On-line test system for vibration measurement and sorting of ball bearings

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Abstract
A system for on-line measurement and sorting of ball bearings is presented in this paper. The structures and functions of its automatic testing mechanics and control system are described in detail. The system sorts the tested bearings into four grades by measured values of vibration parameters such as root-mean-square value, peak value, crest factor and kurtosis. Its stability of indication values are between ± 1.0dB. The mechanism generating abnormal sounds of bearings is also investigated emphatically and the characteristics of abnormal sound signals are described on the basis of vibration model of tested bearing.

Key words: Bearings, vibration, abnormal sound, online test, virtual instrument

List of Symbols

\[ m \quad \text{mass of outer ring} \quad x \quad \text{displacement of outer ring} \quad \xi \quad \text{damping ratio} \]
\[ k \quad \text{stiffness} \quad c \quad \text{damping factor} \quad \omega_n \quad \text{nature frequency without damp} \]
\[ p_0, p_i \quad \text{impact intensity} \quad \delta(t) \quad \text{unit pulse function} \quad \omega_d \quad \text{nature frequency with damp} \]
\[ F \quad \text{applied force} \quad F_s \quad \text{spring force} \quad F_d \quad \text{damping force} \]

1. Introduction
Ball bearings find widespread applications in domestic and industrial facilities. Performances of these facilities depend, to a great extent, on qualities of bearings. With the progress in science and technology the users call for higher and higher qualities of bearings. Even now the quiet bearings or the bearings without abnormal sound are needed in many applications instead of low vibrations or noises. Therefore test of bearing quality, especially bearing vibration, is getting more and more important for the manufacturers.

Vibration of a bearing originates in its configuration designed improperly, manufacturing errors, and working conditions, and it can be evaluated with such parameters as its root-mean-square (RMS), peak value, crest factor, probability density, and kurtosis [1-2]. The RMS of vibration could be well used to describe mean amplitude of the vibration, but it can’t reflect the abnormal sound component of the vibration. Thus, more attention should be pay to test and evaluation of bearing abnormal sounds.

Therefore the authors have developed an on-line automatic test system for measuring and sorting ball bearings according to their vibrations and abnormal sounds.
2. The on-line test system

The automatic machinery (see Fig. 1) delivering the tested bearings in this system mainly consists of three parts, i.e. a feeding mechanism, a measuring mechanism and a sorting mechanism. From entering the system to its exiting, a tested bearing should sequentially pass through these mechanisms and meantime implement such actions in turn as its turning over, elevating, positioning, two times measuring, and grouping. Figure 2 shows a schematic diagram of the automatic machinery.

![Fig. 2. Functionality of the machinery.](image)

The measurement and control system includes its hardware and software. The control console and main interface can be seen in Fig. 3. The schematic diagram of the hardware is illustrated in Fig. 4.

The strategy of measuring and evaluating vibrations is based on conception of virtual instrument. While testing, a YD-1 type of piezoelectric accelerometer picks up acceleration signals of the bearing vibration. After pre-amplifying, then band filtering and amplifying, voltage of the signals becomes within ±5 Volts, and they are sent to an A/D converter (12-bits, 100kHz). Then the processed acceleration signals are sampled and converted by the A/D into digital signals under the control of an industrial personal computer (IPC). By means of related software modules, the IPC implements in-time data processing inclusive of calculating the vibration parameters, sorting tested bearings, statistically analyzing tested results and meantime displaying and
saving the results. According to tested results, the bearings are sorted into four grades and then sent to next working procedure of production line.

3. The test results

The system has been used in site with specifications shown in Table 1.

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter of tested bearing</td>
<td>Φ10~Φ60 mm</td>
</tr>
<tr>
<td>Frequency range</td>
<td>50~10000 Hz</td>
</tr>
<tr>
<td>Speed of spindle</td>
<td>1500±30 r/min</td>
</tr>
<tr>
<td>Axial load</td>
<td>0~160 N</td>
</tr>
<tr>
<td>Indication range</td>
<td></td>
</tr>
<tr>
<td>Range I</td>
<td>0~40dB</td>
</tr>
<tr>
<td>Range II</td>
<td>30~70dB</td>
</tr>
<tr>
<td>Range III</td>
<td>60~100dB</td>
</tr>
<tr>
<td>Indication stability</td>
<td>±1.0 dB</td>
</tr>
<tr>
<td>Inspection time</td>
<td>≤5 seconds per bearing</td>
</tr>
</tbody>
</table>

In order to examine the indication stability of the test, tree of 4607A-2RS type of bearing were tested on this system and each of them was tested 10 times repeatedly. Table 2 shows the results with their RMS values. It can be seen from the results that all of the indication stabilities of the tests are within ±1.0dB around its average for each of the bearings.

<table>
<thead>
<tr>
<th>No.</th>
<th>Times</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Average</th>
<th>Indication stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>44.5</td>
<td>43.6</td>
<td>43.7</td>
<td>43.3</td>
<td>44.8</td>
<td>44.0</td>
<td>43.4</td>
<td>44.1</td>
<td>44.3</td>
<td>44.0</td>
<td>43.97</td>
<td>+0.83~0.67</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>44.6</td>
<td>44.9</td>
<td>44.1</td>
<td>44.8</td>
<td>44.2</td>
<td>43.9</td>
<td>43.6</td>
<td>43.5</td>
<td>43.1</td>
<td>44.1</td>
<td>44.08</td>
<td>+0.81~0.98</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>47.4</td>
<td>47.9</td>
<td>48.2</td>
<td>48.3</td>
<td>47.0</td>
<td>48.2</td>
<td>47.9</td>
<td>48.1</td>
<td>47.1</td>
<td>48.0</td>
<td>47.81</td>
<td>+0.49~0.81</td>
</tr>
</tbody>
</table>

4. Analysis on mechanism generating abnormal sound

When a bearing is tested under specified conditions (see Fig. 4), the inner ring is fitted on a quiet turning spindle and the stationary outer ring subjects to a thrust load \( \mathbf{F} \) axially. Meantime an accelerometer contacts with the outer ring to probe its vibration in radial. This vibration system [3] concerns with such tree factors as mass \( m \) of vibration body, system stiffness \( k \) and damping factor \( c \). Although stiffness and damping factor are nonlinear functions of load and surface stress deformation, the system could be considered to be linear as the load and the deformation are very small. Therefore, the system could be simplified to be a linear, one-dimensional and spring damped system as shown in Fig. 5.

Abnormal sound of a bearing is related with the localized defects [1-3], such as scratches, cracks or pits on the working surfaces of rollers and rings, as well as the contaminations or spalls within grease filled in bearing, and so on. Thus the abnormal sound should be the result of non-periodic or periodic pulses \( \delta(t) \) excited by these localized defects during bearing running.

![Fig. 5. Schematic diagram of vibration model.](image)
Response on single pulse excitation. A single impulse function $\delta(t)$ impacting on the system can represent non-periodic pulse [4], which is expressed as

$$F(t) = p_0 \delta(t)$$

(1)

Thus, differential equation of the system is as follows.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = p_0 \delta(t)$$

(2)

After solution of Equation (2), the vibration acceleration is expressed as

$$\ddot{x}(t) = p_0 c_1 e^{-\xi \omega_n t} \sin(\omega_d t - \psi_1)$$

(3)

Where

$$c_1 = \omega_n^2 (m \omega_d), \quad \psi_1 = \arctan[2\xi \omega_n \omega_d / (\xi^2 \omega_n^2 - \omega_d^2)]$$

Figure 6 qualitatively shows the wave shape of vibration acceleration $\ddot{x}(t)$. It is an obvious damped ringing response on a single pulse excitation. If the damped ringing response is strength enough, it will make abnormal sounds, hence the wave like that shown in figure 6 is defined here as abnormal sound signal with a single pulse. Figure 7 shows an example of abnormal sound signal with single pulse, which is given by measuring a real bearing on the developed system.

Response on periodic pulses excitation. A periodic impulse function $\delta(t)$ with period $T$, impacting periodically on the system, can represent periodic pulses, which is expressed as

$$F(t) = \sum_{i=0}^{\infty} p_i \delta(t - iT)$$

(4)

Thus, differential equation of the system is given as

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = \sum_{i=0}^{\infty} p_i \delta(t - iT)$$

(5)

and the vibration acceleration is expressed as

$$\ddot{x}(t) = \sum_{i=0}^{\infty} p_i c_1 e^{-\xi \omega_n (t - iT)} \sin(\omega_d (t - iT) - \psi_1)$$

(6)
Figure 8 qualitatively shows the wave shape of vibration acceleration $\ddot{x}(t)$ excited by periodic pulses. It is a series of damped ringing responses on periodic pulse excitations. Also when the damped ringing responses are strength enough, they will make abnormal sounds, hence the wave like that shown in figure 8 is defined here as abnormal sound signal with periodic pulses. Figure 9 shows an example of abnormal sound signals with multi-pulses, which is given by measuring a real bearing on the developed system.

**About evaluation parameter of abnormal sound.** Based on the above analysis of its source and mechanism of abnormal sound, it can be seen that the wave of vibrations of a tested bearing will be obviously superposed by single or multi damped ringing impulses, if the vibrations carry abnormal sound signals. Therefore, to describe amplitude character of the impulses, Peak of the vibration is a best evaluation parameter. On the other hand, the peak-to-RMS ratio, i.e. crest factor of the vibrations should be used as an important parameter for detection between abnormal sound signals and common vibration. In other word, Peak is used for evaluating the strength of abnormal sound signals and Crest Factor is used for detecting abnormal sound component of the vibrations.

5. **Conclusion**

The system introduced here could join up with a bearing assembly line to test vibrations and to detect abnormal sound of assembled bearings and to sort the tested bearings into four grades by measured values of vibration parameters such as RMS, peak value, crest factor and kurtosis. It could also be used for vibration analysis off-line and technology analysis.

Owing to abnormal sounds caused by localized defects of tested bearings, the characteristics of abnormal sound signals can be got by means of applying a pulse function to the mathematical model of system vibration. Giving an impact of non-periodic and periodic respectively to the model, its vibration acceleration shows a damped ringing response and a series of damped ringing responses. Therefore peak value, crest factor and kurtosis of the vibration can be used for evaluating the strength of abnormal sound signals.

**References**


