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Research Article

Majority Rule-based Vibrational Signal Analysis Method for the Fault Diagnosis of Rolling-Element Bearing of Vehicle Brake Tester

Selman KULAÇ

Department of Electrical-Electronics Engineering, Faculty of Engineering, Düzce University, Düzce, TURKEY
Corresponding author's e-mail address: selmankulac@duzce.edu.tr
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ABSTRACT

Vehicles with different weights are subjected to vehicle brake tests at vehicle inspection stations at regular intervals due to government regulations. Safety and efficacy of vehicle roller brake testers are important for reliable inspections at vehicle inspection stations. Over time, mechanical faults occur in these vehicle roller brake testers. Failure of the rolling-element bearing used in vehicle roller brake testers is one of the most common faults. In this study, total energy, mean, variance, cross-correlation and correlation coefficient values of median filtered signals were calculated based on the signals obtained using real-time vibration measurement data of rolling-element bearings used in a vehicle brake tester. With this study, it has been confirmed that, with use over time, the values acquired by all the methods go up and exceed the thresholds identified. Proposed majority rule based combined excession of these thresholds expresses that the rolling-element bearing used in a vehicle roller brake tester is too close to a mechanical fault.

Keywords: *Rolling-element bearing, Fault diagnosis, Vibration measurement, Vibration signals*

Araç Fren Test Cihazının Döner Elemanlı Rulmanın Arıza Teşhisi için Çoğunluk Kuralına Dayalı Titreşimsel Sinyal Analizi Yöntemi

ÖZET

Farklı ağırlıktaki araçlar, yasal düzenlemeler gereği düzenli aralıklarla araç muayene istasyonlarında araç fren testlerine tabi tutulmaktadır. Araç fren test cihazlarının güvenliği ve etkinliği, araç muayene istasyonlarında güvenilir denetimler için önemlidir. Zamanla bu araç fren test cihazlarında mekanik arızalar oluşmaktadır. Araç fren test cihazlarında kullanılan döner elemanlı rulmanın arızalanması ise en sık karşılaşılan arızalardandır. Bu çalışmada bir araç fren test cihazında kullanılan döner elemanlı rulmanların gerçekçi titreşim ölçüm verileri kullanılarak elde edilen sinyallere dayalı olarak, medyan filtreli sinyallerin toplam enerji, ortalama, varyans, çapraz korelasyon ve korelasyon katsayısı değerleri hesaplanmıştır. Bu çalışma ile zaman içerisindeki kullanımlarla tüm yöntemlerle elde edilen değerlerin yükselerek belirlenen eşikleri aştığı doğrulanmıştır. Bu eşiklerin çoğunluk kuralına dayalı olarak önerilen birleşik aşımı, bir araç fren test cihazında kullanılan döner elemanlı rulmanın mekanik bir arızaya çok yakın olduğunu ifade etmektedir.

Anahtar Kelimeler: *Döner elemanlı rulman, Arıza teşhisi, Titreşim ölçümü, Titreşim sinyalleri*

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I. INTRODUCTION

Vehicles with different weights are subjected to vehicle brake tests at vehicle inspection stations at regular intervals due to government regulations. Safety and efficacy of vehicle roller brake testers are important for reliable inspections at vehicle inspection stations. Failure of the rolling-element bearing used in vehicle roller brake testers is the main cause of problems. Some studies on rolling-element bearing problems from the literature are presented below.

In [1], artificial local defects on the running surface of the ball bearing are built. Theoretical model and simulation program were developed for the ball bearing vibration measurements. It was demonstrated that experimental and theoretical results were correlated. In [2], the vibration monitoring and analysis were presented in order to detect failures in machineries that were running in real operating conditions. In [3], statistical moment analysis approaches were used to detect the bearing failures at an earlier stage. Various parametric auto-regressive spectrum analysis methods and conventional spectrum (correlogram) analysis techniques are applied and compared for ball bearing defects [4]. In [5], adaptive noise cancellation, fault characteristic order and rotational-order-sideband analyses to diagnose bearing fault type were presented. In [6], vibration analysis of normal state condition bearing and defected bearings running under different shaft speeds with two load levels were performed. Real time vibration signals are subjected to autocorrelation difference and Goertzel algorithm methods (different from the proposed methods in this study) and over time, the values acquired by all the methods rise and exceed the thresholds defined by the study [7]. But in [7], any combined or hybride evaluation of these two methods was not performed. In [8], fault detection in rolling mill roller bearings by acoustic emission and vibration analysis was examined. In [9] the authors described a number of signal processing techniques used to diagnose faults in rolling element bearings. Finally, in [10], a wireless three-axis on-rotor sensing system was developed to greatly improve the SNR, and fast Fourier transform and Hilbert envelope analysis were introduced for accurate early bearing fault detection.

In this study, according to the proposed majority rule-based combined vibrational signal analysis for the rolling-element bearing fault diagnosis, some thresholds indicating that the rolling element is approaching fault in short time were obtained. For any measurement, it is recommended to consider majority rule based combined excession of these thresholds expressing that the rolling-element bearing used in a vehicle roller brake tester is approaching fault.

II. METHODOLOGY

In this section, real time vibration signals are used as before also used in [7]. Two rolling element bearings were used for comparison. The first one was used to get the measurement 1, 2 and 3 data, and the other was used to get the measurement 4 and 5 data for comparison. Their time domain representations (with figures) of median filtered vibration amplitude signals of first and second rolling-element bearings can be seen in [7]. In this study, different methods were discussed and higher performance was achieved with the combination of these new methods. These different methods were presented below.

Total energy of all median filtered vibration amplitude signals in time domain was calculated using 1.

$$E_T = \sum_{n=1}^{N} |x[n]|^2 \tag{1}$$

Here, the N-length discrete-time x[n] sequence corresponds to the vibration amplitude signals. The results were obtained from 1 in time domain. As can be seen from Figure 1, the total energy values of the vibration signals increase over time. The first bearing was completely broken down and replaced with the new one. The 3rd measurement was taken before the first bearing was broken down, the vibration signal total energy reached a peak value of 304.934 $(m/s^2)^2$. This value can be accepted as the threshold level. After the first bearing broke down, vibration energy for the second bearing went up from low to high over time.

Mean values of all median filtered vibration amplitude signals were calculated by 2 and presented in Figure 2.

$$\mu = \frac{1}{N}\sum_{n=1}^{N} x[n] \tag{2}$$

Here, the N-length discrete-time x[n] sequence corresponds to the vibration amplitude signals.

As can be seen from Figure 2, mean values of the vibration signals increase over time. The final measurement (3rd one) before the first bearing was broken down, the vibration signal mean value reached to peak value of 0.1611 m/s^2. This value can be accepted as the threshold level. After the first bearing broke down, vibration mean value for the second bearing went up from low to high over time.

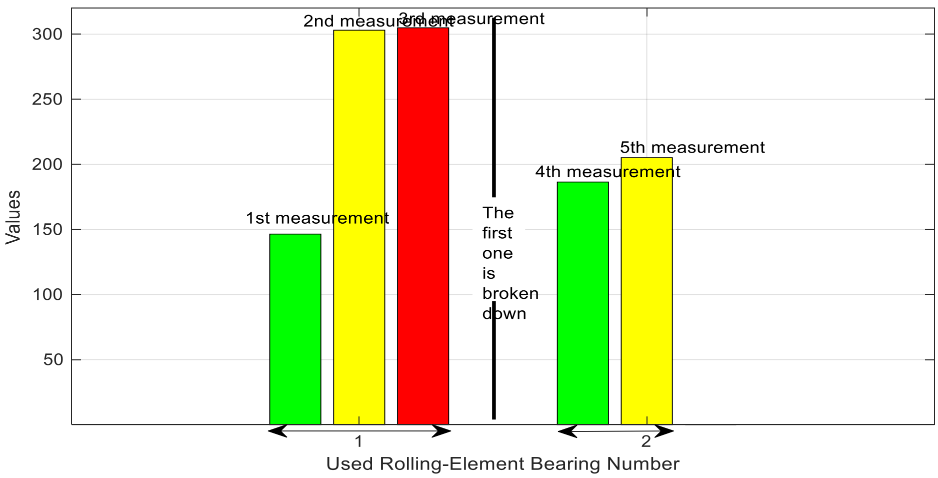

Figure 1.*Total energy values of filtered vibration amplitude signals from rolling-element bearings for each measurement*

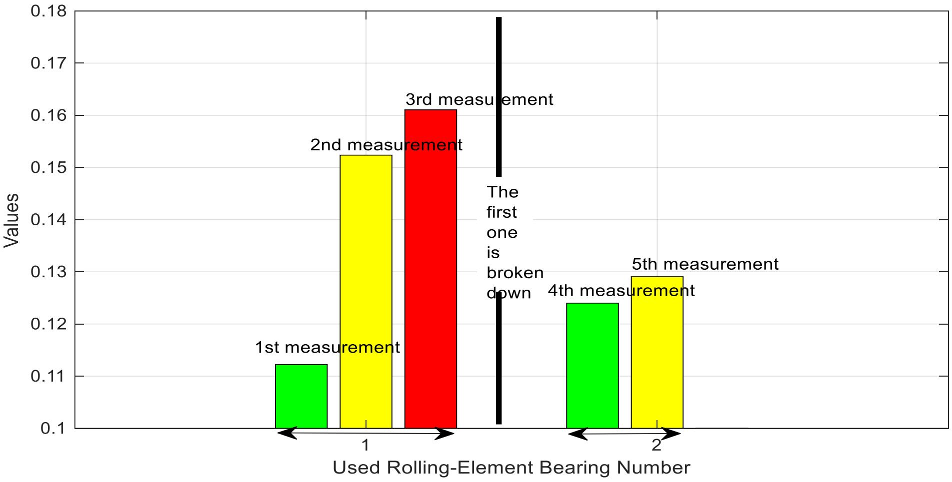

Figure 2.*Mean values of filtered vibration amplitude signals from rolling-element bearings for each measurement*

Variance values of all filtered vibration amplitude signals was calculated by 3 and presented in Figure 3.

$$\sigma^2 = \frac{1}{N}\sum_{n=1}^{N}\left(x[n] - \mu_x\right)^2 \tag{3}$$

Here, the N-length discrete-time x[n] sequence corresponds to the vibration amplitude signals. μ is the mean value of x[n] sequence. It can be concluded from the Figure 3, as the time passes, variance values of the vibration signals rise. The measurement (2nd one) before the first bearing was broken down, the vibration signal variance value reached a peak value of 0.01378. Since the variance value for the vibration signal of 3rd measurement is lower than the value of 2nd one, peak value of 0.01378 m/s^2 can be accepted as the threshold level. After the first bearing was broken down, the vibration variance value for the second ball bearing went up from low to high over time.

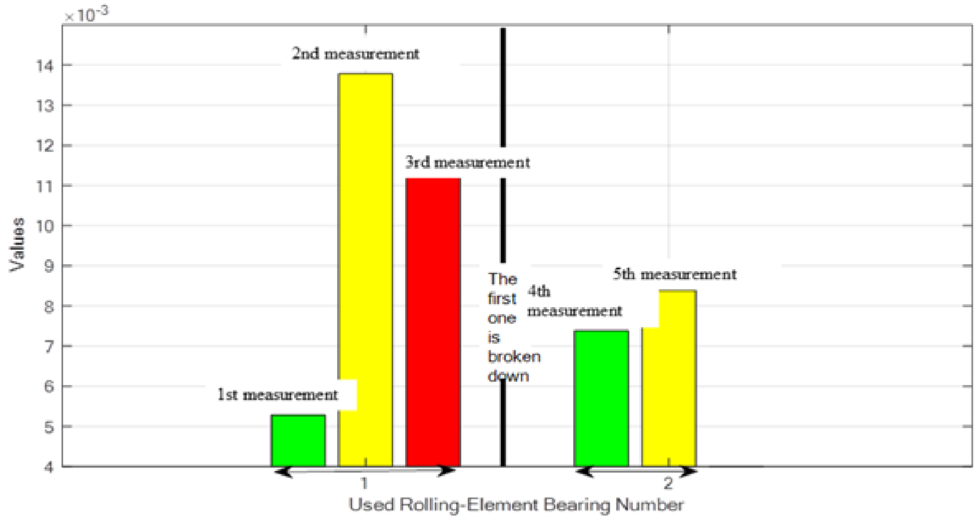

Figure 3.*Variance values of filtered vibration amplitude signals from rolling-element bearings for each measurement*

Cross correlation is a measure of the similarity of the two signals to each other. The cross correlation function is generated when one of the two signals is shifted (by n value) relative to the other and calculated by 4.

$$R_{xy}[\mathrm{n}] = \sum_{m=-\infty}^{\infty} x[m+n]y[m] \tag{4}$$

The cross-correlation functions were created with reference to the vibration signal of 3rd measurement. Cross-correlation functions, which show the similarities of the 3rd measurement vibration signal (x[m]) to the other different bearing vibration measurement signals (used as y[m] in each comparison), were generated and the maximum values of these functions are shown in Figure 4 respectively. It can be seen in Figure 4, as the time passes, maximum values of cross correlation functions go up.

The peak value of 0.0001751 before the first bearing was broken down was obtained as expected since the cross-correlation function was autocorrelation function of the same vibration signal. The next highest value of 0.0001352 which the maximum value of cross-correlation of 3rd measurement and 2nd measurement vibration signals can be accepted as the threshold level. After the first bearing was broken down, the maximum values of cross-correlation of 3rd measurement and the second ball bearing vibration signals went up from low to high over time.

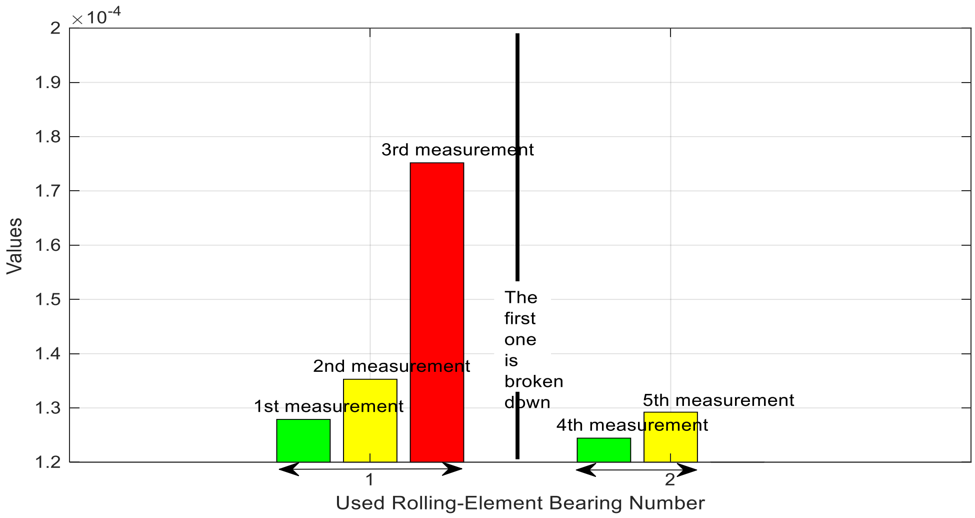

Figure 4.*Maximum values of cross correlation functions*

Correlation coefficient is a numerical measure of the correlation that gives the dependency relationship between two variables. The value of correlation coefficient is always between '+1' (perfect positive linear relationship) and '–1' (perfect negative linear relationship). In '0' case, it is understood that there is no relationship between two variables and these variables are independent. Correlation coefficient is calculated by 5.

$$r = \frac{\sum_{n=1}^{N}(x[n]-\mu_x)(y[n]-\mu_y)}{\sqrt{\sum_{n=1}^{N}(x[n]-\mu_x)^2}\sqrt{\sum_{n=1}^{N}\left(y[n]-\mu_y\right)^2}} \tag{5}$$

Here, the N-length discrete-time x[n] and y[n] sequences corespond to the vibration amplitude signals. μ_x is the mean value of x[n] sequence and μ_y is the mean value of y[n] sequence. The correlation coefficient calculations were done with reference to the vibration signal of 3rd measurement. The correlation coefficient values, which show the dependency of the 3rd measurement vibration signal (x[n]) to the other bearing vibration measurement signals (used as y[n] in each comparison), are obtained and are shown in Figure 5 respectively. Figure 5 shows that as the time passes, correlation coefficient values increase.

The peak value of '1' before the first bearing was broken down was obtained as expected since the vibration signals were the same as of 3rd measurement vibration signal. The next highest value of 0.1198487 which the correlation coefficient value of 3rd measurement and 2nd measurement vibration signal can be accepted as the threshold level. After the first bearing was broken down, the correlation coefficient values of 3rd measurement and the second rolling bearing vibration signals increased from low to high over time.

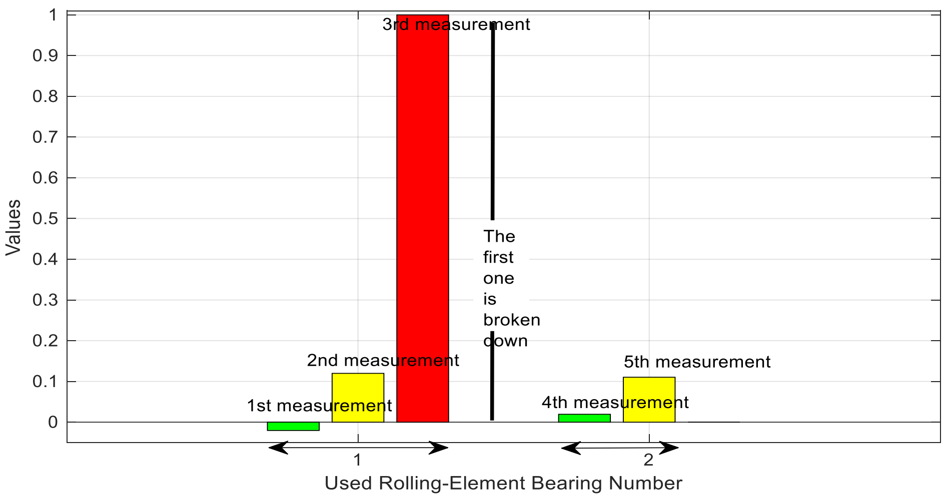

Figure 5.*Correlation coefficient values*

III. RESULTS AND DISCUSSIONS

Over time, all values acquired by all the above methods increase and exceed the reference thresholds set by this document. Majority rule-based combined excessing of these thresholds proposed in this paper expresses that the rolling-element bearing used in a vehicle roller brake tester is approaching fault.

It has been confirmed that the calculated value for each method increases as the bearing is used. A coarse reference threshold value obtained by a calculation according to only one method is not sufficient for decision alone because some threshold offset may have been occurred. Therefore, it is stated that effective fault analysis is performed by applying the majority rule combined with these coarse reference threshold values.

For any bearing, calculations are made according to the three methods given in the previous section. The values obtained are compared with the reference thresholds. At least two values are expected to exceed the corresponding reference thresholds in order to evaluate bearing as unhealthy according to the majority rule.

For instance, for the second ball bearing, the calculation values obtained in Figure 1, 2, 3, 4 and 5 according to the methods in the previous section were compared with the reference threshold values. The majority rule applied bearing was judged as healthy for 4th measurement as seen in the Table 1. According to the final measurement, all the calculation values of the bearing increased, but it was still found to be healthy and continued to be used due to the majority rule method.

Table 1.*Majority rule-based checklist*

Method	**4th measurement calculation**	**5th measurement calculation**
Total Energy	<304.934	<304.934
Mean	<0.1611	<0.1611
Variance	<0.01378	<0.01378
Cross-correlation	<0.0001751	<0.0001751
Correlation coefficient	<0.1198487	<0.1198487

For any rolling-element bearing, only if the total energy level due to vibration exceeds the threshold value of 304.934, or only if it exceeds the mean threshold value of 0.1611, or only if the variance exceeds the threshold value of 0.01378, or only if the cross correlation exceeds the threshold value of 0.0001751, or only if the correlation coefficient exceeds the threshold value of 0.1198487, the possibility of a failure can be foreseen. However, taking all these methods into account, exceeding the thresholds for the majority gives more accurate results in understanding the impending rolling-element bearing failure.

IV. CONCLUSION

Vehicles of different weights are subjected to vehicle brake tests at regular intervals at vehicle inspection stations in accordance with official regulations. The safety and effectiveness of vehicle roller brake testers are essential for reliable inspections at vehicle inspection stations. The rolling-element bearing used in the vehicle roller brake tester is the main cause of problems.

In this study, real time vibration signals were subjected to obtain total energy, mean, variance, cross-correlation and correlation coefficient values after median filtering process. According to the individual vibrational signal analysis for the fault diagnosis, some thresholds indicating that the rolling-element bearing is approaching fault in short time were obtained. These threshold values were 304.934 for the total energy, 0.1611 for the mean, 0.01378 for the variance, 0.0001751 for the cross-correlation and 0.1198487 for the correlation coefficient. For any measurement, it is recommended to consider majority rule based combined excession of these thresholds expressing that the rolling-element bearing used in a vehicle roller brake tester is approaching fault.

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