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ACCURACY, EFFECTIVENESS AND IMPROVEMENT OF VIBRATION-BASED MAINTENANCE IN PAPER MILLS: CASE STUDIES

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Many current vibration-based maintenance (VBM) policies for rolling element bearings do not use as much as possible of their useful lives. Evidence and indications to prolong the bearings' mean effective lives by using more accurate diagnosis and prognosis are confirmed when faulty bearing installation, faulty machinery design, harsh environmental condition and when a bearing is replaced as soon as its vibration level exceeds the normal. Analysis of data from roller bearings at two paper mills suggests that longer bearing lives can be safely achieved by increasing the accuracy of the vibration data. This paper relates bearing failure modes to the observed vibration spectra and their development patterns over the bearings' lives. A systematic approach, which describes the objectives and performance of studies in two Swedish paper mills, is presented. Explanations of the mechanisms behind some frequent modes of early failure and ways to avoid them are suggested. It is shown theoretically, and partly confirmed by the analysis of (unfortunately incomplete) data from two paper mills over many years, that accurate prediction of remaining bearing life requires: (a) enough vibration measurements, (b) numerate records of operating conditions, (c) better discrimination between frequencies in the spectrum and (d) correlation of (b) and (c). This is because life prediction depends on precise knowledge of primary, harmonic and side-band frequency amplitudes and their development over time. Further, the available data, which are collected from relevant plant activities, can be utilized to perform cyclic improvements in diagnosis, prognosis, experience and economy.

1. INTRODUCTION

Primary vibration frequencies and their harmonics, generated by bearing defects whose amplitudes exceed predetermined levels, can be utilized to indicate bearing condition, [1–6]. They can be used for identification of failure causes, damage developing mechanisms and failure modes of most types of damage in rotating and reciprocating machines.

Detecting failure causes, and not just imminent failures, provides possibilities to control the machine's or component's condition before the deterioration becomes intolerable. Damage, which began in one part of a bearing, often cause damage to

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other parts after a while. Thus, a bearing's condition can be assessed more reliably by considering all the significant damage as recorded by its vibration history.

Vibration monitoring (VM) systems provide earlier indications of the changes in the machine's state. These indications can also be used in detecting deviations in the product quality before they show on quality control charts [7].

In spite of using VM programs, manufacturing machinery still experience failures and unplanned-but-before-failure replacements, (UPBFR). The latter arise when damage develop without being detected early by the system or maintenance staff due to personnel or system error, or some unexpected failure cause.

The seriousness of the condition indicated by the amplitudes of particular vibration frequencies or frequency bands is usually evaluated subjectively. The usual replacement rule in industry is; replace the bearing as soon as the amplitude of any of the bearing defect frequencies exceeds the normal. Analysis strongly suggests that more of the potential life of the bearings can be used if more accurate data and better records are available.

2. CASE STUDIES

The study analyses vibration measurements collected during 2 to 4 years from four types of roller bearings and used by two different paper machines in two companies. The paper mill companies, A and B, have 4 and 3 paper mill machines respectively, of different ages. Vibration is the main parameter used for monitoring the machines.

The vibration measurements are collected using Microlog and Presim[2] software in A, and CSI with the Master Trend Program from Computational Systems Inc. in B. The measurements are all in mm/s, root mean square (r.m.s.). The interval between vibration measurements varied between 2 and 5 months in A and was about 3 weeks in B.

The paper machines, PM10 at A and PM01 at B, were selected for more investigation because their databases included more replacements of identical bearings than the other machine databases. The systematic approach adopted for the analysis is summarized in Figure 1. The above-mentioned data were collected from these companies in January 1996.

2.1. CASE STUDY A

Data are formed from the measurements of 10 identical replaced spherical roller bearings of type 23228ck/SKF, which are usually used at the driven side of the leading roller of drying cylinders in PM10. The bearings were selected because they belong to the most troublesome area in the machine.

Also, there were not enough replaced bearings from other types to be included. Table 1 gives a summary of the information regarding these 10 bearings.

2.1.1. *Analysis and results*

The higher machine stiffness in the vertical direction makes the vibration amplitude lower than at the horizontal direction. Bearing frequencies of amplitude

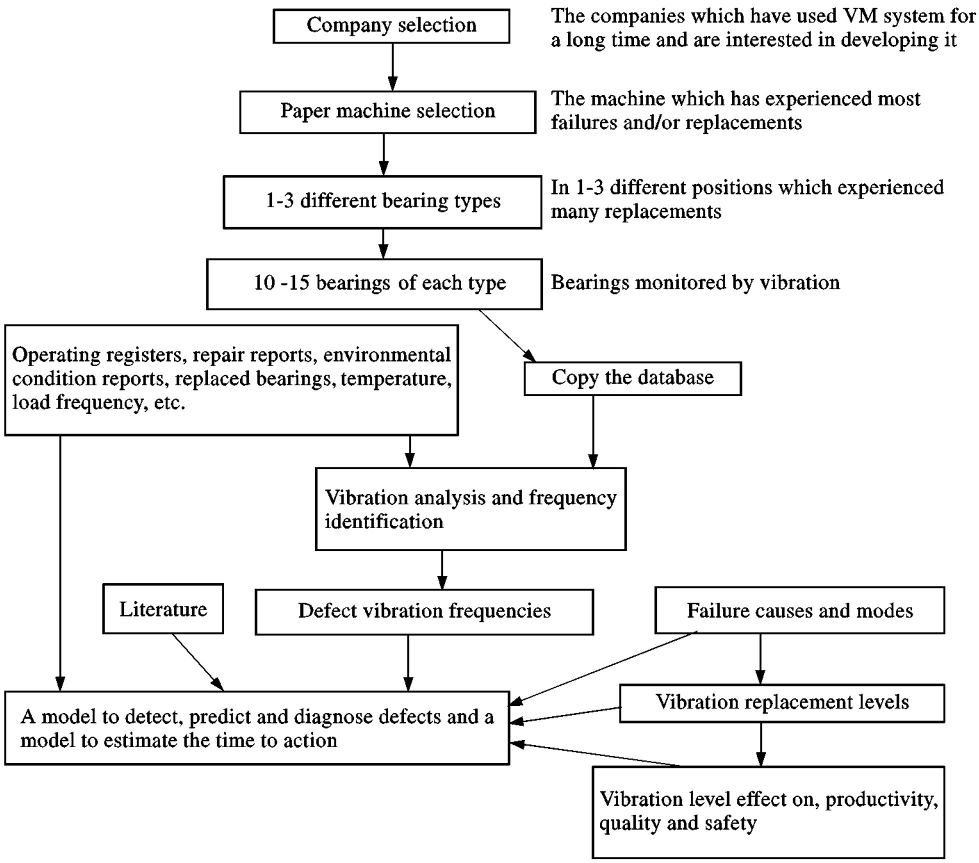


Figure 1. Investigation plan.

equal to or less than the noise level (0·05 mm/s) experienced at the machine, are considered insignificant and those equal to or larger than 0·15 mm/s, significant. In general, the change in the vibration amplitude can be considered significant if it exceeds double the original level [1, 8].

Frequencies with amplitudes between 0·05 and 0·15 mm/s are considered significant if there are other detectable bearing defect frequencies in the spectrum. This means that the significance of a defect vibration frequency amplitude is weighted by its own severity and also by the overall bearing damage severity. Let X and $i*X$ denote the machine speed and its ith multiple respectively. The existence of $2*X$ only, $1*X$ and $2*X$ simultaneously, many multiples of X, and many multiples of X and especially $2*X$ in each vibration spectrum, are denoted in Table 1 by $2X$, $1{\cdot}2X$, iX and $i{\cdot}2X$ respectively.

Let $BPFO$, $BPFI$, BSF and FTF denote ball pass frequency outer, ball pass frequency inner, ball spin frequency and fundamental train frequency respectively. The vibration levels of $BPFO$, $BPFI$, BSF, FTF, X and their higher multiples are given in the vertical and axial directions, and are classified into high and low. Undetectable frequencies are denoted by (—) and the detectable frequencies with

TABLE 1

Replaced bearings information

Roller no.	Date of installation	Date of replacement	Direction	Low level: BPFI	Low level: BPFO	Low level: BSF	Low level: FTF	Low level: 1X 2X 3X	High level: BPFI	High level: BPFO	High level: BSF	High level: FTF	High level: 1X 2X 3X	Replacement vibration level is the overall level, r.m.s. (mm/s): Vertical	Horizontal	Axial
41	880331	941027	Ver.	*I*	*O*	*B*	*F*	*iX*	—	—	—	—	2*X*	2·68	5·27	2·68
			Axi.	—	—	—	—	—	*I*	*O*	*B*	*F*	2*X*			
56	July/83	940929	Ver.	*I*	*O*	*B*	*F*	*iX*	—	—	—	—	—	1·21	5·13	2·03
			Axi.	*I*	*O*	*B*	*F*	*iX*	—	—	—	—	—			
59	July/83	950228	Ver.	—	—	—	—	—	*I*	—	—	—	—	0·86	0·87	1·66
			Axi.	—	*O*	—	—	*iX*	*I*	—	—	*F*	—			
64	July/83	941124	Ver.	*I*	*O*	*B*	*F*	*iX*	—	—	—	—	2*X*	0·97	2·26	2·54
			Axi.	—	—	—	—	*iX*	*I*	—	*B*	*F*	1·2*X*			
65	July/83	940721	Ver.	—	*O*	*B*	*F*	*iX*	*I*	—	—	—	2*X*	0·93	1·29	1·17
			Axi.	—	*O*	*B*	—	*iX*	*I*	—	—	*F*	2*X*			
72	July/83	941208	Ver.	*I*	*O*	*B*	*F*	—	—	—	—	—	*iX*	1·58	6·55	2·85
			Axi.	—	—	—	—	—	*I*	*O*	*B*	*F*	*iX*			
75	July/83	941226	Ver.	—	—	*B*	—	*iX*	*I*	*O*	—	*F*	—	2·94	2·66	2·94
			Axi.	—	—	—	—	—	*I*	*O*	*B*	*F*	2*X*			
80	July/83	941027	Ver.	—	*O*	—	*F*	*iX*	*I*	—	*B*	—	2*X*	2·07	6·64	4·35
			Axi.	—	—	—	—	—	*I*	*O*	*B*	*F*	*iX*			
85	July/83	950228	Ver.	*I*	*O*	*B*	*F*	*iX*	—	—	—	—	—	0·72	1·53	1·32
			Axi.	—	—	*B*	*F*	*iX*	*I*	*O*	—	—	2*X*			
95	July/83	950227	Ver.	—	*O*	*B*	*F*	*iX*	*I*	—	—	—	2*X*	0·91	1·31	3·14
			Axi.	—	—	—	—	—	*I*	*O*	—	*F*	*i*·2*X*			

Note: Ver. = vertical; Axi. = axial.

high or low levels have been denoted by I, O, B, F and jX, corresponding to $BPFI$, $BPFO$, BSF, FTF and X, respectively, for $j = 2$, 1·2, i, i·2.

Vibration levels larger than 0·3 mm/s are considered high and less than 0·3. Low vibration levels are considered high if other bearing defect frequencies are also detectable in the spectrum. The analysis of the vibration spectra history of these 10 bearings reveals that it is possible to discern changes in the bearing condition at an early stage when using bearing defect frequencies, their higher multiples and the combined frequencies. This use can be improved if the following conditions are met:

1. The frequency band covered by one resolution line should be less than 1 Hz. Its exact value depends on machine speed and the required diagnostic accuracy.
2. The interval between measurements should not be too long to avoid missing damage initiation and development.
3. Vibration measurements after maintenance actions, especially renewals, are most important to control the action quality, identify defects and their causes and follow their development easily.
4. The use of the frequencies representing the sum or difference of some of the bearing defect frequencies $BPFI$, $BPFO$, BSF, FTF) or their multiples, e.g. ($BPFI + 2*FTF$) or ($BPFO + 2*BSF$), is a reliable technique for detecting bearing defects, especially when it is impossible to recognize its defect frequencies and their multiples.
5. For an effective diagnosis, variations in bearing defect frequencies should be considered.

Bearings at the leading rollers of the drying cylinders suffered high ambient temperature, which reduced the lubricant viscosity and led to a reduced thickness of the oil film and severe wear due to metal-to-metal contact. This caused more frequent replacements of the bearings and is noticed at all leading roller bearing positions.

A combination of this phenomenon and high axial vibration level was (probably) behind the failure involving looseness of the tapered clamping sleeve in one of the leading rollers. Hence, the company considers changes in either the machine construction or in the lubricant system to be necessary. Several multiples of the machine speed can be found in almost all the spectra indicating.

1. waviness in the inner and/or outer races,
2. Rotation of the outer ring in the bearing housing or of the inner ring on the shaft, and/or
3. bearing misalignment due to faulty installation of the bearing or bent shaft.

The third reason is the most probable due to existence of high vibration levels at $2*X$ in both radial and axial directions in almost all the examined spectra, when no coupling misalignment is recorded. The “bent” shaft is probably due to excessive thermal expansion against end-stops, leading to hogging, which results in misalignment in the bearing. This is a design fault [9].

2.2. CASE STUDY B

In the database of the VM program at company B, three types of spherical roller bearing, which are usually used in the drying cylinders, were selected for deeper analysis due to their large number of replacements. These bearings are 23052 cck/SKF at the driven side (DnS) and 23060/HA3C4V33/SKF (replaced by 23060 cck/C4S3V33/SKF which has the same defect frequencies) at the driving side (DS): 89 bearings are considered in this study, i.e., 49 bearings of each type.

Only 42 bearing positions experienced replacements. The replacements are divided into five generations, see Tables 2 and 3. Fifty-six bearings (20 at DnS and 36 at DS) have run since their installation in August 1997, i.e., 221 months. There is only one bearing position that has experienced four replacements, 2 have experienced three, 16 have two replacements and the rest, i.e., 20 bearings, have one replacement during the period August 1977–January 1996.

The company started keeping the vibration measurements in November 1992. The measurements taken straight after the installation of bearings are available only for the bearings at the drying cylinders with number (11, 12, 15 and 32)/DnS and 27/DS because they were installed during the last 3 years of the period under consideration. The vibration measurements covered the frequency range 0–300 Hz, with 400 resolution lines.

The comparison between the first two replacement generations at both DS and DnS is given in Table 4. The maximum and minimum life lengths reveal the extreme limits of these groups. The number of replaced and unreplaced bearings, replacement date and position are stated in Table 5. The replacements, which are performed at DnS is 220% more than that performed at DS.

The number of replacements at DS and DnS during the same period and for the first two generations are plotted against bearings's life lengths, see Figures 2–5. In the plots, the time intervals are 12 months. These four groups of replacements are, however, distinguishable from each other. Each group clearly exhibits several modes, each of which probably represents a different damage syndrome, but the records are not clear on this.

2.2.1. *Bearing life length and spectra analysis*

The first bearing generation was installed on August 1977 and the installation of the second bearing generation was performed at different opportunities, i.e. failures or assessed conditions. The condition of the replaced bearings might vary between the slightly damaged and completely deteriorated, because their conditions were usually assessed subjectively. Further, the replaced bearings could not be found at the case companies. In many cases, the quality of bearing installation could not be evaluated due to the lack of vibration measurements, which should be done straight after installation. Some bearings have run without replacement for over 221 months at DS and DnS. The maximum bearing life length was about 207 and 180 months for the second generations at DnS and DS respectively. From Tables 2 and 3, it is obvious that

1. The average life of the first generation/DnS is longer by about 59% than that for the second generation/DnS in spite of improvements in bearing manufacturing due to implementation of TQM.

TABLE 2

Replacements of bearing 23060cck/drying cylinder/DS/PM01, company B

No.	Cylinder no.	1st generation Installation date	2nd generation Replacement date	Life length	3rd generation Replacement date	Life length	4th generation Replacement date	Life length	5th generation Replacement date
1	1	77·815	—	221					
⋮									
22	22	770815	—	221					
23	23	770815	890331	140	—	82			
24	24	770815	—	221					
25	25	770815	—	221					
26	26	770815	780119	5	870119	108	—	98	
27	27	770815	831103	75	840910	10	931123	110	—
28	28	770815	—	221					
29	29	770815	—	221					
30	30	770815	—	221					
31	31	770815	—	221					
32	32	770815	890719	143	—	78			
33	33	770815	—	221					
34	34	770815	—	221					
35	35	770815	881124	137	890530	6	—	78	
36	36	770815	851008	98	—	122			
37	37	770815	890530	142	910903	27	—	51	
38	38	770815	920819	180	—	40			
39	39	770815	861204	112	—	109			
40	40	770815	—	221					
41	41	770815	—	221					
42	42	770815	—	221					
43	43	770815	—	221					
44	44	770815	821104	63	840917	22	—	136	
45	45	770815	900904	157	—	64			
46	46	770815	—	221					
47	47	770815	840910	85	—	136			
48	48	770815	—	221					
49	49	770815	831130	76	910619	91	—	55	
	$n = 49$		$s_{DS1} = 13$	1413	$s_{DS2} = 6$	264	$s_{DS3} = 1$		$s_{DS4} = 0$

TABLE 3

Replacements of bearing 23052cck, PM01/drying cylinders/DnS, company B

No.	Cylinder no.	1st generation Installation date	2nd generation Replacement date	Life length	3rd generation Replacement date	Life length	4th generation Replacement date	Life length	5th generation Replacement date
1	1	770815	—	221					
2	2	770815	—	221					
3	3	770815	—	221					
4	4	770815	—	221					
5	5	770815	—	221					
6	6	770815	830629	71	—	150			
7	7	770815	890906	145	—	76			
8	8	770815	—	221					
9	9	770815	880831	133	—	87			
10	10	770815	—	221					
11	11	770815	830403	68	930421	120	—	31	
12	12	770815	791129	28	930803	164	—	28	
13	13	770815	—	221					
14	14	770815	860611	106	—	114			
15	15	770815	830127	66	940817	139	—	16	
16	16	770815	891205	148	900214	2	—	70	
17	17	770815	840924	86	—	134			
18	18	770815	—	221					
19	19	770815	821214	64	—	156			
20	20	770815	—	221					
21	21	770815	—	221					
22	22	770815	—	221					
23	23	770815	850729	96	870223	19	—	105	
24	24	70815	—	221					
25	25	770815	841214	88	901016	70	—	62	
26	26	770815	900201	150	—	70			

27	27	770815	830915	73	910417	91	—	56	
28	28	770815	—	221					
29	29	770815	920625	179	—	41			
30	30	770815	—	221					
31	31	770815	880622	131	900815	26	—	64	
32	32	770815	941102	207	—	13			
33	33	770815	840905	85	860729	23	890119	30	—
34	34	770815	860512	105	880211	21	—	94	
35	35	770815	880823	132	—	88			
36	36	770815	901218	160	—	60	—		
37	37	770815	830929	73	900612	81	—	66	
38	38	770815	—	221					
39	39	770815	—	221					
40	40	770815	—	221					
41	41	770815	830523	69	900105	80	—	72	
42	42	770815	—	221					
43	43	770815	860729	108	—	112			
44	44	770815	821104	63	—	157			
45	45	770815	910122	161	—	60			
46	46	770815	910207	162	—	59			
47	47	770815	810203	42	851015	56	880907	35	890921
48	48	770815	—	221					
49	49	770815	910612	166	—	55			
	$n = 49$		$s_{FS1} = 29$	3165	$s_{FS2} = 13$	892	$s_{FS3} = 2$		$s_{FS4} = 1$

TABLE 4

Comparison between two bearing replacement generation at PM01/DS & DnS

	DnS, 1st generation	DnS, 2nd generation	DS, 1st generation	DS, 2nd generation
Number of replacements, s	29	13	13	6
Number of bearings, n	49	29	49	13
Total life length, months	3165	892	1413	264
Average life length, months	109·14	68·6	108·7	44
Sample standard deviation, months	45·5	50·6	47·6	44
Maximum life length, months	207	164	180	108
Minimum life length, months	28	2	5	6
The number of bearings, k, which have life length < 60 months	2	6	1	4
(k/s) 100%	7%	46%	8%	67%

2. The average life of the second generation/DnS is only about 40% of the first generation/DS due to one or more of the following reasons:
   (a) Faulty installation.
   (b) A design fault, which was passive during first replacement generation period, or induced faulty construction due to some constructional changes in the machine.
   (c) Changes in operating conditions such as rotational speed, loading and temperature.
   (d) Misuse of bearings, e.g., overloading, high felt tension.
   (e) Faulty service, e.g., excess of grease, unsuitable lubricant, pollution in the lubricant. Damage initiated in DS bearings due to one or more of these reasons may develop faster because of, e.g., higher loading or temperature, or both [9].

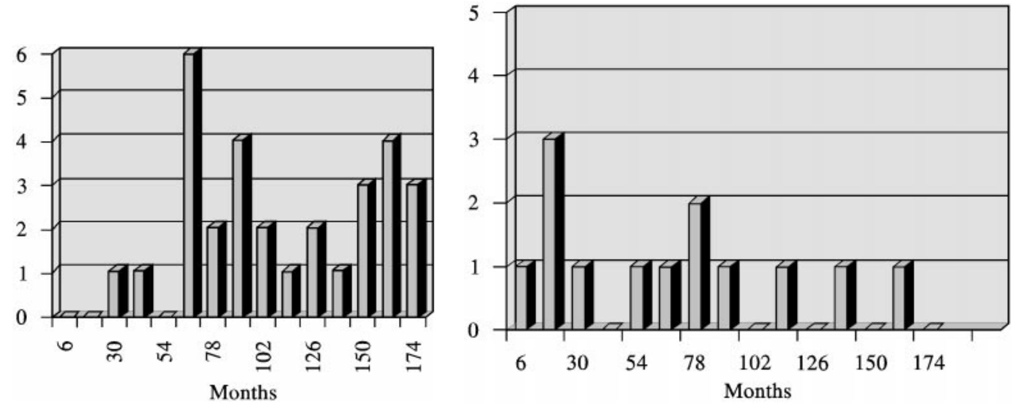
(3) The average life of the second generation/DnS is longer than that experienced at the second generation/DnS by about 56%.
(4) Maximum lives of the first generation/DnS and DS are longer by about 26 and 67% respectively than second generation/DnS and DS.
(5) The lowest and highest sample standard deviations, 44 and 50·6 months, occurred in the second generations at DS and DnS respectively. The spread in bearing lives was very large so that some of them are still functioning well after 19 years while others were replaced a few months after installation.

Assume that the bearings of life lengths less than or equal to 60 months are those exposed to some of the above-mentioned causes of rapid deterioration. Faulty installation can seriously decrease bearing life and make the replacements much more frequent (about 3–5 times) during the final stage of operation [10]. The quantities of such bearings are 6 and 4, i.e., 46 and 67%, in the second generations/DnS and DS, respectively.

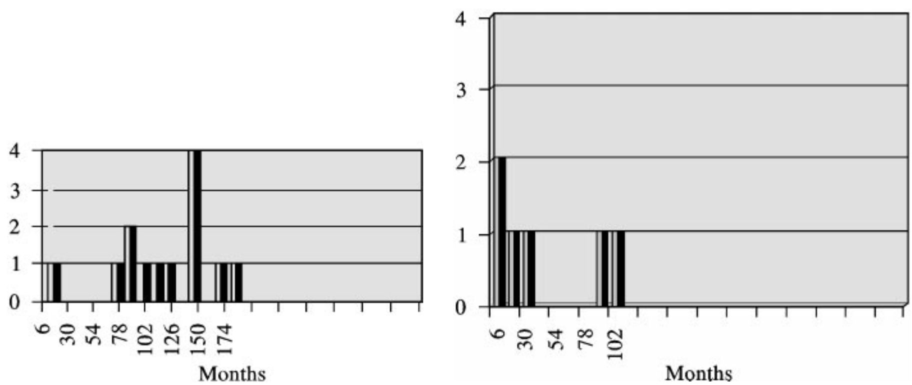
TABLE 5

Bearing replacements at drying cylinders/PM01

Bearing type	Side	Bearing n	Replacements, s	Unreplaced, m	m/n	s/n	$s/(n-m)$	Time interval
23052 cck	DnS	49	44	20	0·41	0·90	1·52	Aug. 77–Jan. 96
23060 cck	DS	49	20	36	0·73	0·41	1·54	Aug. 77–Jan. 96
Total		98	64	56	0·57	0·65	1·53	



Figures 2 & 3. Replacements at DnS/1st and 2nd generation. ▢, 1st generation/DnS; ▢, 2nd generation/DS.



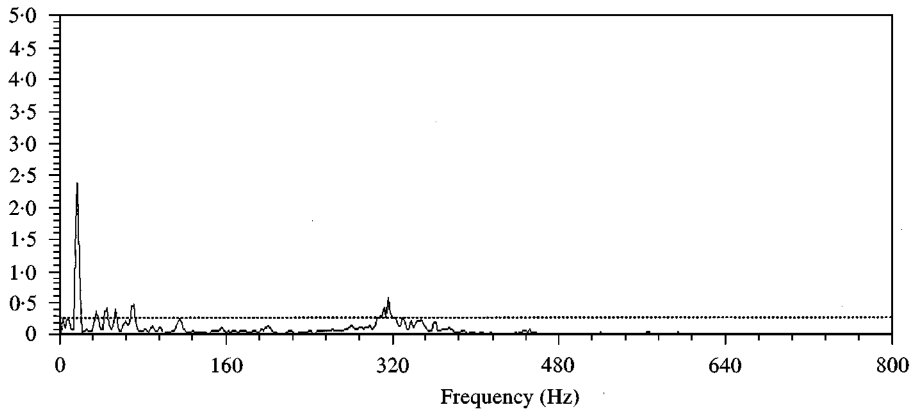
Figures 4 & 5. Replacements at DS/1st and 2nd generation. ▢, 1st generation/DS; ▢, 2nd generation/DS.

It is possible to recognize from the histograms that there exists four modes which may be due to two failure modes, probably abrasive wear and surface fatigue, and two replacement policies, probably replacement when the vibration level first deviates from normal and replacement at higher levels, i.e., failures or UPBFR. Lack of information regarding censored and full failure data and the replaced bearing condition, made statistically reliability analysis impossible.

The vibration spectra of 13 bearings installed at drying cylinders at both DnS and DS were selected for deeper analysis. These bearings were selected because there were vibration measurement records covering most of their lives, including measurements taken straight after installation. The analysis results can be summarized by the following:

1. Using 400 resolution lines for a range of 300 Hz made the diagnosis easier, but the assessment of badly damaged bearings, possibly generating frequencies above 300 Hz, became difficult. The speed of the machine was about 210 r.p.m.

2. Some of the bearings had detectable vibration frequencies in the measurements straight after the installation. Later measurements revealed damage developments.
3. In many spectra it was not difficult to identify multiples of FTF. This probably occurred because the cage and the rollers were strongly squeezed due to thermal hogging [9].
4. In many cases, the overall r.m.s. vibration level increased appreciably when several harmonics of the machine speed and bearing defect frequencies became detectable [9]. This phenomenon is noticed in many spectra, which have high vibration levels in both radial and axial directions.
5. Variations in bearing defect frequencies were detectable in almost all the cases.
6. When the frequencies *BPFO* and *BPFI* or their multiples are detectable it is possible to find a side-band, whose frequencies are modulated by $1{*}X$ or higher [9].
7. For some bearings, the vibration levels of several defect frequencies were in some occasions higher than the levels at which these bearings were replaced.



Identification of spectral peaks above threshold

Amp.	Freq.	Order	No.	Amp.	Freq.	Order
0·2639	4·0	0·439	9·0	0·4156	312·0	34·223
2·3801	18·0	1·974	10·0	0·5840	316·0	34·662
0·3824	36·0	3·949	11·0	0·2832	322·0	35·320
0·4300	46·0	5·046	12·0	0·2594	330·0	36·197
0·4011	54·0	5·923				
0·4828	72·0	7·898				
0·2550	116·0	12·724				
0·2963	308·0	33·784				

Spectral energy summary

Overall	Sync	Subsync	Non-sync
2·939	2·777	0·2155	0·9384

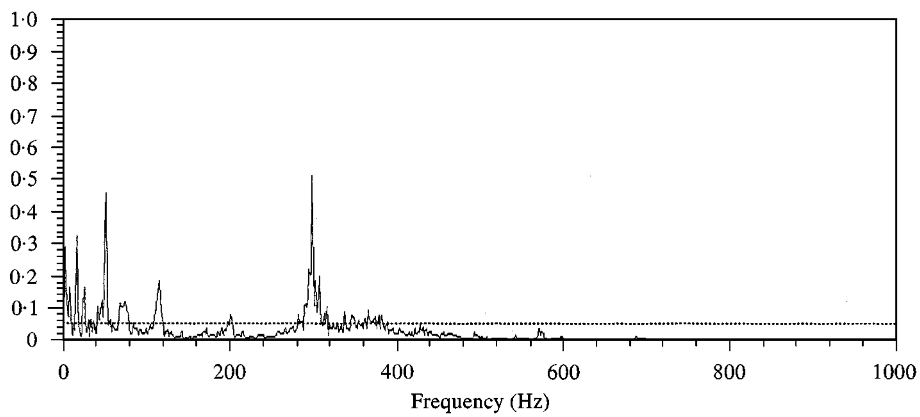
Figure 6. Bearing 23228ck/SKF, company A, $BPFO = 8{\cdot}2$, $BPFI = 10{\cdot}77$, $BSF = 3{\cdot}57$ and $FTF = 0{\cdot}433$ Hz. Bearing defect frequencies such as *FTF*, *BPFO* and multiples of *BSF* are detectable.

8. At almost all the analysed spectra, no multiple of the machine speed was identified when it was recorded as 219 r.p.m. The reason for this may be that the machine speed was not correctly recorded.

3. RESULTS

The major results reported from these two case studies are:

1. Identification of the shortcomings in the available data which prevent an effective improvement in the maintenance system.
2. Emphasizing the requirements to establish a routine for maintenance improvement by using new knowledge and experience.
3. Identification of vibration frequencies at a low-frequency range (0–100 Hz), which characterize particular failure causes and bearing damage and can be used to detect bearing defects at an early stage. These frequencies are the bearing discrete defect frequencies together with the sums and differences of some of these frequencies, see Figures 6–8.



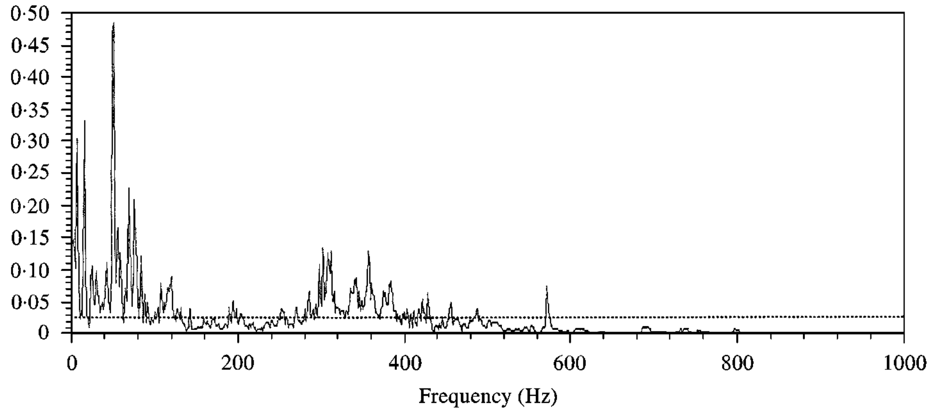
Identification of spectral peaks above threshold

Amp.	Freq.	Order	No.	Amp.	Freq.	Order
0·2896	3·8	0·430	9·0	0·1232	75·0	8·604
0·1670	8·8	1·004	10·0	0·1884	116·3	13·337
0·3249	17·5	2·008	11·0	0·1156	291·3	33·413
0·1694	26·3	3·011	12·0	0·2231	295·0	33·843
0·1274	47·5	5·449	13·0	0·5198	298·8	34·273
0·4597	52·5	6·023	14·0	0·1878	302·5	34·704
0·1173	70·0	8·031	15·0	0·2014	307·5	35·277
0·1102	72·5	8·317	16·0	0·1056	316·3	36·281

Spectral energy summary

Overall	Sync	Subsync	Non-sync
1·243	0·8719	0·3428	0·8174

Figure 7. Bearing 23228ck/SKF, company A, $BPFO = 8{\cdot}2$, $BPFI = 10{\cdot}77$, $BSF = 3{\cdot}57$ and $FTF = 0{\cdot}433$ Hz. Frequencies FTF, $BPFO$, $(BPFO + FTF)$ and several multiples of the machine speed are detectable.



Identification of spectral peaks above threshold

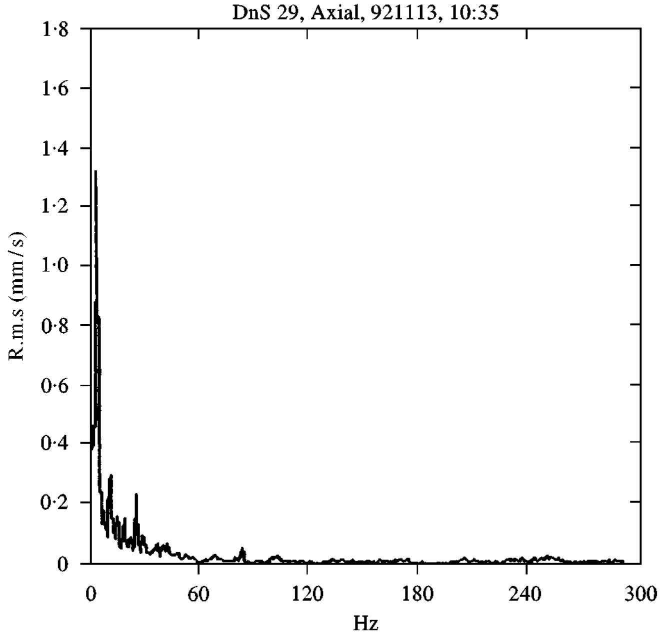
Amp.	Freq.	Order	No.	Amp.	Freq.	Order
0·1536	2·5	0·287	9·0	0·1634	68·8	7·887
0·1489	5·0	0·574	10·0	0·2288	71·3	8·174
0·3050	8·8	1·004	11·0	0·2099	77·5	8·891
0·3341	17·5	2·008	12·0	0·1231	85·0	9·751
0·1113	43·8	5·019	13·0	0·1359	302·5	34·704
0·4866	52·5	6·023	14·0	0·1265	308·8	35·421
0·1653	57·5	6·597	15·0	0·1310	312·5	35·851
0·1285	60·0	6·883	16·0	0·1307	357·5	41·013

Spectral energy summary

Overall	Sync	Subsync	Non-sync
1·133	0·9444	0·2101	0·5889

Figure 8. Bearing 23228ck/SKF, company A, $BPFO = 8{\cdot}2$, $BPFI = 10{\cdot}77$, $BSF = 3{\cdot}57$ and $FTF = 0{\cdot}433$ Hz. Frequencies FTF, $BPFO$, $(2BSF + FTF)$ and multiples of the machine speed are detectable.

4. An attempt to provide the technicians with better tools in vibration diagnosis and prognosis to be improved continuously by cyclic improvement model presented in reference [9].
5. Identification of the basic reasons behind earlier vibration indications and shorter bearing lives, see Figures 9–12.
6. It is found that bearing faulty installation and/or thermally hogged shafts made some of the bearings generate detectable vibration frequencies in the measurements done straight after installation. These causes probably made the lives of these bearings shorter, see for example Figures 6–9.
7. No clear vibration-level-based replacement policy could be identified at the companies under study. Some bearings were replaced at vibration levels much lower than they had experienced during their operating lives, see Figures 13 and 14.
8. The objectives of this study are not completely achieved due to insufficient replacements, numerate records of the operating conditions, loss of on-renewal examination data and replaced bearings.



Freq.	Amp.	Mult.	Freq.	Amp.	Multi.
3.44	1·4781	0·99	39·08	0·0715	11·18
6·11	0·1857	1·75	41·30	0·0754	11·82
7·00	0·1564	2·00	44·12	0·0375	12·63
9·95	0·3326	2·85	47·07	0·0458	13·47
14·08	0·1664	4·03	51·54	0·0356	14·75
17·40	0·1546	4·98	66·77	0·0350	19·11
20·90	0·0995	5·98	67·56	0·0348	19·34
24·38	0·2522	6·98	82·60	0·0555	23·64
28·00	0·1013	8·02	101·74	0·0364	29·12
31·07	0·0461	8·89	242·02	0·0298	69·27
34·67	0·0576	9·92	249·25	0·0325	71·34
36·03	0·0722	10·31	252·25	0·0323	72·20

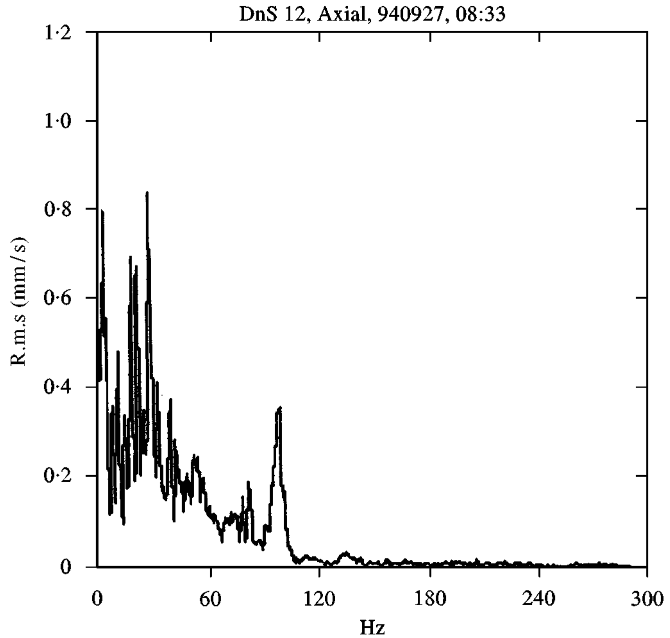
Overall	Subsync	Sync	Non-sync
1·7354	0%	1·6194/87%	0·6238/13%

Figure 9. Bearing 23052cck/SKF, company B, $BPFO = 11{\cdot}21$, $BPFI = 13{\cdot}79$, $BSF = 4{\cdot}73$ and $FTF = 0{\cdot}45$ Hz. The bearing was installed at 920625. Frequencies FTF and $BPFO$ and several multiples of the machine speed were detectable after a while. The reason is probably faulty installation or thermal hugged shaft.

4. RECOMMENDATIONS

The most important practical suggestions and recommendations to be considered by the companies are summarized by the following:

1. In order to develop a proactive and predictive vibration-based maintenancepolicy for monitoring and controlling machine condition, see Al-Najjar [11], it is important to establish changes in the policies for measurement, analysis, diagnosis and feedback to improve the mentioned shortcomings in these policies.

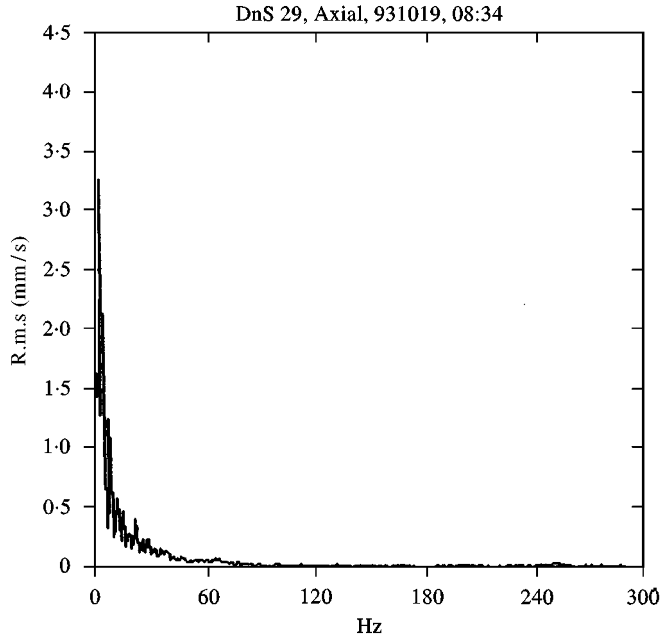


Freq.	Amp.	Mult.	Freq.	Amp.	Mult.
2·44	0·6887	0·70	38·41	0·4149	11·00
3·52	0·8146	1·01	41·86	0·3067	11·99
6·99	0·4053	2·00	43·51	0·2430	12·46
10·37	0·4974	2·97	44·96	0·2129	12·88
14·02	0·3479	4·02	47·80	0·2424	13·69
17·36	0·7180	4·97	51·53	0·2830	14·76
20·84	0·7703	5·97	53·72	0·2770	15·39
23·81	0·3874	6·82	57·31	0·2382	16·41
27·90	0·8699	7·99	78·41	0·1786	22·46
29·62	0·3321	8·48	82·02	0·2107	23·50
31·76	0·4876	9·10	98·93	0·4197	28·34
34·01	0·2180	9·74	101·16	0·1952	28·98

TotalNiv	Under 1 × r.p.m.	1 × r.p.m. mult.	Osynkront
2·5292	0%	2·2101/76%	1·2297/24%

Figure 10. Bearing 23052cck/SKF, company B, $BPFO = 11{\cdot}21$, $BPFI = 13{\cdot}79$. $BSF = 4{\cdot}73$ and $FTF = 0{\cdot}45$ Hz. Frequencies FTF, $BPFO$, $BPFI$ and their higher multiples in addition to several multiples of the machine speed were all detectable. Also, there were frequencies which were modulated with the machine speed. The reason is probably faulty installation or thermal hugged shaft.

2. Establish a clear and written vibration-based replacement policy to be improved based on its cost-effectiveness, for more details see Al-Najjar [12].
3. Enough vibration measurements, to avoid missing damage initiation and development, and better resolution of vibration spectra are a pre-requisite for more effective diagnosis.
4. For an effective diagnosis, variations in bearing defect frequencies should be considered.

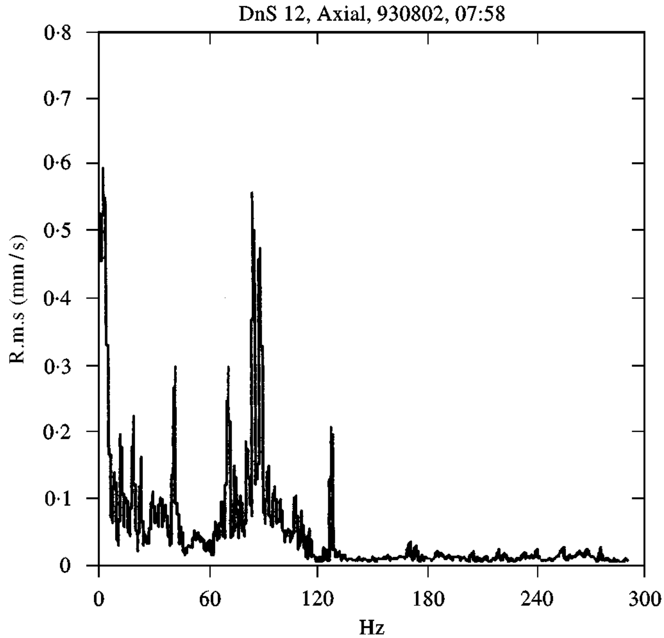


Freq.	Amp.	Mult.	Freq.	Amp.	Mult.
3·42	3·7044	1·00	41·16	0·1100	12·02
6·82	1·2892	1·99	44·05	0·0929	12·87
10·60	0·6769	3·10	45·73	0·0996	13·36
13·74	0·4875	4·01	50·62	0·0720	14·79
17·11	0·3197	5·00	53·67	0·0806	15·68
20·64	0·4230	6·03	55·93	0·0777	16·34
22·96	0·1910	6·71	57·39	0·0725	16·77
24·26	0·2473	7·09	60·24	0·0753	17·60
27·38	0·2807	8·00	63·04	0·0747	18·42
30·36	0·1794	8·87	64·47	0·0841	18·83
34·62	0·1691	10·11	66·16	0·0860	19·33
37·51	0·1537	10·96	69·71	0·0641	20·36

Overall	Subsync	Sync	Non-sync
4·5883	0%	4·2039/84%	1·8384/16%

Figure 11. Bearing 23052cck/SKF, company B, $BPFO = 11{\cdot}21$, $BPFI = 13{\cdot}79$, $BSF = 4{\cdot}73$ and $FTF = 0{\cdot}45$ Hz. Multiples of the machine speed were detectable, e.g. 1st, 2nd and 3rd multiple acquired high amplitudes. This is probably because of bearing misalignment due to either faulty installation or thermal hugged shaft.

5. Investigate closely the operating conditions suffered by the bearings of shorter life in order to identify and eliminate the real causes.
6. Numerate records of operating conditions, which were insufficient in these databases, are useful to discover reasons behind vibration-level variations and to improve maintenance efficiency and company's economy.
7. A record describing bearing damage is important to correlate vibration history with damage found on renewal. This will help maintenance personnel to improve their experience and knowledge cyclically.

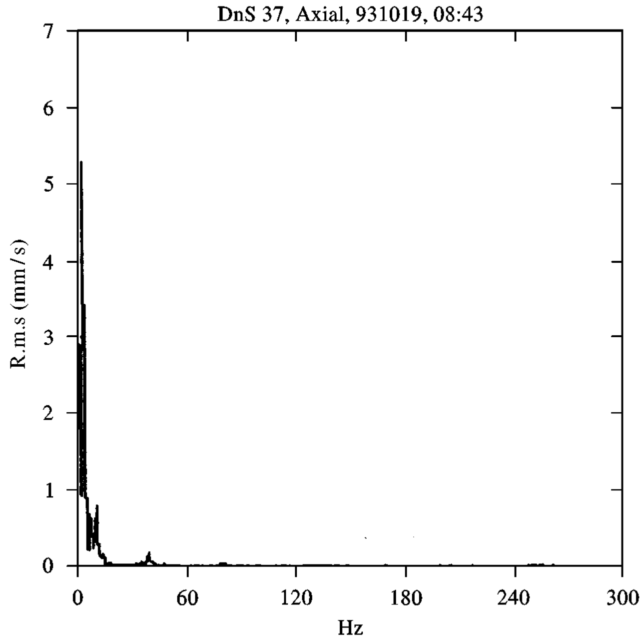


Freq.	Amp.	Mult.	Freq.	Amp.	Mult.
2·46	0·6541	0·68	70·67	0·3072	19·36
7·54	0·1483	2·06	74·69	0·1597	20·46
11·20	0·2130	3·07	77·62	0·1134	21·27
13·56	0·1173	3·72	81·32	0·2077	22·28
17·73	0·2407	4·86	84·92	0·6002	23·27
22·02	0·1673	6·03	88·73	0·5408	24·31
28·30	0·1170	7·75	92·40	0·1684	25·32
30·23	0·0905	8·28	96·12	0·1300	26·33
33·18	0·1179	9·09	100·17	0·1026	27·44
36·13	0·1071	9·90	100·73	0·1206	29·51
40·64	0·3215	11·14	111·43	0·0909	30·53
66·89	0·1083	18·33	127·33	0·2346	34·88

Overall	Subsync	Sync	Non-sync
1·4991	0%	1·1225/56%	0·9937/44%

Figure 12. Bearing 23052cck/SKF, company B, $BPFO = 11{\cdot}21$, $BPFI = 13{\cdot}79$, $BSF = 4{\cdot}73$ and $FTF = 0{\cdot}45$ Hz. Multiples of the machine speed are detectable. Frequencies BPFO, BPFI and their higher multiples acquired significant amplitudes. The bearing was installed at 930803.

8. Analysis of complete data (vibration history, working conditions, damage on renewal) for long-lasting bearings would lead to improvement of other bearing's lives, establishment of deterioration models and better company's economy.
9. In order to identify the moment and the vibration level when damage is initiated it is necessary to use a technique, which makes it easier to see any trend present in the vibration measurements. Cumulative Sum (CUSUM), chart proposed in reference [11] can be utilized for this purpose.



Freq.	Amp.	Mult.	Freq.	Amp.	Mult.
3·46	5·8190	1·00	42·15	0·0539	12·21
6·89	0·7388	2·00	46·31	0·0379	13·42
10·27	0·8002	2·98	47·22	0·0410	13·68
13·60	0·1932	3·94	50·78	0·0339	14·71
17·23	0·0625	4·99	77·44	0·0261	22·44
20·18	0·0401	5·85	79·25	0·0632	22·96
25·91	0·0266	7·51	81·21	0·0559	23·53
26·70	0·0270	7·74	99·71	0·0350	28·90
31·76	0·0507	9·20	127·27	0·0255	36·88
35·21	0·0801	10·20	131·13	0·0384	38·00
38·65	0·1925	11·20	142·10	0·0286	41·18
40·59	0·0784	11·76	250·62	0·0339	72·63

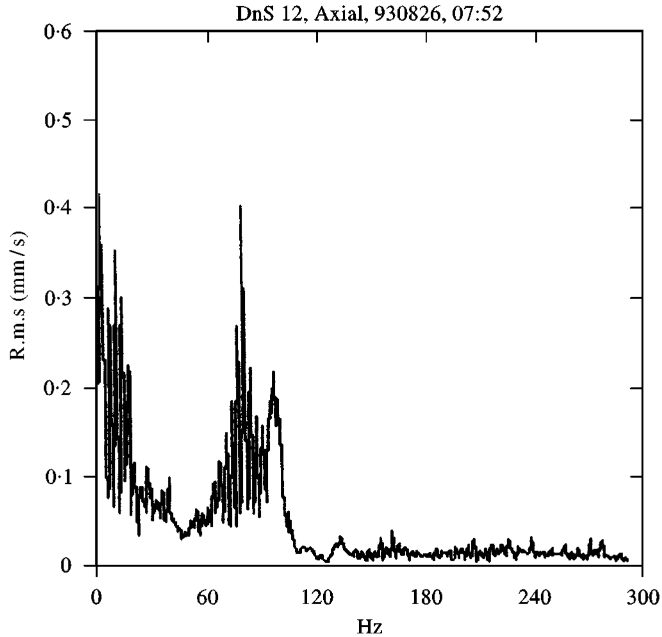
Overall	Subsync	Sync	Non-sync
6·5673	0%	6·0631/85%	2·5236/15%

Figure 13. Bearing 23052cck/SKF, company B, $BPFO = 11{\cdot}21$, $BPFI = 13{\cdot}79$, $BSF = 4{\cdot}73$ and $FTF = 0{\cdot}45$ Hz. Frequencies BSF, $BPFO$ and the overall r.m.s. level are not high, but the bearing was replaced the day after.

5. GENERAL COMMENTS AND CONCLUSIONS

The study results were presented and discussed with the maintenance staff including the analysts and technicians responsible for vibration monitoring. The objectives were to establish changes in the measurement, analysis, diagnosis and replacement policies based on these results.

The importance of analysing variations in bearing life length may be considered from different aspects, e.g. operational safety, product quality, maintenance cost, production losses, which may be divided into economical, technical and organizational categories. A high sample standard deviation in bearings' lives is, in



Freq.	Amp.	Mult.	Freq.	Amp.	Mult.
2·38	0·4363	0·69	67·50	0·1388	19·70
3·35	0·3809	0·98	70·97	0·1557	20·71
6·86	0·3217	2·00	74·19	0·2037	21·65
10·34	0·3620	3·02	77·55	0·2793	22·63
13·63	0·3241	3·98	80·99	0·4056	23·63
17·12	0·2603	5·00	84·46	0·2373	24·65
20·08	0·1376	5·86	87·89	0·1884	25·65
23·73	0·1057	6·92	90·15	0·1293	26·30
27·35	0·1310	7·98	91·09	0·1644	26·58
28·91	0·0981	8·44	95·21	0·2093	27·78
38·50	0·1056	11·23	97·46	0·2606	28·44
63·89	0·1117	18·64	99·68	0·2155	29·09

Overall	Subsync	Sync	Non-sync
1·3309	0%	1·0482/62%	0·8202/38%

Figure 14. Bearing 23052cck/SKF, company B, $BPFO = 11{\cdot}21$, $BPFI = 13{\cdot}79$, $BSF = 4{\cdot}73$ and $FTF = 0{\cdot}45$ Hz. Multiples of the machine speed are detectable, e.g. 1st, 2nd, 3rd, 4th and 5th multiple acquired high amplitudes. The overall r.m.s. level is also high, but no action was done.

general, translated into higher proportion of failure cycles, which increases maintenance costs [12], unless the modes can be separated by better data discrimination and records.

Insufficient on-renewal vibration spectra made the identification of failure causes less certain. No data concerning bearing replacements from company A were received. The speed of PM10 as measured varies from 489 to 547 r.p.m. This made following the development of the amplitudes of bearing defect frequencies impossible when using Palogram in Prism[2] because they are functions of r.p.m. Deficiencies in data coverage and quality prevented the identification of all the actual vibration levels at failures and other renewals, which would be necessary for statistical analysis and optimization.

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