534.13:621-822

Paper No. 204-18

Studies on the Vibration and Sound of Defective Rolling Bearings*

(First Report: Vibration of Ball
Bearings with One Defect)

By Teruo IGARASHI** and Hiroyoshi HAMADA***

An investigation was undertaken with a view to establishing a procedure for diagnosing rolling bearings for defects from their vibration and sound. In the present investigation the vibration and sound of a rolling bearing with one dent on the race surface of the inner or outer ring or on the ball surface were studied. When the inner ring was caused to rotate at a constant speed under a given thrust load applied to the outer ring, the outer ring radial vibration velocity was determined by a moving coil type converter. Using the data so obtained, vibration waveforms were observed, peak vibration pulses measured, and real time frequencies of the vibration analyzed by Fast Fourier Transform analyzer. As a result, the fundamental characteristics of ball bearings having one defect were clarified, and a method by which to locate the defect and determine its size was established.

1. Introduction

A rolling bearing which carries a load by means of a finite number of rolling elements has an inherent drawback in that it is liable to produce vibration and sound. Much work has been done over a period of years to find a means to prevent rolling bearing vibration and sound (1)(2). However, the bulk of the work so far done concerns normal rolling bearings, and little work has been done concerning the vibration and sound of defective rolling bearings, with the exception of studies conducted to find a method for defect detection (3)(4). Vibration and sound of rolling bearings constitute an important theme of basic research indispensable to early detection of rolling bearing defects. In the first part of the present investigation, therefore, an attempt was made to elucidate the fundamental characteristics of ball bearings having one defect.

2. Theoretical equation

An attempt to determine the vibration of ball bearings with one defect starts by establishing the necessary theoretical equations. Assume for the present that the inner ring is rotating at a constant speed with the outer ring under a constant thrust load, as shown in Fig.1. Putting the inner ring revolution speed as f_r (Hz),

the speed of the retainer or ball revolution, f_c (Hz) and the speed of ball rotation f_b (Hz) can be obtained from the equations (5)

$$f_c = \frac{f_r}{2} \left(1 - \frac{d}{D} \cos \alpha \right) \dots\dots\dots (1)$$

$$f_b = \frac{f_r D}{2d} \left(1 - \frac{d^2}{D^2} \cos^2 \alpha \right) \dots\dots\dots (2)$$

where,

d = ball diameter

D = pitch circle diameter

α = contact angle

The formula for calculating the vibration of a ball bearing with one defect will be derived from these equations.

2.1 Recurrence frequency of vibration pulses

Assume that there is one defect p on the inner surface of a ball bearing, as shown in Fig.1. Since the defect on the inner race comes into contact with balls, the speed of the inner ring revolution f_i relative to the ball revolution speed (or retainer revolution) is given by the equa-

Fig.1 Motion of Ball Bearing under a Constant Thrust Load

* Received 30th July, 1980.

** Professor, Technological University of Nagaoka, Kamitomioka-cho, Nagaoka, Niigata.

*** Mitutoyo Mfg. Co. Ltd., Kawasaki, Kanagawa.

tion

$$f_i = f_r - f_o \dots\dots\dots (3)$$

During the time the ball bearing makes one revolution through 360 deg., it comes into contact with a certain number of rotating balls. Putting the number of balls as Z, the recurrence frequency of the vibration pulses arising from the defect on the inner race is given by the equation

$$zf_i = z(f_r - f_o) = \frac{zf_r}{2} \left(1 + \frac{d}{D} \cos \alpha\right) \dots\dots\dots (4)$$

If there is a defect on the outer race, as shown at q in Fig.1, Z balls pass over this defect at f_o speed of revolution. Accordingly, the vibration pulses arising from the defect on the outer race have a recurrence frequency which can be calculated by the equation

$$zf_i = \frac{zf_r}{2} \left(1 - \frac{d}{D} \cos \alpha\right) \dots\dots\dots (5)$$

If there is a defect on the periphery of a ball, as shown at r in Fig.1, the defect comes into contact with both the inner and outer races each time the ball bearing makes one complete turn. In this case the recurrence frequency of vibration pulses arising from the defect is calculated from the equation

$$2f_i = f_r \frac{D}{d} \left(1 - \frac{d^2}{D^2} \cos^2 \alpha\right) \dots\dots\dots (6)$$

2.2 Reciprocal of the defect contact-ing element passage time

The main frequency component of the vibration pulses due to a ball bearing having a defect on its periphery is assumed to be related to the reciprocal f_t of the time required for the element to pass over the defect in the circumferential direction, that is, the duration of a shock pulse, and f_t can be calculated as follows:

Assume that there is a defect of circumferential width b on the inner race. From Fig.1 and Eq.(3) the speed V_i of inner race relative to the speed of ball revolution is given by the equation

$$v_i = \frac{D_i}{2} 2\pi f_i = \frac{\pi D_i f_r}{2} \left(1 + \frac{d}{D} \cos \alpha\right) \dots\dots\dots (7)$$

Since $D_i = D - d \cos \alpha$,

$$v_i = \frac{\pi D f_r}{2} \left(1 - \frac{d^2}{D^2} \cos^2 \alpha\right) \dots\dots\dots (7)'$$

Therefore, the reciprocal f_t of the time

Fig.2 Measuring Principle of Vibration of Outer Ring

required for the ball to pass over the circumferential width b of the defect on the inner race can be calculated by the equation

$$f_t = \frac{v_i}{b} = \frac{\pi D f_r}{2b} \left(1 - \frac{d^2}{D^2} \cos^2 \alpha\right) \dots\dots\dots (8)$$

f_t for a defect of circumferential width b on the outer race or the ball can also be calculated by Eq.(8). In other words, the value of f_t is the same, no matter whether the defect is on the outer race or on the ball, so long as its circumferential width b is the same. The value of f_t calculated from Eq.(8) will be referred to as the calculated frequency in this paper.

3. Vibration measurement method and test ball bearing

An andersonmeter (Sugawara Laboratory) was employed in the measurement of ball bearing vibration. The andersonmeter is an instrument which is designed to make a measurement of radial vibration at one point of the outer ring of a rolling bearing while its inner ring is rotating at a speed of 1,800 rpm. The measuring principle of the andersonmeter is schematically represented in Fig.2. A thrust load of 29.4 N is applied to the outer ring of the test ball bearing by a preloader, and the radial vibration of the outer ring is measured by the andersonmeter. As shown in Fig.3, the output of the andersonmeter pre-amplifier PA₁ is amplified, and using the signal thus obtained, vibration waveform observations, peak vibration measurement and real time frequency analysis by Fast Fourier Transform (FFT) are made.

The test rolling bearing was a single row deep groove ball bearing designated 6205CM (incorporating 9 balls). A defect was made in the inner or outer ring of such a ball bearing by pressing a steel ball against it or by electrospark machining. It is, however, difficult to make a dent in a steel ball. In our experiments, therefore, a flat scratch was made on the

C: Converter (moving coil type) M: Meter
T: Transformer MA: Measuring amplifier
PA1: Pre-amplifier WM: Wave memory
LS: Loud speaker LPF: Low pass filter
ATT: Attenuator OS: Oscillo-scope
PA2: 2nd pre-amplifier FFT: Fast Fourier Transform
BPF: Band pass filter analyzer
A: Meter amplifier X-Y: X-Y recorder

Fig.3 Arrangement of Vibration Measuring Instruments

steel ball by surface grinding. The methods employed to obtain test ball bearings with an artificial defect are described in Tables 1, 2 and 3, and the typical defect shapes are shown in Fig.4. Defects of these shapes were made in the inner and outer rings at a position where they would contact the steel balls at a thrust load of 29.4 N, and the circumferential width b and defect depth h were determined from Fig.4. The loading directions shown in Tables 1, 2 and 3 are those of the thrust load. The bearing identification number was stamped on one side of the outer ring, and the direction of loading was distinguished by use of the letters M and NM, M indicating the direction of load application which is toward the marked end and NM indicating the direction of load application which is toward the opposite side. The lubricant used in the experiments was kerosene.

Table 1 Working Method of Inner Ring Defect and Test Ball Bearing

Working Method of Defect	Test Ball Bearing	Loading Direction	Circumferential Width of Defect $b : \mu\text{m}$	Defect Depth $h : \mu\text{m}$
Pressing a steel ball 7.938 mm in diameter	1 - 1	M	672	4.5
		NM	670	5.0
	1 - 2	M	904	9.0
		NM	896	10.0
	1 - 3	M	1066	14.0
		NM	1070	14.0
	1 - 4	M	1240	20.0
		NM	1200	18.5
	1 - 5	M	1310	22.0
		NM	1314	22.6
Pressing a steel ball 4.762 mm in diameter	2 - 3	M	1080	16.5
		NM	940	14.5
	2 - 4	M	1120	22.0
		NM	1240	26.0
	2 - 5	M	1240	27.0
		NM	1320	31.5
Electrospark machining by a copper wire electrode 2.5 mm in diameter	5 - 3	M	1092	85
		NM	1020	70
	5 - 4	M	1280	115
		NM	1190	105
	5 - 5	M	1280	115
		NM	1290	115

M indicating marked side and NM indicating the opposite side

Table 2 Working Method of Outer Ring Defect and Test Ball Bearing

Working Method of Defect	Test Ball Bearing	Loading Direction	Circumferential Width of Defect $b : \mu\text{m}$	Defect Depth $h : \mu\text{m}$
Pressing a steel ball 7.938 mm in diameter	3 - 3	M	880	4.0
		NM	840	4.0
	3 - 4	M	1180	8.0
		NM	1280	7.4
	3 - 5	M	1320	5.0
		NM	1200	4.5
Pressing a steel ball 6.350 mm in diameter	7 - 3	M	1400	10.0
		NM	-	-
	7 - 4	M	920	5.6
		NM	1120	8.0
	7 - 5	M	1280	13.0
		NM	1220	12.0
Electrospark machining by a copper wire electrode 1.5 mm or 2.0 mm in diameter	9 - 3	M	1060	65
		NM	1170	90
	9 - 4	M	1260	50
		NM	1260	45
	9 - 5	M	1280	70
		NM	1260	50

4. Results and analysis

4.1 Waveforms of vibration due to defects

The waveforms of vibrations occurring in the defective ball bearings were observed through use of a wave memory, shown in Fig.3, and other instruments. A few examples of ball bearing vibration waveforms observed with an oscilloscope are given in Fig.5. From these oscillograms the following observations were made: (1) The pulse intervals are fixed regardless of the dent size, and the pulse recurrence frequency is Zf_i for the inner ring defect, Zf_o for the outer ring defect, and $2f_b$ for the ball scratch, where Z indicates the number

Table 3 Working Method of Ball Defect and Test Ball Bearing

Working Method of Defect	Test Ball Bearing	Loading Direction	Circumferential Width of Defect $b : \mu\text{m}$	Defect Depth $h : \mu\text{m}$
Surface grinding	8 - 1	M	800	20.2
	8 - 2	M	890	25.0
	8 - 3	M	1050	34.9
	8 - 4	M	1260	50.3
	8 - 5	M	1500	71.5

(a) Inner Ring Defect (Test Ball Bearing 1-4 NM)

(b) Inner Ring Defect (Test Ball Bearing 2-4 NM)

(c) Inner Ring Defect (Test Ball Bearing 5-4 M)

(d) Outer Ring Defect (Test Ball Bearing 3-4 NM)

(e) Outer Ring Defect (Test Ball Bearing 7-5 NM)

Fig.4 Typical Circumferential Shapes of Defect

of balls, f_i inner ring revolution speed (Hz) relative to the retainer revolution speed, f_c , retainer revolution speed (Hz), and f_b , ball rotation speed (Hz). These ball bearing vibration waveform observations are in agreement with the results of calculations made by the equations in section 2; (2) the high frequency component increases with an increasing defect size (as in test bearings 1-1 and 1-5); (3) in the case of an inner ring defect or ball scratch the pulse peak value varies with time by a large amount.

4.2 Peak value of vibration pulse and vibration measuring position

Using the peak value measuring circuit shown in Fig.3, the mean peak value of pulse waveforms appearing in oscillograms was determined. As a result, it was found that the peak value of pulse had nothing to do with the outer ring vibration measuring position for the inner ring defect and ball scratch, whereas it was affected by the outer ring vibration measuring position for the outer ring defect. The results of vibration measurements for the outer ring defect are presented in Fig.6. In both panels, the value 1 is assigned to the maximum peak value and the vibration measuring position relative to the position of a defect is indicated by relative angle of (θ) of rotation of the inner ring. As is obvious from Fig.6, the defect shape differs from position (a) to (b). In other words, in the case of test ball bearings of series 3, the peak value becomes largest when the measurement is taken at the defect position ($\theta = 0$), and becomes

smallest when the measurement is taken at 45 deg. ($\theta = 45$ deg.) in the direction of the inner ring rotation, as shown in (a) in Fig.6. In the case of test ball bearings in series 7, on the other hand, the peak value becomes largest when θ is near 247.5 deg. or 270 deg. and becomes smallest when θ is 45 deg. The peak value varies with each series of test ball bearings. This is probably because defects of differing shapes give rise to vibrations in shock pulse waveform, which in turn causes the mode of outer ring vibration to vary. When θ is 45 or 315 deg., the peak value is small, and when θ is 135 or 225 deg., the peak value is large, but may show a tendency to decrease in some cases. It can be supposed that this phenomenon appears because the vibration measuring position corresponds to the node of the first natural mode of the outer ring radial bending.

(a) Inner Ring Defect
(Test Ball Bearing 1-3 M)

(b) Normal Bearing (Test Ball Bearing 1-0 M)
1 V = 1.03 mm/s

Fig.5 Oscillograms of Vibration Waveform

(a)

(b)

Fig.6 Peak Value and Vibration Measuring Position (Case of Outer Ring Defect)

4.3 Real time frequency analysis by Fast Fourier Transform

Frequency analysis was made of the vibration occurring in test ball bearings over a wide band. As the vibration occurring in a ball bearing owing to a defect is pulse-like, the Fast Fourier Transform (FFT) analyzer shown in Fig.3 was used in the frequency analysis of ball bearing vibration due to a defect. In the results, it was found that the frequency spectrum of ball bearing vibration due to a defect had three peaks and one to three troughs (which will be referred to as nodes), as shown in Fig.7. The three peaks correspond, from left to right, to the axial natural frequency of the outer ring mass system (f_{AM}), the 1st radial bending mode natural frequency of the outer ring (f_{R1}), and the 1st axial bending mode natural frequency of the outer ring (f_{A1}), respectively. These peaks also occur in normal ball bearings (as in test ball bearing 1-0) (2). One to three nodes occur due to a defect, and the lowest frequency node (indicated by the arrow in Fig.7), that is, the first nodal frequency f_{n1} is associated with the circumferential width b of the defect. The values of f_{n1} and the

Fig.7 Frequency Spectra of Vibration due to a Defect
(Inner Ring Defect, Marked Side)

Table 4 First Nodal Frequency f_{n1} and Calculated Frequency f_t
(Case of Inner Ring Defect)

Test Ball Bearing	Load- ing Direc- tion	First Nodal Frequency f_{n1} : KHz	Calculated Frequency f_t : KHz	$\frac{f_{n1}}{f_t}$
1 - 1	M	3.25	2.62	1.24
	NM	3.20	2.61	1.23
1 - 2	M	2.10	1.96	1.07
	NM	2.15	1.93	1.07
1 - 3	M	1.75	1.64	1.07
	NM	1.65	1.65	1.00
1 - 4	M	1.55	1.46	1.06
	NM	1.50	1.42	1.06
1 - 5	M	1.50	1.34	1.12
	NM	1.55	1.34	1.16
2 - 3	M	1.70	1.63	1.04
	NM	1.70	1.87	0.90
2 - 4	M	1.60	1.57	1.02
	NM	1.60	1.42	1.13
2 - 5	M	1.60	1.42	1.13
	NM	1.60	1.33	1.20
5 - 3	M	1.90	1.61	1.18
	NM	2.25	1.72	1.31
5 - 4	M	1.75	1.37	1.28
	NM	1.85	1.48	1.25
5 - 5	M	1.80	1.37	1.31
	NM	1.70	1.36	1.25

M indicating marked side and NM indicating the opposite side

reciprocals of the times required for the ball to pass over the defect circumferential width b , that is, values of the calculated frequency f_t obtained from Eq.(8) are shown in Tables 4 and 5. The values of f_{n1} and the reciprocals of the times required for the inner or outer ring to pass over the defect circumferential width b , that is, values of the calculated frequency f_t are shown in Table 6. The f_{n1}/f_t ratios indicated in the rightmost column of these tables range from about 1 to 1.3 for the inner ring defect, from about 1.3 to 2 for the outer ring defect and from about 1.2 to 1.4 for the ball defect. Therefore, if f_{n1} can be known, an approximate value of defect circumferential width b can be derived.

The frequency spectrum of ball bearing vibration due to a defect was also analysed in the 1 KHz frequency range. The frequency spectra so obtained are illustrated in Fig. 8. As is clear from this figure, the frequency spectrum of ball bearing vibration is composed mainly of mZf_i and $mZf_i \pm n f_r$ for an inner ring defect, of mZf_c for an outer ring defect and $2mf_b$ and $2mf_b \pm n f_c$ for a ball defect, where m and n are positive integers, and f_r the speed (Hz) of the inner ring revolution. The frequency components mZf_i , mZf_c and $2mf_b$ arise from vibration pulses having the recurrency frequencies Zf_i , Zf_c and $2f_b$

Table 5 First Nodal Frequency f_{n1} and Calculated Frequency f_t
(Case of Outer Ring Defect)

Test Ball Bearing	Load- ing Direc- tion	First Nodal Frequency f_{n1} : KHz	Calculated Frequency f_t : KHz	$\frac{f_{n1}}{f_t}$
3 - 3	M	2.95	2.01	1.47
	NM	2.85	2.10	1.36
3 - 4	M	2.23	1.50	1.49
	NM	2.20	1.38	1.59
3 - 5	M	2.10	1.34	1.57
	NM	2.05	1.47	1.39
7 - 3	M	3.10	1.26	2.46
	NM	-	-	-
7 - 4	M	3.35	1.92	1.74
	NM	2.63	1.58	1.66
7 - 5	M	2.60	1.38	1.88
	NM	3.10	1.45	2.14
9 - 3	M	2.65	1.66	1.60
	NM	2.30	1.51	1.52
9 - 4	M	1.98	1.40	1.41
	NM	2.00	1.40	1.43
9 - 5	M	1.90	1.38	1.38
	NM	1.90	1.40	1.36

Table 6 First Nodal Frequency f_{n1} and Calculated Frequency f_t
(case of Ball Defect)

Test Ball Bearing	Load- ing Direc- tion	First Nodal Frequency f_{n1} : KHz	Calculated Frequency f_t : KHz	$\frac{f_{n1}}{f_t}$
8 - 1	M	2.75	2.21	1.24
8 - 2	M	2.45	1.98	1.24
8 - 3	M	1.95	1.68	1.16
8 - 4	M	1.80	1.40	1.29
8 - 5	M	1.60	1.17	1.37

respectively. The frequency component mZf_i of vibration due to an inner ring defect and the frequency component $2mf_b$ of vibration due to a ball defect will be discussed in the section that follows.

4.4 Prolonged waveform observation

To clarify the cause of occurrence of the two kinds of frequency spectra mentioned above, ball bearing vibration waveforms were stored in the wave memory (Fig.3) for as long a time as it permitted. The oscillograms of reproduced vibration waveforms so stored are illustrated in Fig.9. In this figure the waveform of ball bearing vibration due to an outer ring defect is also shown. This waveform is characterized by a pulse amplitude which is nearly constant. In the case of an inner ring defect, however, the vibration pulse repeats $1/f_r$ cycle amplitude modulation and in the case of a ball defect the vibration pulse repeats $1/f_c$ amplitude modulation. It can therefore be assumed that whereas the frequency component mZf_i of vibration due to an inner ring defect occurs because the vibration pulse train occurring at the recurrence frequency Zf_i undergoes amplitude modulation at the recurrence frequency f_r , the frequency component $2mf_b$ of vibration due to a ball defect occurs because the vibration pulse train occurring at the recurrence frequency $2f_b$ undergoes amplitude modulation at the recurrence frequency f_c (6). These amplitude modulations of the vibration pulse trains seem ascribable to time-related changes in

defect position relative to the vibration measuring position.

5. Consideration and summary

5.1 Ratio of first nodal frequency

f_{n1} and calculated frequency f_t

As is clear from Tables 4 and 5, the f_{n1}/f_t ratio is smaller with an inner ring defect than with an outer ring defect. The cause of the difference in f_{n1}/f_t ratio will be discussed in this section.

Let us compare the shapes of inner and outer ring defects produced by means of steel balls of the same diameter. The inner ring defect (a) and the outer ring defect (d) shown in Fig.4 are dents produced by the use of steel balls 7.938 mm in diameter in such a way that the dents might have much the same circumferential width. The inner ring dent has a protruding shoulder, while the outer ring dent has a rounded one. It may therefore be posulated that in the case of inner ring defects like the one shown in (a) in Fig.4, a shock pulse resembling a rectangular wave occurs in the bearing under the influence of the protruding shoulder of the defect, whereas in the case of outer ring defects like the one shown in (d) in Fig.4, a shock pulse resembling a half cosine wave occurs in

(a) Inner Ring Defect
(Test Ball Bearing 2-3 M)

(b) Outer Ring Defect
(Test Ball Bearing 3-3 M)

(c) Ball Defect
(Test Ball Bearing 8-3 M)

0 dB = 0.757 (mm/s)_{rms}

Fig.8 Components of Frequency Spectrum

(a) Inner Ring Defect
(Test Ball Bearing 2-3 M)

(b) Outer Ring Defect
(Test Ball Bearing 3-3 M)

(c) Ball Defect
(Test Ball Bearing 8-3 M)

1 V = 1.03 mm/s

Fig.9 Oscillograms of Prolonged Vibration Waveform

the bearing under the influence of the rounded shoulder of the defect. Further, the outer ring dent shown in (e) in Fig.4 has its center protruding. It can be assumed that in the defect of this shape a shock pulse resembling a symmetrical triangular wave occurs in the bearing. As the frequency response of outer ring vibration in ball bearings receiving various shock pulses is not known as yet, the assumption is made in the present discussion that the frequency response of the outer ring vibration over a relatively low frequency range bears a close resemblance to the shock spectrum. The residual shock spectra of the three kinds of shock pulses, i.e., rectangular pulse, half cosine pulse and symmetrical triangular pulse, are shown in Fig.10 (7)~(9). In Fig.10, A indicates the maximum value of shock pulse, T, the duration of shock pulse, $S(f)$, the residual shock spectrum, and f , the frequency. The lowest zero-point frequency derived from this figure is $1/T$ for the rectangular pulse, $1.5/T$ for the half cosine pulse, and $2/T$ for the symmetrical triangular pulse. Since $1/T$ is equal to f_t , the value that corresponds to f_{n1}/f_t is 1.0 for the rectangular pulse, 1.5 for the half cosine pulse and 2.0 for the symmetrical triangular pulse. Accordingly, it can be understood that f_{n1}/f_t is near 1.0 for a dent made in a convex surface, like an inner race or a steel ball surface in the circumferential direction, while the corresponding value ranges from 1.5 to 2.0 for a dent made on a concave surface like an outer race in the circumferential direction. In our experiment, a flat ball defect was made for convenience's sake, but its f_{n1}/f_t is assumed to be near that of an inner ring defect. Accordingly, it may be said that the value of f_{n1}/f_t is governed by the circumferential shape of the defect.

5.2 Frequency spectrum components of bearing vibration due to defects

The frequency spectrum components of bearing vibration due to defects were discussed in Sec.4.3 and 4.4. In the case of inner ring and ball defects, however, it is necessary to take into account the frequency components which arise from the modulation of vibration pulse trains.

Fig.10 Residual Shock Spectra of Rectangular Pulse, Half Cosine Pulse and Symmetrical Triangular Pulse

ation of vibration pulse trains. This section will deal with the question of modulation-induced frequency components of bearing vibration.

As ball defects of differing shape were not used in our present experiment, mention will be made here of inner ring defects. The inner ring dents made in the axial direction in the series 1 and 5 test ball bearings had much the same circumferential width and depth, while in the case of series 2 test ball bearings a dent was made only in the center area of the inner race in the axial direction. In the former bearings the vibration frequency spectrum contains various frequency components, such as $mZf_i \pm f_r$, $mZf_i \pm 2f_r$, and $mZf_i \pm 3f_r$, while in the latter bearings only the frequency component $mZf_i \pm f_r$ predominates (as shown at (a) in Fig.8). In association with these frequency components, the vibration pulse train occurring in the series 1 and 5 test bearings underwent pulse amplitude modulation at the recurrence frequency f_r , while the vibration pulse train occurring in the series 2 test bearing underwent sinewave-like amplitude modulation at the recurrence frequency f_r (as shown at (a) in Fig.9). These observations suggest that the modulation of the vibration pulse train is related to the axial length of the defect.

5.3 Summary

The results of the present investigation are summarized in Table 7.

6. Conclusions

The following conclusions are drawn from the experimental results, the analysis and the considerations:

(1) The vibration 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, where Z indicates the number of balls, f_i the speed (Hz) of inner ring revolution relative to the speed of retainer revolution, f_c , the speed (Hz) of retainer revolution, and f_b , the speed (Hz) of ball rotation.

(2) The first nodal frequency f_{n1} occurring in the frequency spectrum of bearing vibration due to a defect is related to the reciprocal f_t of the time required for the element to pass over the circumferential width of the defect, and f_{n1}/f_t is about 1 to 2. Further, it is

Table 7 Vibration of Simple Ball Bearing with One Defect

Position of Defect	Recurrence Frequency of Pulse	f_{n1}/f_t	Components of Frequency Spectrum	Recurrence Frequency of Amplitude Modulation of Pulse Train
Inner Ring	Zf_i	$1 \sim 1.3$	mZf_i $mZf_i \pm nf_r$	f_r
Outer Ring	Zf_c	$1.3 \sim 2$	mZf_c	Little Modulation
Ball	$2f_b$	$1 \sim 1.4$	$2mf_b$ $2mf_b \pm nf_r$	f_c

m, n : Positive Integers. Z : Number of Balls.
 f_r : Inner Ring Revolution Speed Hz.
 f_c : Retainer Revolution Speed Hz.
 f_i : $f_r - f_c$. f_b : Ball Rotation Speed Hz.
 Kerosene Lubrication.

postulated that the value of f_{nl} is governed by the circumferential shape of the defect.

(3) The frequency spectrum of bearing vibration due to defects comprises mainly mZf_i and $mZf_i \pm nf_r$ for the inner ring defect, mZf_c for the outer ring defect and $2mf_b$ and $2mf_b \pm nf_c$ for the ball defect, where m and n indicate positive integers and f_r , the speed (Hz) of inner ring revolution.

(4) These frequency components, i.e., mZf_i in the inner ring, mZf_c in the outer ring, and $2mf_b$ in the ball, arise from the vibration pulses which occur at the recurrence frequencies of Zf_i , Zf_c and $2f_b$ respectively. Further, the frequency component $mZf_i \pm nf_r$ occurring in the presence of an inner ring defect results from amplitude modulation at f_r of the vibration pulse train having the recurrence frequency Zf_i , and the frequency component $2mf_b \pm nf_c$ occurring in the presence of a ball defect results from amplitude modulation at f_c of the vibration pulse train having the recurrence frequency $2f_b$. It is postulated that these amplitude modulation of vibration pulse trains are ascribable to time-related changes in defect position relative to the outer ring vibration measuring position.

(5) The peak value of vibration pulse is not related to the outer ring vibration measuring position in the case of inner ring and ball defects, but the reverse is true for outer ring defects.

Acknowledgments

We express our deep appreciation to Assistant Professors Noriyoshi KANBAYASHI and Akira KYUSOJIN at the Technological University of Nagaoka for their valuable

advice and assistance in their specialized fields of electronics and mechanical engineering. We are also indebted to Mr. Takeo TAMURA at the Department of Engineering of Niigata University and Messrs. Hiroshi FURUKAWA and Yasunobu HOSOKAI at the Technological University of Nagaoka for their assistance in the preparation of test specimens. We must also extend our thanks to Mr. Shiroji YABE, a postgraduate of the Technological University of Nagaoka, for his assistance throughout the present investigation.

References

- (1) Igarashi, T., J. of Japan Soc. Lubrication Engrs. (in Japanese), Vol. 16, No. 4 (1971-4), p. 300.
- (2) Igarashi, T., J. of Japan Soc. Lubrication Engrs. (in Japanese), Vol. 22, No. 12 (1977-12), p. 751.
- (3) Braun, S. and Datner, B., Trans. ASME, J. Mach. Des., Vol. 101, No. 1 (1979), p. 118.
- (4) Gustafsson, O. G. and Tallian, T., ASLE Trans., Vol. 5, No. 1 (1962), p. 197.
- (5) Izawa, M., J. of Japan Soc. Lubrication Engrs. (in Japanese), Vol. 15, No. 10 (1970-10), p. 685.
- (6) Kawakami, M., Electronic Circuit II (in Japanese), (1976), p. 79, Kyōritsu-shuppan.
- (7) Broch, J. T., Mechanical Vibration and Shock Measurements, p. 38, Brüel and Kjaer.
- (8) Taniguchi, O. et al., Vibration Engineering Handbook (in Japanese), (1976), p. 332, Yōkendō.
- (9) Institute of Electronics and Communication Engineers of Japan, Electronics and Communication Handbook (in Japanese), (1979), p. 176, Ohm-sha.