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EARLY FAULTS DETECTION IN A BALL BEARING USING MINIMUM VARIANCE CEPSTRUM; APPLICATION TO AN AUTOMOTIVE HUB BEARING

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Abstract
A hub bearing in a wheel is connected to suspension system of an automobile. Noise and vibration from the faults of the bearing can diminish trust of the vehicle and also reduce comfort and delightfulness. Therefore, it is critical to find the faults in the bearing as early as possible for preventing from noise and vibration. To detect early faults signal in noise, we have to distinguish different characteristics between them. Minimum Variance Cepstrum (MVC) is introduced for observing periodicity of faults under noisy environment. This paper shows how the method is useful for detecting small faults. From the results of experiment, we found early faults in several bearings passed acceptance test. Moreover, we compared the results with other signal processing methods' one for inspecting how effective the method is.

INTRODUCTION

The hub bearing not only sustain the body of the automobile, but permit wheels to rotate freely. Excessive loads or many other reasons can cause faults to be produced and grown in components of the bearing. Noise and vibration from the faults can diminish the trust of the vehicle and also reduce comfort and delightfulness. Therefore, it is necessary to find faults as early as possible before making severe noise and vibration.

Various signal processing methods for fault detection have been studied, because it is important for rotational machinery components: bearings and gears to find faults before the machinery are severely damaged. These methods can be categorized by their signal processing algorithm. Firstly, there is spectral analysis[1] and its various application methods: directional spectrum[2], moving window method[3], etc.. Secondly, cepstral analysis- power cepstrum[4], minimum variance cepstrum[5], etc.-is used for detecting fault periods. Thirdly, envelope detection method- high frequency resonance technique (HFRT) [6~7], complex envelope[8], etc.- is introduced and applied. Fourthly, time-frequency analysis, which is known for an efficient way to detect transient signals, has been studying for a long time and by many researchers. Especially, the method using wavelet is suggested in fault detection because of good resolution of both time and scale [9~11]. Besides, Lee and White[12] proposed active noise cancellation algorithm for fault detection and machinery diagnostic method using statistical approach[13~15] is also suggested.

Although there are many methods to find faults in a ball bearing, all the methods are not efficient for detecting early faults in the bearing. We need to decide the most effective method to find early faults in the bearing among the various methods from understanding about the characteristics of the bearing fault signal.

CHARACTERISTICS OF FAULT SIGNAL IN A BALL BEARING

To devise the best means to find faults as early as possible, we have to know the features of fault signal for detecting early faults produced in a ball bearing. If we know the characteristics of early faults signal, we can choose a specified signal processing method separating fault information from other signals. For these purposes, it is needed to study structure of ball bearing and inspect the characteristics of fault signal.

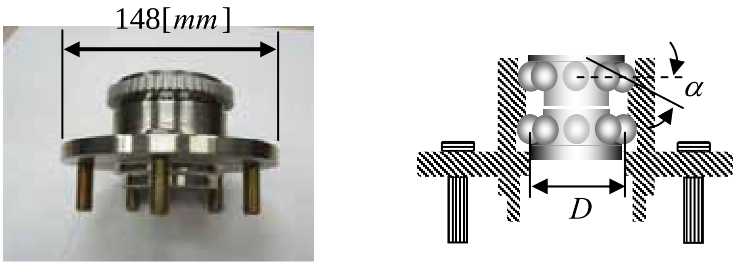
Structure of an automotive hub bearing

The structure and geometric information of ball bearing determine the characteristic frequencies related with faults location in a bearing. Automotive hub bearing is a double-row angular-contact ball bearing as depicted in Figure 1. The specification of the hub bearing is described in Table 1. Pitch diameter is the distance between centers of balls which are positioned in opposite direction about the axis center of the bearing. Contact angle is the angle at which the balls contact with races.

Characteristics of bearing fault signal

Balls in a bearing rotate in state of contacting with outer and inner races and also support loads at the contact points between balls and races. If faults are created at the contact surface, impact force is generated by collision between faults and confronting surfaces in a bearing. Fault signal measured by a sensor can be expressed as a convolution of impact force with transfer function between collision point and measurement point. If we assume the transfer function is invariant with time and the bearing rotates constantly, the fault signal can be written as

$$f(t) = A \cdot \sum_{m=0}^{N} h(t) * \delta(t - mT_c). \tag{1}$$



(a) *(b)*

Figure 1- A hub bearing, (a) Photograph of the bearing, (b) Schematic diagram of the bearing, where α is contact angle and D is pitch diameter

Pitch diameter (D)	54 mm
Ball diameter (d)	12.7 mm (1/2 inch)
Contact angle (α)	35°
Number of balls(z)	12 EA

Table 1- Shape information of the hub bearing

Where, A is amplitude of the vibration signal, $h(t)$ is transfer function, $\delta(t)$ is delta function indicating impact force, m is integer, and T_c is characteristic (fault) period.

The equation (1) says that we need to detect the characteristic periods to decide whether or not the faults start to grow significantly. The periods are obtained by the distance which balls move divided by relative rotating speed of each race.[16] If the magnitude, A, in equation (1) is large enough, we can observe whether faults exist or not from just measured signal. However, in case of a bearing being equipped in a system with high operating noise, early fault signal could be buried by the noise. In other words, in spite of being faults, we can not recognize the fault signal because of high noise level or small faults.

DETECTION METHOD USING CHARACTERISTICS OF EARLY FAULTS SINGNAL AND NOISE SIGNAL

We can not observe early fault signal in measured signal, because early fault signal is so small that it is buried by operating noise. For detecting such early faults, we have to use the different characteristics between fault signal and operating noise. The fault signal has periodic feature as described in equation (1) in contrast with random one of noise. Even though we can not distinguish periodic signal from random one in time domain, using appropriate transformation, which can separate periodic signal from other random signals, the fault signal can be observable in transformed domain.

Periodic signal with deterministic feature has a line spectrum in contrast with a continuous spectrum of noise in frequency domain. Hence, periodic signal can be observed in frequency domain using method which decreases continuous signal power transmitted to band-pass filters as bandwidth of the filters becomes narrower. In frequency domain, nevertheless, it is difficult to observe the periodic signal because system information is multiplied to the periodic signal. In quefrency domain, however, system information is emerged low quefrency band, because the information in frequency domain has envelope-like characteristics. Therefore, we can observe the periodic signal more clearly in quefrency domain than frequency domain. Minimum variance cepstrum (MVC) [5] is proposed to use the concept which separate periodic signal from random one as stated above. Therefore, minimum variance cepstrum is selected as an appropriate method in this paper for detecting early fault signal buried by operating noise.

EXPERIMENTAL SETUP AND CONDITION

The bearings used in experiment are automotive hub bearings, which are an angular contact ball bearing. Contact angle can be changed by the variation of loads and speed.[16] When the angle is changed, fault signal of early faults can not be produced because it is possible for the faults not to meet confronting surface. This means that experimental condition is very important to early fault detection of bearings. The most realistic and useful experimental condition is operating condition itself of the system, because the condition is a plausible way to find early faults made by operating malfunctions. Moreover, the experimental condition can save much effort, cost, and time by not being disassembled the bearing from a whole system.

An automotive experimental set-up and conditions

Figure 2 shows a diagram of dynamo experimental set-up. Dynamo wheel rotates rear wheels of a vehicle in contact with itself at a speed of 120[km/h]. The characteristic frequencies of faults according to the speed can be obtained easily and listed: outer race- 13.4[ms], inner race-9.1[ms], and ball element-15.9[ms].

The choice of measurement position should be considered stiffness of vibratory source and transmission media[18] and also direction of load. In angular contact ball bearing, the direction being exerted by larger load is recommended between radial and axial direction, and close position to the bearing location is favored. Considering the conditions, sensors are located at a part connected to the bearing directly in Figure 2.

The measurement and record devices set-up of the experiment is also outlined in Figure 2. Sensors are a delta shear type of piezo-electric accelerometers of B&K Type 4374. HP35670A was used for analyzing and storing the data with 65[kHz] sampling frequency for inspecting high frequency components of fault signal.

Hub bearings which are used for experiments

The hub bearings used for the experiment are divided by two groups. One group is composed of artificial fault bearings in each part of a bearing. Another one is made up of normal bearings passed an acceptance test. The artificial bearings are used for

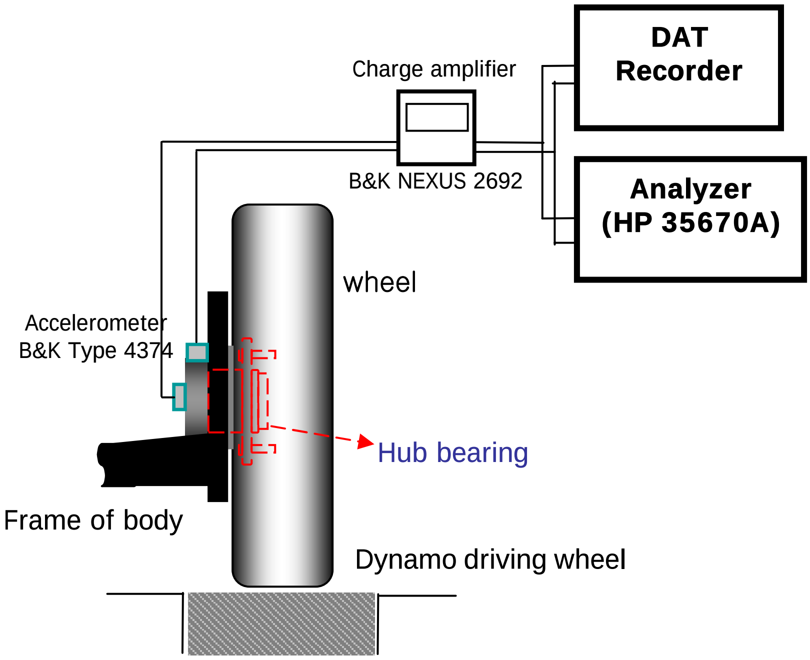


Figure 2- Experimental set-up; a diagram of measurement condition and devices set-up

contrastive samples for checking the experiment and programs of the signal processing. One of the faults is showed in Photo 1 which was made by electric drill pen artificially. The other 12 normal bearings passed the acceptance test are selected as candidates possibly having early faults in them.

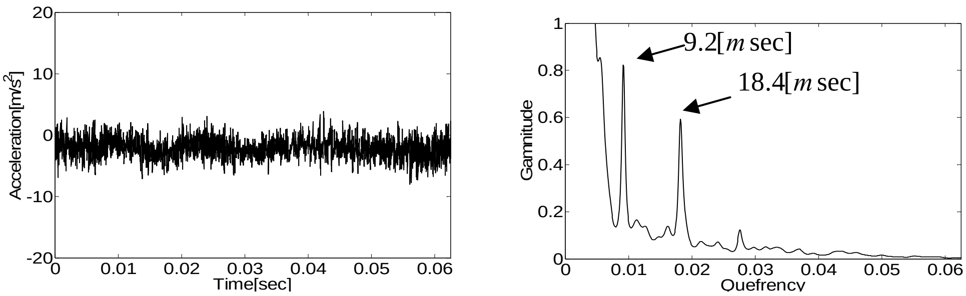
RESULTS AND COMPARISONS

Results of minimum variance cepstrum

We analyzed the measured vibration signal using MVC. Figure 3 shows measured acceleration signal and results of MVC. In Figure 3 (a), we can only know the existence of fault from acceleration level in compared with level of normal bearing, which is already known as $\pm 1[m/s^2]$, but do not know where the fault is though there is a large fault in inner race. However, the result of MVC shows the characteristic period clearly in Figure 3 (b).

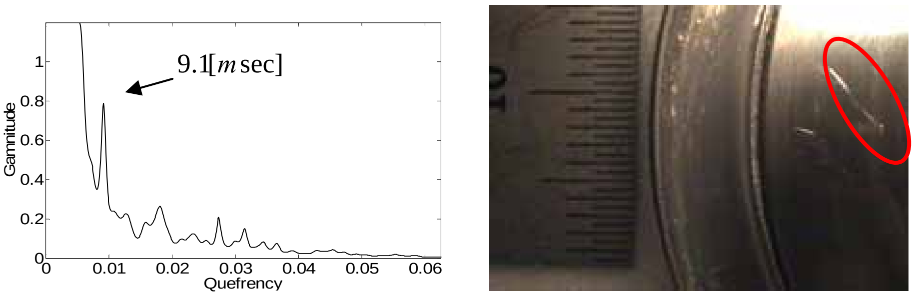
We can verify the experiment procedure and programs from the result of an artificial fault bearing. Moreover, we examine twelve bearings expected containing early faults in the bearings. In the end, we find that ‘four’ bearings out of twelve normal bearings have small faults from the results of MVC. Figure 4 is the result and a photo of one early fault. We did not know whether the bearings have faults or not and, if they have, where the faults are. From the Figure 4 (a), however, we find the faults and their positions from the results of MVC. For checking the results, after the experiments, we disassembled the bearings and verify existence of the faults and their locations.

Photo 1- The inner race fault which were made by electric drill pen artificially



(a) *(b)*

Figure 3 - An inner-race fault (a) Measured acceleration signal, (b) MV Cepstrum: Lifter order-480, Time length-125[msec], Theoretical inner-race fault period-9.2[msec], 18.4[msec]-Rharmonic

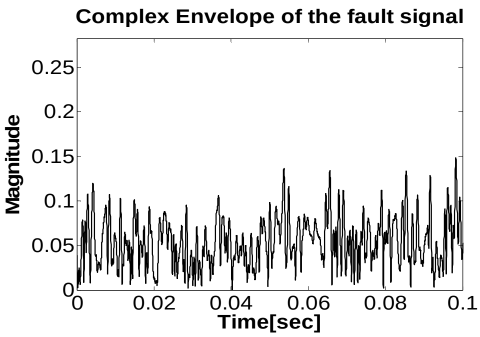


(a) *(b)*

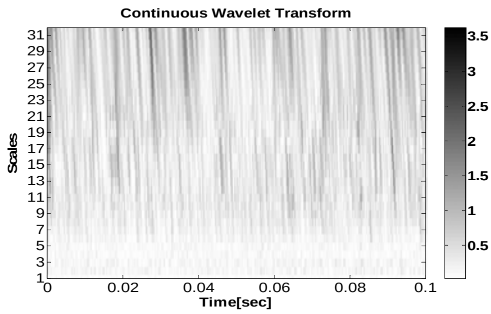
Figure 4 - Result of MV Cepstrum and a photo of an early fault, (a) Minimum Variance Cepstrum: Lifter order-480 and time length-125[msec] and theoretical inner-race fault period: 9.1[msec], (b) A photo of small scratched fault in inner race

Comparison with other methods

We need to compare with well known other methods for verifying the results of MVC. There are many methods for detecting faults. In this paper, however, we choose each representative method out of three different well known algorithms. As a representative of envelope analysis, complex envelope is selected, and moving window



(a)



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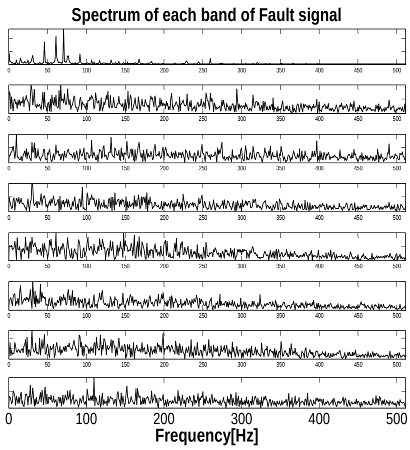

(c)

Figure 5- Results of signal processing: theoretical inner-race fault period: 9.1[msec]and fault frequency:110[Hz], (a) Complex envelope, (b) Continuous wavelet, (c) Moving window.

is picked up as a representative of spectral analysis as well as continuous wavelet analysis is chosen as a representative of time-frequency analysis, because the selected three methods are known for more efficient method than other methods.

Figure 5 shows results of the three methods with the same early fault in Figure 4 (b). We can not observe the periods or frequency in the results in Figure 5. As a result, MVC can be a more efficient method than other three methods for detecting early faults.

SUMMARY

Ball bearings are important rotational components. When a bearing is in state of large loads or fast speed, or any malfunction, noise and vibration from faults in the bearing can make serious problems, because early faults grow quickly. Therefore, it is very important to find early faults in a bearing.

In this paper, minimum variance cepstrum is selected as an efficient method, because it utilizes the different characteristics between fault signal and noise for detecting early faults of ball bearings. It is proved by automotive experiments and comparison with other well-known methods for inspecting the results

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