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Experimental characterization of mechanical vibrations and acoustical noise generated by defective automotive wheel hub bearings

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Abstract

Wheel hub bearing faults in passenger cars cause chattering at the corresponding wheel, increase chassis vibration and generate high noise levels inside the car cabin. In this paper a series of in-situ test with defective and healthy wheel hub bearings were conducted. Mechanical vibrations and sound were measured and data were analyzed with a number of signal processing methods in frequency and time-frequency domains. Additionally, a statistical signal processing method was also performed. The results of the various methods are compared and it was found that most of the methods used in this work are well suited for the analysis. Some methods, however, show certain limitations with respect to their informative value and their ability of implementation.

Keywords: Instrumentation; vibrations analysis; faulty bearing; automotive parts

1. Introduction

Bearings play an important role in any rotary machinery. Not only do bearings influence the quality of the machinery's accuracy, but also do they directly impact the engine's life span. Defects in bearings cause recurrent impacts on the rotating part degrading its performance. Therefore, a lot of research has

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been conducted to the detection of bearing defects at early stages of failure development, especially because early detection decreases production machinery downtime and maintenance costs.

There are a number of measurement, analyses and detection schemes which are widely recognized. It appears that the state of the art is to measure acceleration directly on the bearing casing by means of piezoelectric accelerometers [1, 2]. Furthermore, acoustic measurement methods have been proposed by means of acoustic transducers [3].

Time-domain analyses and detection methods have been proposed, such as phase diagrams [4] and threshold counters [5]. However, the frequency-domain analysis is the most ubiquitous method found in the literature. Pure frequency analyses or time-frequency methods such as the Short-Term Fourier Transform (STFT) have been investigated. In addition, statistical signal processing methods have been published as well. Among these methods are Crest Factor, Kurtosis and Beta Function [6], probability prediction and scatter plots [7] and autocorrelation together with the probability density function [8]. Most research has been done with respect to rotating production machinery bearings, rarely car wheel hub bearings.

In this paper in-situ measurements of mechanical vibrations produced by a defective wheel hub bearing and sound transmitted to the chassis cabin, under normal car usage conditions were conducted and various vibration analysis techniques were applied.

2. Autocorrelation

The autocorrelation function displays information about a signal's self-similarity. More formally speaking, it gives the correlation between two signal points separated by a time lag. For continuous, finite energy signals the autocorrelation function is

$$R(\tau) = \int_{-\infty}^{+\infty} s(t) \cdot s^{*}(t-\tau)dt \tag{1}$$

and for discrete-time signals

$$R[\tau] = \sum_{n} x[n] \cdot x^{*}[n-\tau] \tag{2}$$

In both cases τ is the lag between two observation points whereas * is the complex conjugate. R(0) and R[0], respectively, are the maximum of the function and, furthermore, the autocorrelation is normalized so that the latter points equal unity. Real signals' autocorrelation is an even symmetric function with respect to zero. It gives information about a signal's stationarity, e.g. a clearly pronounced pointy correlation indicates weak stationarity whereas a wide correlation corresponds to a strongly stationary signal. In addition, periodic signals produce periodic autocorrelation functions with the same period as the time signal

3. Experimental setup

In order to acquire the desired data for further processing and analysis, a passenger car was equipped with measurement devices and signal processing hardware. The experiment, as depicted in Fig. 1, was conducted on a conventional highway. During the first measurement series, the left rear wheel hub was equipped with a faulty bearing. Then it was replaced with a healthy bearing. Consequently, two series of measurements were conducted, with the faulty and the good bearing, respectively.

To begin with, a solid-state accelerometer was mounted on the relevant wheel hub. The mounted accelerometer was sensible to acceleration forces perpendicular with respect to the road. All consecutive measurement modules were installed inside the vehicle cabin. The acquired acceleration data were voltages proportional to the gravitational constant and passed first through a conditioner stage whose output terminal held the acceleration data. Furthermore, the obtained acceleration data were sent through two integrator stages. The outputs of the latter held the velocity and the displacement, respectively. Ultimately, all four data streams were connected to a data acquisition device.

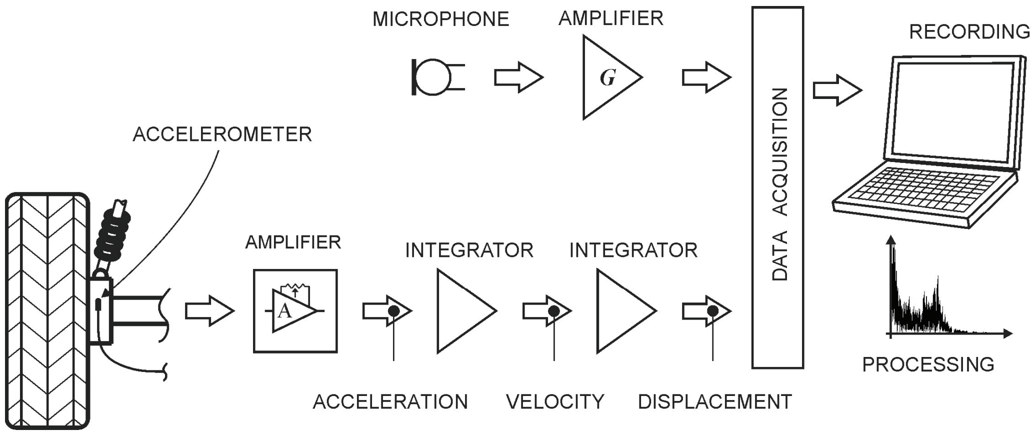

Fig. 1 Experimental setup.

Not only is vibration information of interest, but also acoustic noise perception inside the car cabin. To this end, an electret condenser microphone was mounted onto the inner hull of the cabin.

A high-end data acquisition board NI PCMCIA 6062E was used. For measurement series, all five data streams were sampled at 20 kHz and sent to a control center in a laptop computer for storage. Hence, all the data were available for off-line signal processing. The bearing in use was of the type double-rowed ball bearing for non-driven wheels. A perspective view with a lateral cut is shown in Fig. 2. As depicted, the inner race is stationary whereas the outer race revolves. The latter is connected to the wheel and the former to the vehicle body.

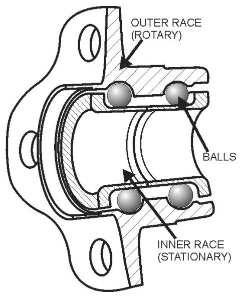

Fig. 2 Wheel hub bearing.

4. Results

As the experiment was conducted with rising vehicle velocity, a proportional increase in the measured vibrations acceleration at the bearing was expected. The corresponding ramp was expected to be of lower inclination with a healthy bearing as opposed to the faulty one. Fig. 3 shows two acceleration surface spectrogram plots for both defective and healthy bearings.

4.1. Acceleration Analysis

Fig. 3 shows the frequency analysis for a defective bearing and a healthy bearing. Interestingly, both spectra have a similarity which could, to some extent, be approximated by a factor. However, it is clearly visible where most of the energy caused by a defective bearing is located in the measured data. Those cumulated peaks evolve at around 4750 Hz with a bandwidth of roughly 2000 Hz. Added to that, a further accumulation of peaks caused by the bad bearing is located at frequencies below 500 Hz (see Fig. 5 for a more detailed view). Both trends are a clear indicator of a defective component in the wheel hub. Bearings show a resonance frequency band in the upper frequencies. Published works, as in [5], stated that low-frequency impulses created by defective bearing parts excite a resonance frequency band in the upper frequencies of the bearing vibration. This resonance can clearly be seen in the spectrogram. The detection technique using this resonance property is called High Frequency Resonance Technique and has been implemented together with envelope detection schemes [9,10].

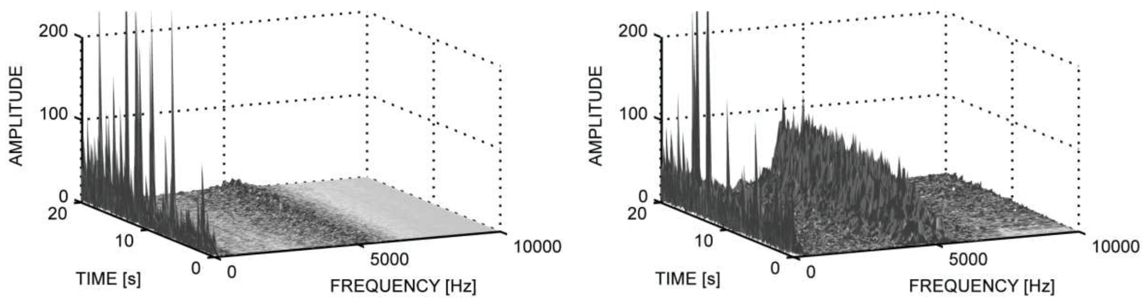

Fig. 3 Surface spectrogram of acceleration data. Good bearing (left), faulty bearing (right).

Statistical signal processing methods were applied to the data. The autocorrelation function results can be seen in Fig. 4 and are surprisingly clear and similar in shape for the good bearing as in [8]. The dominating low frequency components in the healthy bearing result in a smooth autocorrelation. On the other hand, the high frequency resonance conglomerate of the bad bearing produces strong jittering with respect to the lag in the autocorrelation.

4.2. Acoustic Noise Analysis

As a huge amount of the signal energy of the acceleration data were located around 4750 Hz, a similar conglomerate was expected in the acoustic noise measurements. However, Fig. 5 shows clearly that the audio signal of a defective bearing carries hardly any energy above 500 Hz. Most likely the chassis' natural frequencies lie far below the high frequency conglomerate of the acceleration data. Molisani et al. [11] stated that car cabin noise below 400 Hz is mainly structural borne, meaning that it gets translated into the cabin by physical connections, which apparently do omit higher frequencies. On that account, only a partial energy amount initiated by the chattering of the bad bearing was transformed into acoustic waves inside the vehicle cabin.

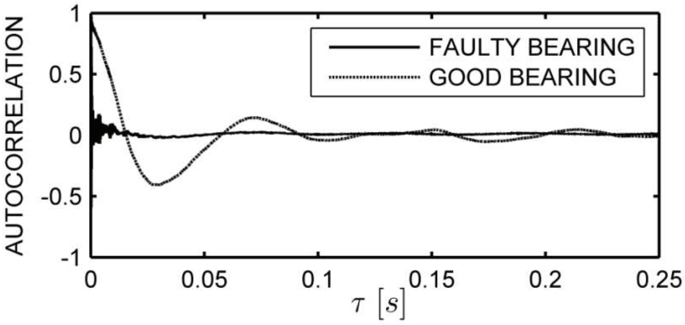

Fig. 4 Statistical analysis.

Plots shown in Fig. 5 indicate the correlation between the acceleration and noise measurements below 500 Hz. Three clearly pronounced peaks in the acceleration data of the bad bearing distinguish it from the good bearing, where such peaks remain unobserved. The peak at 200 Hz translates unequivocally into the noise measurement, where a notable amount of energy is located around 200 Hz, as well.

Post experimental subjective tests confirmed that the most important audible part, which distinguishes the audio signals, is indeed the 200 Hz peak. The same phenomenon was audible while conducting the measurements inside the vehicle cabin, it equaled a booming sound.

5. Conclusions

From our analyses the following conclusions can be established:

The FFT and STFT are powerful and meaningful instruments for off-line analysis of accelerometer measurements of bearings. And what's more, healthy from faulty bearings can be distinguished, observing the upper frequency resonance band, even when the measurements were conducted in a raw environment such as a regular highway road.

Statistical signal processing of acceleration data can also be used. Especially because the computed data are nearly self-explanatory and easy to interpret. Measurements can be used to identify good and bad bearings, respectively.

Noise measurements inside the vehicle cabin are only significant at low frequencies, as higher frequencies are virtually non-existent. Nevertheless, clearly audible frequencies caused by a faulty bearing prove noise perception to be a potent means of evaluating a bearing's state in a moving vehicle.

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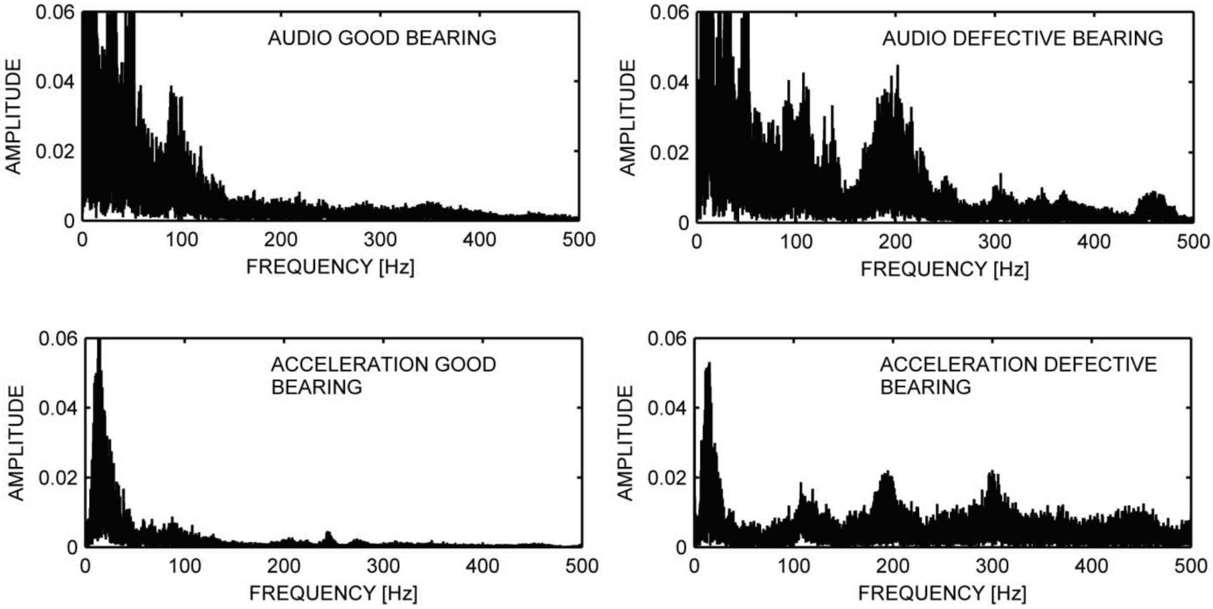

Fig. 5 Correlation between audio (top) and acceleration (bottom) data, good bearing (left) and faulty bearing (right).

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