Abstract
This article deals with the progress of the sound and vibration research of rolling bearings in Japan. The literature mainly cited is written in Japanese. The focus in sound research is the early research, characteristics and generating mechanism of ball bearings, cage sound, squeak in cylindrical roller bearings, sound of defective bearings, contamination noise and sound life. In the vibration research, the early research, rolling element (ball or roller) passage vibration, natural vibration of the outer ring, natural vibration of the cage, vibration caused by geometrical imperfections, nonlinear vibration, abnormal vibration of grease lubricated ball bearings, vibration of defective bearings, damping and squeeze film damper are explored.

Key words: Rolling Bearing, Sound, Vibration

1. Introduction

Production of rolling bearings in Japan was started using imported steel balls in 1915. Domestic production of steel balls began in 1934. The rolling bearings were mainly used in warships, transport machinery, and aircraft before the end of World War II in 1945. However, most of the bearing plants in Japan were destroyed by air strikes during the war. In the early postwar years, buoyed by demand for civilian goods (in the coal, steel, textile, and rail industries) as well as the special procurement boom sparked by the Korean War from 1950 to 1953, the bearing industry in Japan recovered. Later, rolling bearings came to be widely used in home electrical appliances, automobiles and other products [1]. As a result of this, since the 1950s, sound and vibration of rolling bearings have become serious problems and research on them has been carried out. In this article, progress of sound and vibration research of rolling bearings in Japan is explained mainly using literature written in Japanese.

2. Rolling bearing sound

2.1 Early research of rolling bearing sound

The world’s first research paper of rolling bearing sound was published in Germany in 1933 [2]. In Germany, Lohmann analyzed the rolling bearing sound, and discussed the sound generating mechanism of rolling bearings in 1953. He pointed out that main peaks in the sound spectra of rolling bearings are caused by the bending natural vibrations of the outer rings [3, 4].

Most likely, the first Japanese research paper on rolling bearing sound was written by Ito and it was published in 1953 [5]. He explained the relationship between noise levels and asperities on the races and rolling contact surfaces in his papers published in 1953 and 1956.
Yunoki and Tanaka examined the effects of circumferential waviness of races and generatrix shape on the roller bearing noise in 1954 [7].

Soda published a paper regarding the measured sound spectra of ball bearing under high speed operation. He pointed out that, in the measured sound spectra, peaks with the shaft rotational frequency and its multiples as well as peaks with cage natural frequencies appeared [8]. This was pioneering research concerning a high-speed ball bearing sound and cage sound.

Okoshi investigated the measuring conditions for bearing sound in 1956 [9]. His research results formed the basis for the standardization of “Rolling bearings − Measuring methods of A-weighted sound pressure levels (JIS B 1548)” first published in 1960 [10].

In 1956-1957, Ishizaka [11], Utumi and Aoki [12], Hattori et al. [13] discussed the noise increase of bearings. This was pioneering research of the sound life of rolling bearings.

In 1957, Tanaka pointed out that peaks in the sound spectra of ball bearings were caused by the bending natural vibrations of the outer rings as well as rigid-body natural vibrations of the outer rings in the axial or radial directions [14].

After this early work, sound characteristics, sound generating mechanism, and some types of sound have been examined in detail since the late 1950s. In the following sections, the main research work on ball bearing sound is explained.

2.2 Characteristics and generating mechanism of ball bearing sound

Igarashi systematically studied characteristics and the generating mechanism of ball bearing sound under inner ring rotation. Typical sound spectra of a ball bearing in operation are shown in Fig. 1. He pointed out that the ball bearings have the following sound characteristics: (1) the sound has random characteristics, (2) the frequency of the sound is above about 1kHz, (3) the frequencies of the main peaks in the sound spectra do not significantly change and increase as external load increases, (4) the sound pressure increases as radial clearance is reduced or external load increases. He explained the sound generating mechanism of ball bearings as follows: because of the random waviness on the raceways and balls, the Hertzian contact force between raceways and balls fluctuates while...
the ball bearings (under an external static load) rotate. This fluctuating Hertzian contact force is an excitation force to the ball bearings. This results in the outer rings resonating at their natural frequencies, causing them to radiate sound. He explained that, in the case of the ball bearings installed in the bearing housing, although the frequencies of the main peaks in the sound spectra are mainly caused by the natural vibrations of the outer rings, a few peaks are caused by the bending natural vibration of the cages [15-19].

Nagamatsu et al. studied the high-speed ball bearing sound under inner ring rotation and explained that the sound spectra mainly consists of the following: (1) the shaft rotational frequency and its multiples, (2) the ball passage frequency and its multiples, and (3) the natural frequencies of the outer rings [20-22].

Ohta and Satake examined the sound of the all-ceramic ball bearings, the hybrid ceramic ball bearings, and the conventional steel ball bearings. They elucidated that the sound spectra of each bearing mainly consist of the peaks due to the natural vibrations of the outer rings, and the peak frequencies of the all ceramic ball bearings are higher than those of the other bearings. They also pointed out that, for each bearing, the sound pressure is approximately proportional to the vibratory acceleration of the outer rings. In addition, they observed that, comparing the hybrid ceramic ball bearings and the conventional steel ball bearings, the overall sound pressure levels of the all-ceramic ball bearings are low [23].

2.3 Cage sound

Nishimura and Takahashi measured the sound emitted from a ball bearing in which the outer ring was tightly fitted into the belt driven fly wheel. They pointed out that, in this experimental condition, because of the ball/cage impact, the sound caused by the cage in-plain natural vibration (the radial bending natural vibrations of the cages) occurred [24].

Goto and Watanabe dealt with abnormal sound of the cage as a problem in precision ball bearings for machine tools. They explained that abnormal sound of the cage was produced by a self-excited cage vibration resulting from the sliding friction between the balls and cage pockets [25].

Momono and Noda examined experimentally the relationship between the cage sound and the cage motion. They elucidated that two types of the cage sound occurred in operation: one was a rasping sound and the other was a rattle. They pointed out that, when the cage sound did not occur, the orbit of the cage was an almost circular shape. However, the orbits of the cage were hypotrochoid-like shape and an irregular shape during the rasping sound and rattle, respectively [26].

2.4 Squeak in cylindrical roller bearings

Iida studied the noise of cylindrical roller bearings and he found that a greased cylindrical roller bearing type NU310P squeaked at 1200 rpm. Also, he pointed out that the squeak frequency was about 8000 Hz and tended to occur in bearings with larger radial clearances [27-29].

Ito presumed that the main cause of the squeak under a high amount of grease is the change of the roller rotational speed due to the drag of the grease [30].

Kobayashi and Kurita pointed out that the cylindrical roller bearings squeak under the grease lubrication as well as oil lubrication. They presumed that the squeak is related to an unstable vibration in the lubricating film between the outer race and rollers in the unloading zone [31].

Nakai et al. measured the sound, vibration and roller/race slip to explain the squeak of greased cylindrical roller bearings. They elucidated that the natural frequency calculated by the coupled vibration between the outer ring and rollers in the loading zone matches with the main frequency of the squeak [32, 33].

Murai explained that, to prevent the squeak of cylindrical roller bearings, the following
combination is effective: (1) use of straight rollers, (2) use of a wide contact area and a small clearance between the outer ring and the cage [34].

2.5 Sound of defective bearings

Igarashi studied the sound of defective ball bearings. Typical sound waveform of a ball bearing with an outer race defect is shown in Fig.2. He observed that, in the case of a ball bearing with a defect in the raceway or ball, the sound pulses occur in the time waveforms. He also elucidated that the sound pulse recurrence frequency is $Zf_i$ for the inner ring defect, $Zf_c$ for the outer ring defect and $2f_b$ for the ball defect. In these symbols, $Z$ is the number of balls, $f_i$ is the inner ring rotational frequency relative to the cage, $f_c$ is the cage rotational frequency and $f_b$ is the rotational frequency of the ball about its own axis [35]. Furthermore, he investigated the case of a ball bearing with multiple defects on the raceway. He pointed out that the sound pulse recurrence frequency of a ball bearing with multiple defects is similar to that of a ball bearing with a defect in the raceway. Also he showed that, for the multiple defects, pulses with a time delay (related to the angle between the adjacent defects) occur [36].

2.6 Contamination noise

Hirota and Ohashi measured the noise of ball bearings under the oil bath lubrication with solid foreign substances (iron and white alundum particles). They observed that, due to the solid foreign substances, the sound pressure level of the bearings rapidly increased with operating time, and then increased slightly or became saturated [37].

Komiya measured the contamination noise with a pulse counter. He pointed out that the particle size of a contaminant recognized as causing contamination noise was about $10 \mu m$ or larger. In addition, when contaminants were mixed into a grease with a lower base oil viscosity or a greater consistency, the number of pulses caused by contamination noise increased [38].

2.7 Sound life

Toshiro Suzuki and Tomita Suzuki examined the relationship between the grease life and sound deterioration of sealed ball bearings. They found that the time from the initial sound pressure of the bearings increasing to 6dB was half to one thirds of the grease life [39].

Hishiki et al. studied sound life of ball bearings. They pointed out the following: (1) when the bearing load was increased, the sound pressure level of the ball bearings attained the higher saturation values quickly. (2) The sound life of ball bearings can be expressed both by the total number of revolutions until the saturation value is attained, and by the saturation value. (3) Increase of the sound pressure level was caused by the irregularity of

Fig. 2 Sound waveform of ball bearing with outer race defect [35]
the steel ball surfaces. (4) In a steel ball having a larger half value width of martensite (211), the sound pressure level does not increase during the sound life test [40, 41].

3. Rolling bearing vibration

3.1 Early research of rolling bearing vibration

The world’s first research paper on rolling bearing vibration was written by Perret in Germany in 1950 [42]. In Germany, Perret [42-44] and Meldau [45] studied theoretically the motion of a horizontal shaft supported by rolling bearings. They predicted that, even using geometrically-perfect rolling bearings, the shaft center displaces with a rolling element (ball or roller) passage frequency in operation. This phenomenon has been called “rolling element (ball or roller) passage vibration.”

Most likely, the first Japanese research paper on rolling bearing vibration was written by Yamamoto and was published in 1954 [46, 47]. He examined the critical speed of a shaft supported by ball bearings. In the following sections, the main research work on ball bearing vibration in Japan is explained.

3.2 Rolling element (ball or roller) passage vibration

Yamamoto discussed the ball passage vibration of a vertical shaft supported by deep groove ball bearings. He pointed out that, the critical speed with ball passage frequency $Z_{fc}$ especially occurs when the center lines of bearing pedestals are misaligned. He also explained that, for the bent shaft supported deep groove ball bearings, the critical speeds with the frequencies $Z_{fc} - f_r$ and $Z_{fc} + f_r$ (in which $f_r$ is the inner ring rotational frequency) occur

Fig. 3 Simulation results of ball passage vibration [55]
A. Tamura and Taniguchi found that, when the outer ring was distorted in an oval shape, the amplitude of the ball passage vibration in the radial direction became larger than that of the non-distorted outer ring [49]. They also elucidated that, in actuality, the ball passage vibration occurs not only in the radial direction but also in the axial direction [50, 51].

H. Tamura et al. carried out the quasi-static vibratory analysis for the ball passage vibration of an ideal ball bearing in which the inner ring moves in the radial plane under a radial load. They presented a complete package for the estimation of the magnitudes and characteristics of the inner ring motion [52, 53]. Hara et al. performed the quasi-static vibratory analysis for the roller passage vibration of a rotor supported by cylindrical roller bearings [54].

Fukata et al. [55], and Tsuda et al. [56] carried out the computer simulation for the ball passage vibration of an ideal ball bearing in which the inner ring has mass, rotates with a constant speed, and is loaded by a constant force. Their simulation result is shown in Fig. 3. Also, they pointed out that, based on the simulation results, superharmonic, subharmonic, beat and chaos-like vibrations appear, in addition to harmonic vibration synchronizing with the ball passage frequency.

3.3 Natural vibration of outer ring

To explain the dominant peaks in the measured sound and vibration spectra of a loaded ball bearing in operation, the natural vibrations of the outer ring have been examined since 1950s, as mentioned above in section 2.1.

Tanaka presented vibratory models (including the Hertzian contact stiffness) of the outer ring of a ball bearing under axial load and showed the natural frequency expressions for the axial and radial rigid-body modes [14].

Igarashi derived the natural frequency expressions for the tilt rigid-body mode and the radial bending modes of the outer ring of a ball bearing under an axial load [57, 58].

Ohta studied the vibratory modes and natural frequencies of the outer ring itself for the deep groove ball bearings [59], tapered roller bearings [60] and cylindrical roller bearings [61]. He pointed out that measured vibratory modes and natural frequencies of the outer ring can be explained by combinations of the natural frequency expressions proposed by Kirkhope and Love.

Igarashi and Ohta measured the modes of the outer ring and developed, based on the Hertzian theory as well as Kirkhope’s and Love’s theory, the accurate natural frequency expressions for the tilt, axial and vertical rigid-body modes, the axial and radial bending modes, the extensional mode and the torsional mode of the outer ring of an axially loaded deep groove ball bearing [62-65]. An example of the measured natural modes of the outer ring is shown in Fig. 4. They showed the natural frequencies and modes calculated by the presented expressions almost match the measured frequencies and modes of the dominant peaks on the conventional steel bearings [62-65] as well as the hybrid ceramic ball bearings [66] and the all-ceramic ball bearings [67]. Ohta et al. also carried out natural

![Fig. 4 Measured radial modes of outer ring [63]](image)
vibration analysis for the outer ring of a deep groove ball bearing under a radial load [68-70] and also that of a tapered roller bearing under an axial load [71-73]

3.4 Natural vibration of cage

Ohta and Kataoka measured the natural frequencies and modes of ribbon cages for deep groove ball bearings and carried out natural vibration analysis using a finite element method (FEM). They elucidated that, in the ribbon cage itself, four types of natural vibrations exist: the axial bending, the radial bending, the torsional and the extensional natural vibrations. They also showed that the measured natural frequencies and modes almost matched the calculated results obtained by FEM [74].

3.5 Vibration caused by geometrical imperfections of rolling bearings

Actual rolling bearings have geometrical imperfections such as the diameter variations among the rolling elements, waviness of the rolling elements and races, and unequally-spaced rolling elements. These are the main causes of sound and vibration of rolling bearings. Landmark analytical work in this type of vibration was carried out by Gustafsson [75, 76] in the USA and Yhland [77] in the Netherlands. In Japan, experimental work and simulation for this type of vibration have been carried out as follows:

Yamamoto measured the critical speed of a shaft supported by ball bearings having the diameter variations among the balls. He pointed out due to the diameter variations among the balls, two types of excitation occur. One has the cage rotational frequency $f_c$, and the other has $2f_c-f_r$. He also pointed out that there are two types of critical speeds caused by these excitations [46, 47].

A. Tamura investigated the axial vibration of the ball bearing with two oversized balls [78]

Goto and Watanabe measured the orbit of the machine tool spindle supported by preloaded ball bearings. They pointed out that epitrochoid-like and hypotrochoid-like orbits relate to the waviness of the races of ball bearings [79]. They also measured the orbit of the machine tool spindle supported by roller bearings and discussed the relationship between the orbit

![Fig. 5 Simulation results of the effect of the outer ring bends on the orbit [86]](image_url)
shapes and the diameter variations among the rollers as well as the waviness of the races [80].

Noguchi et al. simulated the effects of geometrical imperfections on the non-repeatable run-out (NRRO) of ball bearings [81-85].

Okamoto et al. analyzed the effects of the form error of the outer ring, inner ring eccentricity and diameter variations among the balls in a ball bearing on the orbit of the shaft. In their analysis, they assumed that each bearing part is a rigid-body and the Hertzian contact forces and deformations were ignored. Their simulation result is shown in Fig. 5. They explained that the calculated and measured orbits are affected by both the number of balls and the number of outer ring bends (waviness). Their calculated results closely matched the experimental results [86].

Sakaguchi and Akamatsu took into account the Hertzian contact forces and deformations in the model by Okamoto et al. From a qualitative standpoint, their calculated results are similar as those by Okamoto et al. [87].

Tada developed a 3-Dimensional Analytical program of ball bearings and explained the effects of the waviness of the races on the NRRO [88].

3.6 Nonlinear vibration

Yamamoto et al. [89-94] and Ishida et al. [95, 96] systematically studied the nonlinear vibrations (subharmonic, ultra-subharmonic, summed-and-differential harmonic oscillations, etc.) of a rotating shaft supported by ball bearings caused by the clearance, nonlinear stiffness and so on of these ball bearings.

A. Tamura and Taniguchi [97] analyzed the nonlinear axial vibration of a ball bearing. Shimizu and H. Tamura [98-100] and H. Tamura and Tsuda [101, 102] examined the nonlinear contact stiffness of the ball bearings in association with the vibrations of a rotor supported by ball bearings.

In addition, Fukata et al. [55], and Tsuda et al. [56] studied the nonlinear vibration of a ball bearing as mentioned above in Sec. 3.2.

3.7 Abnormal vibration of grease lubricated ball bearings

Igarashi et al. [103, 104] and Itagaki et al. [105-107] investigated the abnormal vibration of grease lubricated ball bearings. They explained the abnormal vibration using the nonlinear and the self-excited vibration models including the grease property.

3.8 Vibration of defective bearings

Igarashi et al. studied the vibration of defective ball bearings. They elucidated that, for the defective ball bearings, the vibration pulse recurrence frequency is the same as the sound pulse recurrence frequency [108, 109]. Furthermore, they investigated the diagnosis method of defects in a ball bearing using vibration measurements [110, 111].

3.9 Damping and squeeze film damper

Shoda [112], Mitsuya et al. [113] and Takehara [114] examined experimentally the vibration damping characteristics of rolling bearings. Saito [115, 116] and Kobayashi [117, 118] studied the vibrations of the a rotor supported by ball bearings with the squeeze film dampers.

4. Closure

In this article, the progress of the sound and vibration research of rolling bearings in Japan has been explained. As a typical application of this research, in recent years, a condition-based monitoring for the rotational machinery with rolling bearings (using the
sound and vibration measurements) is widely used in the industrial fields.

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