FLYWHEEL BEARING FAULT MONITORING BASED ON CLUSTERING FUSION OF NORMAL OPERATING ACOUSTIC PARAMETER

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The rolling bearings in flywheels are the core component of satellites. Its health condition plays a decisive role in the performance and the life of spacecraft. As the long-time test of flywheels on the ground, a convenient and reliable method for monitoring the operating state of abnormal bearings in flywheels is needed. Due to the unclear of fault mechanism and the insufficient of fault samples, a monitoring method based on the clustering fusion of normal operation acoustic parameter is proposed for abnormal of bearings. Firstly, the characteristics of flywheel’s acoustic signals and its feasibility are clarified based on the tests. Then, statistical parameters and sound quality parameters are introduced to characterize the changes caused by bearing anomalies, and root mean square, roughness and sharpness are selected to construct the feature vectors. The K-medoids clustering technology is used to fuse the feature parameters, and the safe distance of normal operating bearings can be obtained. Finally, the safe distance is used to judge the bearing abnormal condition of several types of bearings through test. The research results indicate that the presented monitoring method based on the clustering fusion of the normal operation acoustic parameters can not only identify various abnormalities (ball pitting, outer ring pitting, cage instability) of the flywheel bearing operation effectively, but also give quantitative evaluation of abnormal severity level.
Keywords: flywheels, fault monitoring, rolling bearing, clustering, acoustic

1. Introduction

Flywheels, which include moment wheel assemblies (MWAs) and Reaction wheel (RWs), have been widely used in spacecraft attitude control over the years in space. The high-speed rotating art of the flywheel is supported by a pair of angular contact ball bearings. Sometimes the bearings operate in abnormal conditions, accompanied with strong vibration, rising action moment and undesirable high temperature during service [1]. Long-life experiments of flywheel bearings on the ground are considered as a necessary and feasible solution. As the long-time test of flywheels on the ground, an effective and convenient health monitoring method is required to monitor the operating state of flywheels bearings [2]. Several techniques have been applied as operating state monitoring on rolling element bear-
ings so far, such as vibration [3], acoustic [4], acoustic emission [5], oil monitoring [6], et al. Among these methods, acoustic method is considered as a simple, convenient, and non-contact rapid measurement. Moreover, normal operation of flywheel could not be affected, and it is easy to conduct online monitoring [7]. Therefore, it can be applied in condition monitoring of flywheel bearings.

The recent research has mainly focused on heavy-duty bearings on the ground that the main fault modes are wear and pitting of rolling elements, inner ring and outer ring. Due to a vacuum and sealed environment, the fault modes of flywheel are significantly different from the heavy-duty bearings on the ground [8]. Moreover, there are not enough fault samples of flywheels and the failure forms have not been fully revealed. In view of the lack of fault samples, a method for monitoring bearing anomalies based on clustering fusion of normal operating acoustic parameter is proposed in the paper, and the method is verified by a series of experiments.

2. Characteristics comparison between acoustic and vibration signals

2.1 Acoustic and vibration test of flywheels

In order to verify the effectiveness of acoustic measurement and analysis, an experiment was performed by using a series of flywheel bearings under different conditions. During the test, the acoustic and vibration signal were obtained by using two sound transducers and an accelerometer separately. Fig. 1 shows a flywheel, an accelerometer, two sound transducers and a data acquisition equipment. As illustrated in Fig. 1, two sound transducers were positioned at the distance of 90 centimetres in front of flywheel with a 0 degree and 45 degree of the flywheel’s axis, while an accelerometer is fixed at the back of the supporter along with the flywheel’s axis. The experiment was executed three times for each flywheel with a sampling frequency of 25.6 kHz, and the acoustic and vibration signals from normal samples and abnormal samples with cage fault.

![Image of acoustic and vibration test of flywheel](image)

Figure 1: Acoustic and vibration test of flywheel.

2.2 Acoustic parameters variation under fault conditions

Considering various fault modes of flywheel bearing and according to different physical meanings of time-domain statistical parameters and sound quality parameters, root mean square (RMS), kurtosis, roughness and sharpness are selected as the characteristic parameters to check whether the acoustic properties have changed. These four parameters, which are calculated from the acoustic signals without DC component obtained from flywheels with normal bearings and abnormal bearings with cage fault, represent four different feature measurements of acoustic signals: RMS describes the intensity of dynamic signal; kurtosis describes the peak convex of probability density function; roughness describes the response from human being to the sudden change of acoustic signal, which is related to several
component such as modulated frequency, modulated amplitude, centre frequency, sound pressure, et al., and roughness can be utilized to reflect the variation of frequency properties; sharpness describes percentage of the high frequency component to the acoustic frequencies, which gives the harsh of acoustic signals. Whether acoustic signals can be used as an effective method for fault diagnosis of flywheel bearings will be validated by comparing the change of the above four parameters with cage fault. The four acoustic parameters can be calculated by use of the acoustic signals which were captured by the sound transducer right in front of the tested flywheel in the operating speed, see Table 1. The error in Table 1 is defined as the ratio of a parameter from a normal flywheel to that of a flywheel with cage fault.

<table>
<thead>
<tr>
<th>Normal flywheel</th>
<th>Fault flywheel</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS(g)</td>
<td>Kurtosis</td>
<td>Roughness</td>
</tr>
<tr>
<td>0.042</td>
<td>3.004</td>
<td>0.230</td>
</tr>
<tr>
<td>0.128</td>
<td>2.756</td>
<td>0.327</td>
</tr>
<tr>
<td>204.8%</td>
<td>-8.3%</td>
<td>42.2%</td>
</tr>
</tbody>
</table>

It can be seen from Table 1 that besides kurtosis, other three parameters from a flywheel with cage fault are larger than that of normal flywheel, which indicates a significant change of the components in acoustic signals after a cage fault appearance. Therefore, acoustic parameters can be utilized to define whether a flywheel bearing has cage fault or not.

2.3 Characteristic frequency comparison between acoustic and vibration signals based on EMD and HT

In order to further verify the validity of acoustic monitoring, the fault characteristics obtained from acoustic signal and vibration signal are compared. EMD is a self-adaptive signal processing method which was first put forward by Huang in 1998 [9]. A complicated signal can be decomposed into a set of complete and almost orthogonal components Intrinsic Mode Functions (IMFs) by EMD. EMD displays numerous advantages such as automatic production of basic function, self-adaptive filter, self-adaptive multi-resolution, etc., which is suitable for disposing nonlinear non-steady signal and has been widely applied in fault diagnosis of rolling bearings recently [8,10].

According to the approach proposed in Ref. [8], the fault features of cage fault, the most common failure mode in flywheel bearings [8] are extracted by using acoustic signals and vibration signals separately in this paper. In this method, the fault features included in the IMF component after EMD decomposition are selected by using the kurtosis, and then the fault features can be extracted based on the envelope demodulation method. The envelope spectrums are illustrated in Fig. 2. The characteristic frequency of a wear retainer bearing with an outer ring’s rotating speed of 3000r/min can be calculated as 30Hz. As illustrated in Fig. 2(a), a characteristic frequency of a wear retainer (30.2Hz) and its multiple frequencies (60Hz, 90.2Hz) can be identified. These characteristic frequencies are consistent with the predicted frequencies (30Hz, 60Hz and 90Hz), which indicate a cage fault in bearings based on the analysis of acoustic signal. However, although the characteristic frequency and its multiply frequencies can be found in Fig. 2(b), the peaks of these frequencies are too small to identify, and the indication of a cage fault is not clear enough. Therefore, the diagnosis of a cage fault using acoustic signals are prior to that of vibration signals.

In the light of the test results and analysis, it can be concluded that a cage fault can be easily identified using acoustic signals analysis. Moreover, comparing to vibration signals, acoustic signals are relatively suitable for the diagnosis of a cage fault and health monitoring of flywheels.
Monitoring method based on normal operation acoustic parameter clustering fusion

The purpose of state monitoring and evaluation of flywheel is to determine the possibility of flywheel failure and provide a guidance for later fault diagnosis or preventive measures so that the occurrence or aggravation of the fault will be prevented, and thus the normal utilization and the life of spacecraft will be guaranteed. During the operating process of the flywheel, the health status and the problems of every single flywheel are distinctive. Therefore, the characteristic parameters should not only include various types of fault states which could reflect global faults, local faults, shock faults, etc., but also can make the fault information from the original signal clearer. Due to the distinct sensitivity of different parameters to different faults, faults might not be identified effectively by using only one single characteristic parameter. Based on this, an acoustic state monitoring method based on a cluster fusion of multi-acoustic characteristic parameters is proposed. In light of the parameters analysis in Section 2.2, it is evident that the acoustic characteristic parameters such as RMS, kurtosis, roughness and sharpness can reflect the fault information from different aspects, which can be used as the characteristic parameters for fault monitoring.

The K-medoids clustering method is applied to perform the fusion of multiple characteristic parameters in this chapter. Since most of the test data come from normal specimen and the faults might appear by accident or unknown reason, it is difficult to carry out fault diagnosis and health monitoring by characteristic parameters’s comparison. In view of this, the characteristic parameters including RMS, kurtosis factor and sharpness based on normal specimens are used to monitor the state of flywheels. The normal boundary of flywheel acoustics is defined by the use of information fusion, which is applied to monitor abnormal state of flywheel. The abnormal monitoring method of flywheels is put forward in this paper, as shown in Fig. 3. As a preparatory step, the acoustic data of normal flywheel operation is attained by tests, then RMS, kurtosis factor and sharpness can be calculated. Based on this, the clustering space and its center can be achieved by using the fusion method of K-medoids clustering. Then the distance from every specimen to the center of clustering space is obtained. The safe distance, which is taken as the normal threshold, is then defined by using 5σ law. The acoustic tests are firstly
performed to the MWAs which are under monitoring, and the three characteristic parameters and the distance from every specimen to the center of normal clustering space can be calculated. Then the number of specimens which the distances exceed the normal threshold will be captured and the distance will be recorded, and the excess rate and the excess distances are used to identify the abnormal flywheel.

![Diagram](image)

Figure 3: State monitoring process of flywheels based on multi-acoustic characteristic parameters fusion.

4. Verification by Experiments

As the process listed in Fig. 3, the acoustic data from normal flywheels and fault suspected flywheels were acquired by a series of experiments. Two operating speeds of 3000r/min and 4600r/min were selected for the experiments, and 30 seconds data, which then are divided into 30 specimens, were captured at each operating speed for each flywheel. Hence, 30 seconds data from one of two normal flywheels were chosen to establish for a total of 60 specimens at a rotating speed of 4600r/min. Based on K-medoids clustering algorithm, the center of the clustering space is calculated as (0.072, 0.426, 2.305) while the radius is 0.461, and a clustering space sphere is created. Then the 30 seconds data from other flywheels were divided into 30 specimens to compare with the clustering space sphere, and the fault probability is defined by the number of the specimens which is out of the clustering space sphere to the total number of specimens. Thus the fault probability of each flywheel can be obtained as listed in Table 2. A comprehensive analysis, considering the excess rate, the maximum distance and the average distance, is then carried out to decide the fault severity of each flywheel.

It can be easily found out from Table 2 that the excess rates of #1, #3, #5 is much large than zero, and the distances of some specimens are far away from the center of the clustering space which indicates an abnormal state. After taking #1, #3, #5 flywheels apart, it can be detected a classical ball pitting fault, outer ring pitting fault and a wear fault between retainer and ball in bearings separately. The excess rate of 2# and 4# flywheel is relatively smaller, and the distance to the center of clustering space of 2# flywheel is larger than that of 4# flywheel though the excess rate is a little smaller. The results of the disassembly test shows that the preloading of #2 bearings were smaller than standard value in the axial direction, and no obvious pitting fault can be detected in #4 flywheel but slight characteristic frequency of outer ring can be found in the envelope demodulation spectrum. The excess rates of #6 and #7 flywheels are zero and the distances of specimens are quite close to the center of clustering space, and these two flywheels are then verified to be normal ones. Therefore, the approach proposed in this
paper will not misjudge the normal flywheels. In summary, the approach can be applied to monitor the health condition of flywheel bearings effectively.

<table>
<thead>
<tr>
<th>No.</th>
<th>Excess rate</th>
<th>Maximum distance</th>
<th>Average distance</th>
<th>Disassembly results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>63.33%</td>
<td>9.720</td>
<td>2.679</td>
<td>Ball pitting</td>
</tr>
<tr>
<td>2#</td>
<td>6.66%</td>
<td>16.516</td>
<td>0.825</td>
<td>Light preloading in axial direction</td>
</tr>
<tr>
<td>3#</td>
<td>93.33%</td>
<td>22.756</td>
<td>3.982</td>
<td>Outer ring pitting</td>
</tr>
<tr>
<td>4#</td>
<td>10%</td>
<td>1.270</td>
<td>0.503</td>
<td>No obvious pitting fault but slight characteristic frequency of outer ring</td>
</tr>
<tr>
<td>5#</td>
<td>100%</td>
<td>2795.867</td>
<td>707.961</td>
<td>Wear fault between retainer and ball</td>
</tr>
<tr>
<td>6#</td>
<td>0%</td>
<td>0.322</td>
<td>0.254</td>
<td>No fault</td>
</tr>
<tr>
<td>7#</td>
<td>0%</td>
<td>0.243</td>
<td>0.149</td>
<td>No fault</td>
</tr>
</tbody>
</table>

5. Conclusions

In order to detect the abnormal bearings in flywheel, a health monitoring approach based on the clustering fusion of acoustic parameters of normal operating flywheels is proposed in the paper. Conclusions can be derived upon the characteristic comparison and experiments verification in the following:

1. There is rich information about faults in acoustic signals from rotating systems in spacecraft, which can then be used to diagnose the faults of bearings. Therefore, acoustic signal is the reliable medium of bearing condition monitoring in the long-life ground experiment of flywheels.

2. A fusion approach of K-medoid clustering is put forward based on the normal specimens, which can be used to monitor different abnormal states of flywheels effectively and a quantitative evaluation can be given as well.

6. Acknowledgement

This work was supported by the Beijing Key Laboratory of Long-life Technology of Precise Rotation and Transmission Mechanisms under Grant BZ0388201703.

REFERENCES


