original attenuation waveforms were magnified and observed. Furthermore, compared with Figure 3 and Figure 4, it is difficult to compare the damping characteristics between the original attenuation waveforms of these two seals.



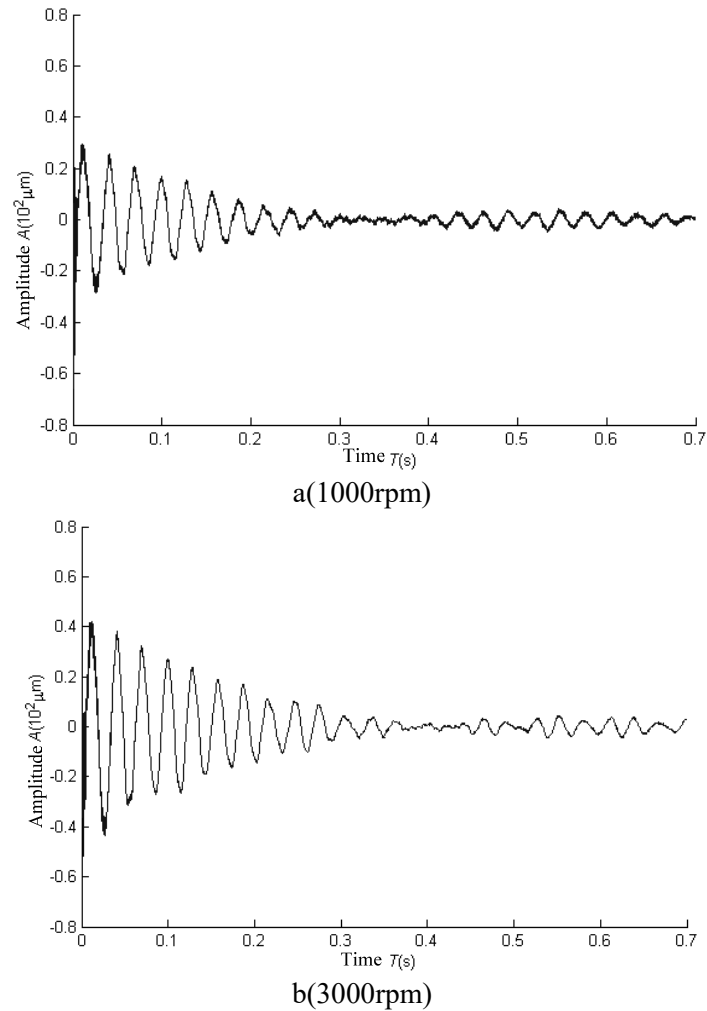
**Figure 4.** Original Waveform of hammering Test for Tilting-pad Seal Cylinder

#### 4.2. Comparison of Attenuation Waveform of Two Kinds of Gas Seal Treated by RDM





**Figure 5.** Attenuation Waveform Treated by RDM for Fixed Seal Cylinder



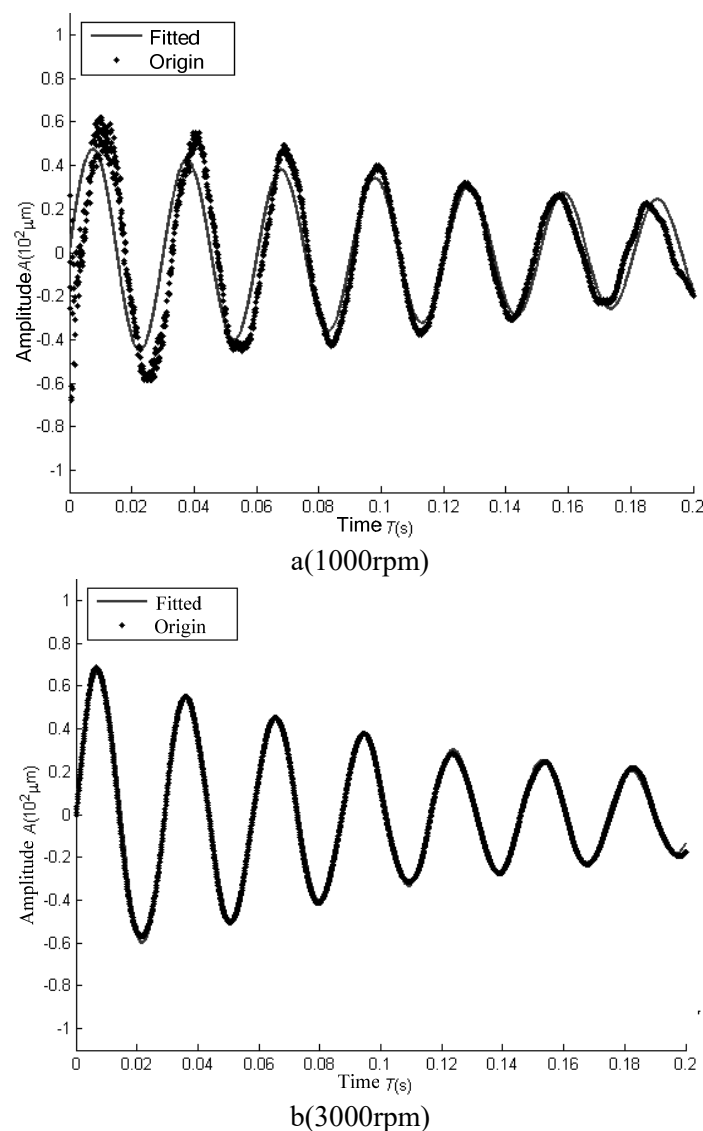
**Figure 6.** Attenuation Waveform Treated by RDM for Tilting-pad Seal Cylinder

Figure 5 and figure 6 show the processed attenuation signals of cylinder installed fixed-pad seals and tilting-pad seals respectively after filtering and RDM processing, from which we can see that the

processed attenuation waveforms are very clear, and because of the advantages of the RDM, the error caused by environmental influence and artificial uncertainty in hammering test signal is effectively controlled. However, it is not clear enough to compare the damping characteristics of the two seals directly from Figure 6 and Figure 7, so it is necessary to introduce damping factor  $\zeta$  to compare the damping characteristics of these two seals.

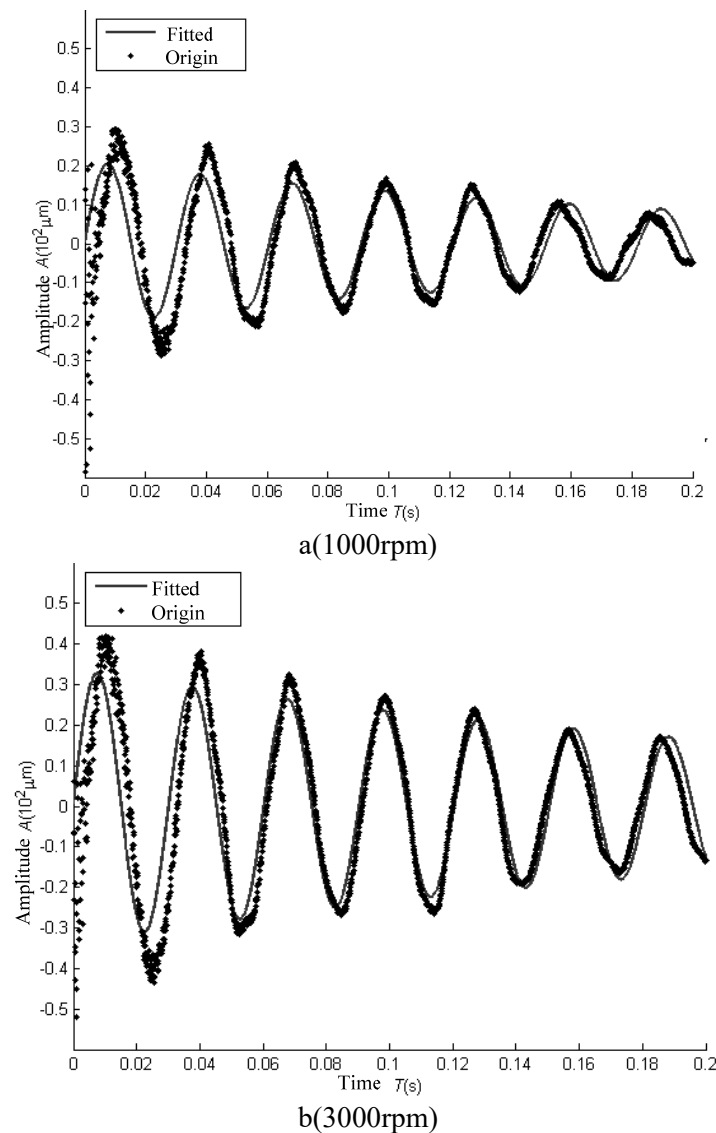
#### 4.3. Comparison of Damping Characteristic of Two Kinds of Gas Seal

Through the function fitting of the processed attenuation signal by Equation (6), two kinds of sealing damping factors  $\zeta$  can be obtained. Figure 7 and figure 8 show the fitting curves of attenuation signals for cylinder installed fixed-pad seals and tilting-pad seals respectively. It can be seen that the attenuation waveforms of the cylinder are basically consistent with the Equation (6).



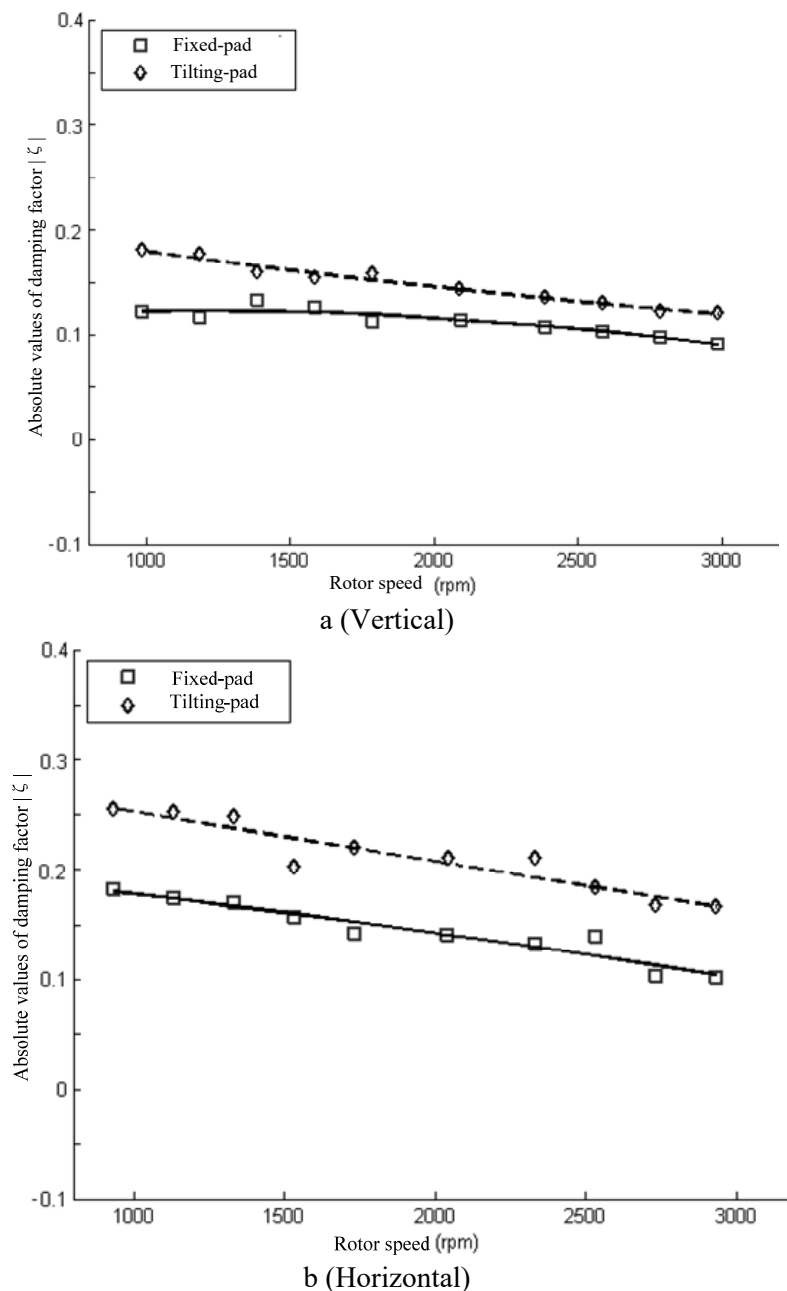
**Figure 7.** Attenuation Signal Fitting Curve for Fixed-pad Seals Cylinder





**Figure 8.** Attenuation Signal Fitting Curve for Tilting-pad Seals Cylinder

The damping factors of these two seals are calculated by fitting, the comparison results are shown in the Figure 9. Figure 9(a) and Figure 9(b) show the comparison result of damping factor  $\zeta$  for fixed-pad seals and tilting-pad seals from vertical and horizontal directions respectively. It can be seen from the diagrams that the absolute values of damping factor  $|\zeta|$  of these two seals decrease with the increase of rotor speed, which indicates that the increase of rotor speed will reduce the stability of the cylinder installed seals. In both directions, the absolute value of damping factor  $|\zeta|$  of tilting-pad seals is larger than that of fixed-pad seals, and the difference of horizontal direction is more obvious, the value of  $|\zeta|$  is about 1.5 times larger than that of fixed-pad seals. This indicates that the cylinder system equipped with tilting-pad seals attenuates faster and more steadily under pulse excitation.



**Figure 9.** Comparison of Damping Factors  $|\zeta|$  of Two Seals from Vertical and Horizontal Directions

## 5. Conclusion

In order to verify the stability of the tilting-pad seals proposed by author, in this paper, an impact test is used to test the damping characteristics of cylinder installed tilting-pad and fixed-pad gas seals respectively. The multiple hammering signals are processed by RDM which can reduce the impact of environmental and anthropogenic factors. The damping characteristics of the cylinder installed fixed-pad seals and tilting-pad seals are obtained by fitting calculation. A comparison have been carried out between these two seals under the same experimental conditions, and the result show that the absolute damping factor of these two seals both decrease with the increase of rotor speed. However, the results of vertical and horizontal damping factor identification show that the absolute value of damping factor

of tilting-pad seals is higher than that of fixed-pad seals, which further indicates that the stability of tilting-pad seals is higher than that of fixed-pad seals.

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