RMS Reliability Maintenance Solutions Ltd

Monitoring Lubrication Using Multi-Frequency a Sonic/Ultrasonic Sensor

by
Ray Garvey CSI
835 Innovation Drive, Knoxville, TN 37932
(423) 675-2110; e-mail: GarveyR@CompSys.com

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ABSTRACT:

This paper describes the use of multi-frequency sonic/ultrasonic measurement as a non-destructive condition monitoring technique to monitor lubrication in greased bearings. Three frequency ranges, 4 kHz, 30 kHz, and 40 kHz, were selected to isolate mechanical faults from friction and lubrication related faults. An experiment was conducted using thirteen grease lubricated conveyor bearings. Measurements were made before and after grease lubrication. Out of thirteen bearings, one was obviously under-lubricated and two others showed some evidence of needing re-lubrication. This multi-frequency sonic/ultrasonic measurement is suggested as a proactive measure intended to eliminate common root causes of failure before costly damage is done.

GREASE IS THE ACHILLES' HEEL OF LUBRICANT CONDITION MONITORING

Multi-frequency sonic/ultrasonic analysis can be used to monitor grease, the Achilles' heel of lubricant condition monitoring. Although grease analysis is practical from a testing point of view, it is impractical from a sampling point of view. Considering the numbers of machines that are grease lubricated, this problem, "How to do condition monitoring on grease?" is a serious one that needs to be addressed.

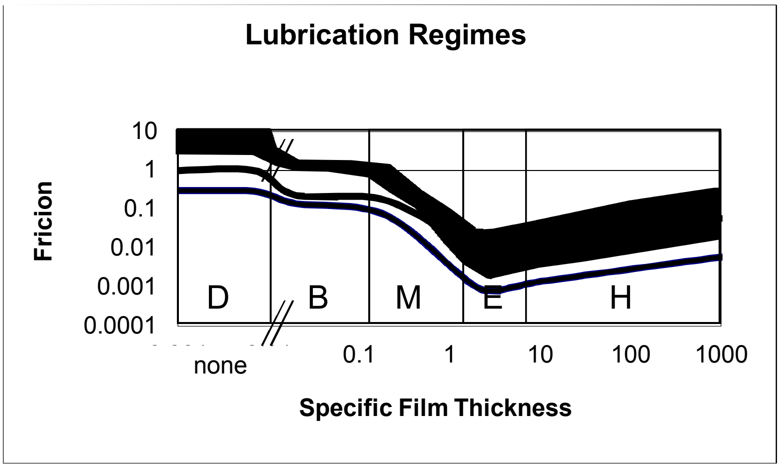
Maintenance professionals often report the biggest problems with their tribology program are over-greasing, under-greasing, wrong grease, and sometimes no grease at all. Over-greasing causes high temperatures and results in shedding of oil from grease. Under-greasing causes inadequate lubricant delivery. The wrong grease in a bearing also has the same effect. It doesn't properly deliver oil to the loaded rollers. All these result in lubricant-starved bearings. These problems (over-greasing, under-greasing, wrong grease, and no grease at all) cause increased energy loss due to friction. This energy shows up as mechanical energy (ultrasonic) and thermal energy (heat).

LUBRICATION REGIMES

A schematic of lubrication regimes as a function of specific film thickness is shown in Figure 1 below. This figure shows the four lubrication regimes along with the case of no lubricant at all (dry contact). This adds up to five regimes: D, B, M, E, and H. Specific film thickness is defined as the minimum lubricant film thickness divided by the composite surface roughness. This translates into the following approximate actual film thicknesses assuming root mean squared surface roughness of 0.3 micron.

	Regime	Lubricant Thickness
D	Dry contact	0.00 micron (possible 0.01 micron oxide)
B	Boundary Lubrication	0.01 micron
M	Mixed Lubrication	0.01 micron
E	Elastohydrodynamic Lubrication	1 micron
H	Hydrodynamic Lubrication	20 micron

Figure 1. Coefficient of friction as a function of specific film thickness.[1]



Rolling element bearings, also called anti-friction bearings, are designed to take advantage of the elastohydrodynamic lubrication regime at the roller-to-race interface, and hydrodynamic lubrication regime at the roller-to-cage interface. Lube starvation often causes boundary and mixed instead of desired hydrodynamic and elastohydrodynamic modes. First to go is probably the hydrodynamic lubrication at the roller-to-cage interface. This means high friction at the cage-to-roller interface.

Why is the cage-to-roller typically the first to show high friction when grease quits delivering oil to the bearing? It takes approximately a 20 micron thick oil film to support hydrodynamic lubrication of the roller-to-cage, compared to the 1 micron thick oil film it takes to support elastohydrodynamic lubrication of the roller-to-race. Fortunately the roller-to-cage interface is lightly loaded, so high-friction doesn't mean immediate, high wear. Eventually the boundary lubrication will take its toll on the cage and adhesive wear debris will be released causing secondary damage and accelerated failure progression. If the load and speed are high, the rollers may overheat. Finally, without adequate oil film between the roller and race, friction and torque increase. The increased torque is focused on damaging the surfaces of the roller, race, and cage.

Our goal is to detect the early signs of lubricant starvation and take corrective action before damage is done. This means look for the mechanical and thermal signatures that reveal increased friction.

A multi-frequency sonic/ultrasonic measurement with calibrated decibel (DB) output can be used to quickly identify bearings starved for grease lubrication. At the same time it can identify and quantify mechanical impacting. The sonic frequency band is optimized for detection of impacting. The first ultrasonic frequency band is optimized for friction-induced noise, and the second ultrasonic frequency band is better suited for leakage detection, such as may be present in compressors, valves, etc.

A study by Robinson[2] shows differences between mechanical impacting, lubrication faults, and other events using multi-frequency sonic/ultrasonic measurement. Figures 2 and 3 taken from this study show that mechanical impacting has a very different frequency response compared to absence of lubrication.

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[1] Chart based on information from "Improving the Reliability of Machines by Understanding the Failure of Their Moving Parts," Master Series Course taught at CSI by M. Neale and D. Summers-Smith, October 1997.

[2] "Machinery Surveillance Employing Sonic/Ultrasonic Sensors" by J. C. Robinson, J. B. Van Voorhis, K. R. Piety, and W. King, Reliability Week 1999.

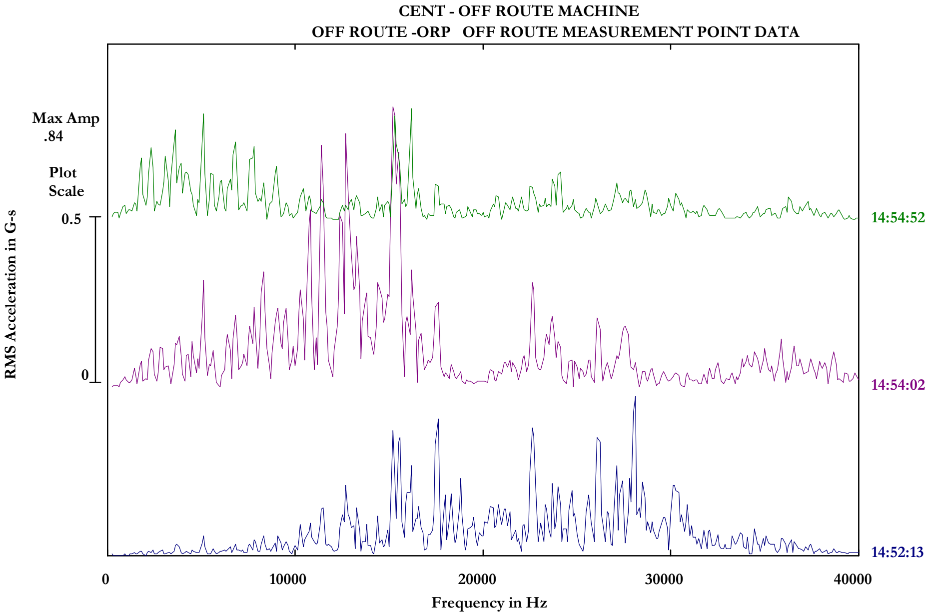

Figure 2. Spectral Data for Steel Balls Impacting on steel plate: 0.5-inch diameter at 14:52:13, 1.0-inch diameter at 14:54:02, and 1.5-inch diameter at 14:54:52.

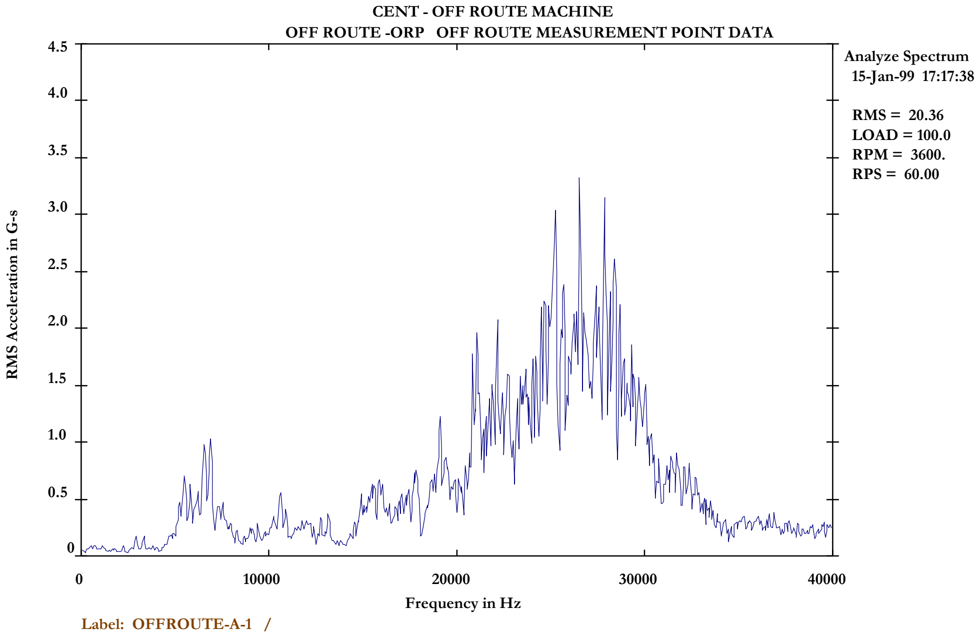

Figure 3. Spectra from a known defective bearing (lacking lubrication) at approximately 4000 RPM.

Temperature measurement is another technology that goes hand in hand with oil analysis. This is the primary tool used by railroads to identify failed bearings in rolling stock. The consequences of missed problems can be disastrous. Most mechanical systems get hot before they fail and rolling stock is no exception. Temperature scans can be done point-by-point using a temperature probe, or they can be done in a rapid scan using a focal plane array infrared camera.

A practical combination to test grease-lubricated bearings is the simultaneous measurement of temperature and multi-frequency sonic/ultrasonic DB levels. Compare the sonic/ultrasonic signatures at low-, mid-, and high-frequencies between similar equipment under similar conditions. Do the same for temperature. Problems will stand out.

TEST EQUIPMENT AND METHOD

A multi-frequency sonic/ultrasonic/temperature contact measurement device shown in Figure 4 was used to collect data.

Figure 4. Ultrasonic system with multi-frequency sensor.

This device was selected because of its ability to measure decibel energy level in three independent frequency ranges. The low-, mid-, and high-frequency ranges are approximately 4-kHz, 30-kHz, and 40-kHz respectively. The sensor has tuned frequency responses in these three ranges, which correspond to common faults. By knowing what fault types show up in which frequency range, you can identify, quantify, and isolate faults. See Figure 5.

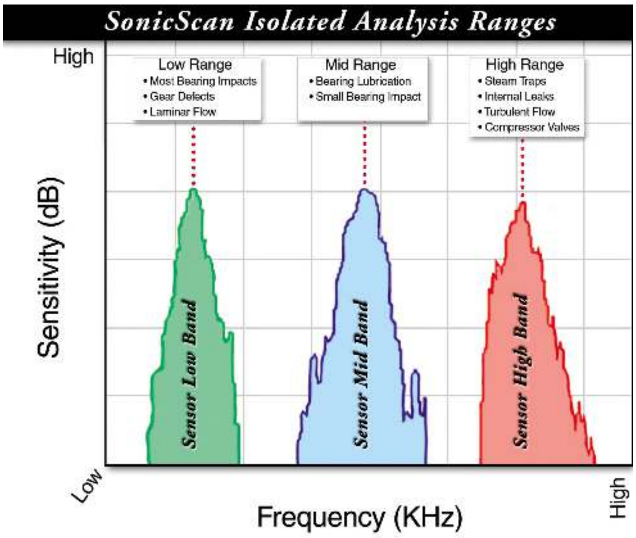

Figure 5. Low-, mid-, and high-frequencies selected for fault isolation.

DATA COLLECTION

An experiment was conducted to test the practicality of using multi-frequency ultrasonic and vibration measurements to monitor grease lubrication effectiveness. The survey included 13 bearings from a conveyor in a food processing plant. Data are reported in Appendix 1. Bearings # 1 to # 6 were selected along areas easily accessed by workers. Bearings # 7 to # 13 were selected from hard to reach locations. All of these bearings were lubricated daily by conveyor operators.

Each bearing was tested six times times. Tests A, B, and C were measured as-is. Then each bearing was lubricated and tests D, E, and F were measured after greasing. Two DB values are reported for each frequency range. The first is Peak Hold ("PH") showing the highest reading during a six-second measurement. The second is Average ("AV") showing the average of all the measurements collected during a six-second measurement.

Headphones were used with the multi-frequency sonic/ultrasonic system in attempt to identify sounds introduced by the periodic events associated with the fault. Unfortunately in this environment there was a lot of noise in all of the measurements. Metal cans were clattering on the conveyor, belts were sliding, and the background was loud. For these or other reasons, the headphones did not provide useful information in this study.

EXPERIMENTAL RESULTS

Table 1 shows the Average, Median, Maximum, and Minimum values for 6 x 13 = 78 measurements in each category. The large difference between the median values and the maximum values for "30k AV" and "40k AV" show how sensitive these measurements are compared to the others. Next most sensitive are the "30k PH" and "40k PH" compared to either of the "4K PH" or "4k AV" measurements.

Table 1. Statistical data for 13 bearings.

	4k PH	4k AV	30k PH	30k AV	40k PH	40k AV	Temperature F
Average	65	41	35	7	35	1	92
Median	64	40	31	5	31	0	92
Maximum	93	56	77	32	71	29	96
Minimum	43	31	20	0	11	0	89

The results in Appendix 1 show that for the first six bearings, the ones that are easy to access for greasing, nothing unusual is detected. None of these have extreme values and none showed any measurable change after greasing (test sequences D, E, and F).

Bearing # 11 reported the most extreme values in most categories before greasing. It is also the one that was hardest to reach. A ladder and long reach were needed to collect these data. A ladder and long reach were also required to grease bearing # 11. This bearing showed very high values before greasing and showed better than average values after greasing. See Table 2.

Table 2. Actual values on bearing # 11 showing major change after greasing.

Bearing	Test	4k PH	4k AV	30k PH	30k AV	40k PH	40k AV	Temperature F
11	A	80	56	77	32	71	29	92
	B	80	56	75	30	68	28	92
	C	77	52	64	20	58	14	92
	D	68	43	26	0	31	0	90
	E	69	44	44	2	39	0	90
	F	65	39	36	0	29	0	90

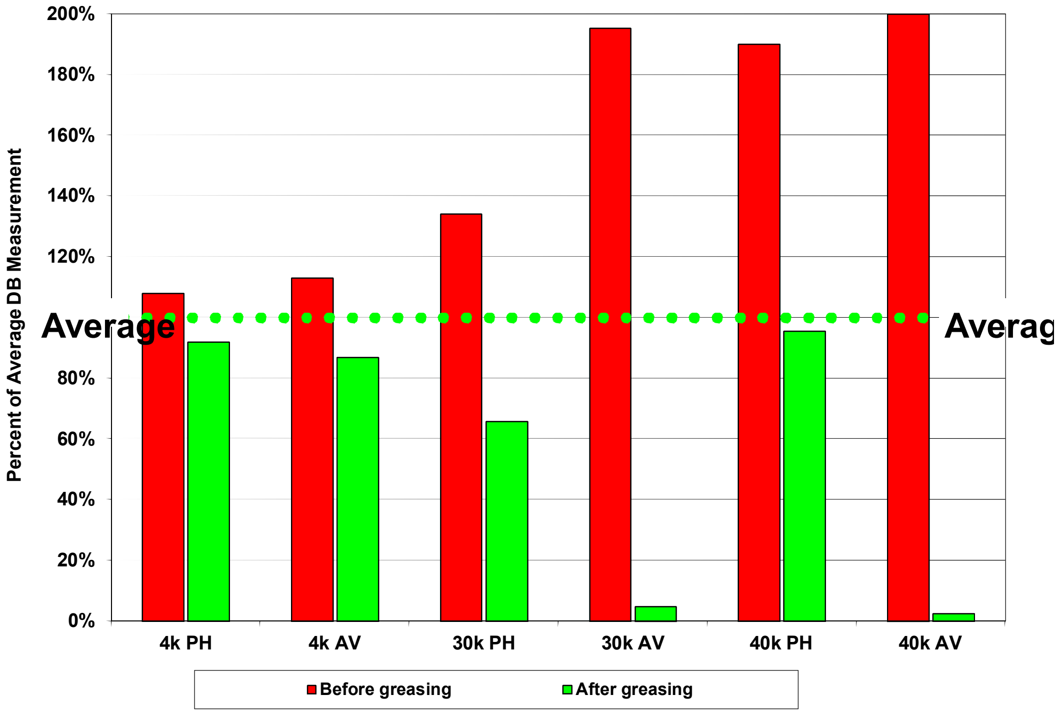

Figure 6. Effect of grease added to bearing # 11.

You can see from Figure 6 how dramatic the change in both the “30k AV” and “40k AV” measurements are for bearing #11. The “30k PH” and “40k PH” are also very revealing. The smallest changes are observable in the “4k PH” and “4k AV” measurements.

Bearings # 12 and # 13 show 37% lower PH values after lubrication. It is interesting that bearing # 12 showed this shift in the mid-frequency range, while bearing # 13 showed this in the high-frequency range. The absolute DB levels for these bearings were not above average.

Bearings # 7, # 8, # 9, and #10 all showed greater than 10 DB in “30k AV” and this did not improve with grease addition. These may already be over-lubricated. They deserve to be flagged for future observation.

The range of temperatures between these bearings was quite small. All temperatures were between 89 F and 95 F. Only one bearing (# 11) showed a 2 F decrease after greasing, and this is less than the scatter in some of the other bearing measurements. All others remained unchanged before and after greasing.

CONCLUSION

These results have confirmed Robinson’s findings that multi-frequency sonic/ultrasonic measurements can be effectively used to monitor grease lubrication. The three frequency ranges, 4 kHz, 30 kHz, and 40 kHz, were shown to isolate mechanical faults from friction and lubrication-related faults. In this study, one of thirteen bearings was starved for lubrication, and two others had inadequate lubrication. This study has shown a practical approach for using multi-frequency sonic/ultrasonic measurements to find bearings which are not properly lubricated. These can then be correctly greased before bearing damage occurs. These proactive measures remove several root causes of failure before they lead to costly machine damage.

APPENDIX 1. Data collected on roller bearings. A, B, C are before greasing. D, E, F are after greasing.

Bearing	Test	4k PH	4k AV	30k PH	30k AV	40k PH	40k AV	Temperature F
1	A	93	38	20	0	36	0	90
	B	61	44	27	0	37	0	92
	C	61	44	27	0	37	0	92
	D	65	44	28	0	37	0	92
	E	63	44	27	0	42	0	92
	F	61	43	28	0	36	0	92
2	A	77	49	49	15	51	2	95
	B	76	47	53	2	46	0	95
	C	79	47	47	5	54	0	95
	D	76	45	44	8	41	0	95
	E	80	47	47	6	55	1	95
	F	79	48	47	11	50	0	95
3	A	56	37	26	0	36	0	92
	B	57	37	28	0	28	0	92
	C	59	36	26	0	29	0	90
	D	44	31	23	0	21	0	96
	E	44	32	31	0	25	0	93
	F	43	31	20	0	31	0	92
4	A	63	39	35	0	28	0	92
	B	65	40	31	0	44	0	92
	C	64	37	38	2	42	0	92
	D	62	39	28	0	30	0	92
	E	65	39	35	0	40	0	92
	F	62	34	32	0	37	0	92
5	A	62	38	28	2	24	0	92
	B	62	41	31	4	23	0	92
	C	60	38	29	4	24	0	92
	D	59	38	28	5	24	0	92
	E	52	38	33	4	27	0	92
	F	58	39	29	4	23	0	92
6	A	68	40	34	8	35	0	92
	B	65	43	31	8	38	0	92
	C	58	44	31	7	30	0	92
	D	67	42	30	7	36	0	92
	E	66	43	32	8	27	0	92
	F	65	43	29	8	29	0	92
7	A	79	43	51	14	46	2	92
	B	72	43	45	10	47	6	92
	C	77	44	49	11	45	1	92
	D	72	44	41	14	32	1	92
	E	72	44	43	13	36	1	92
	F	76	50	45	12	48	2	92
8	A	57	38	32	19	30	0	92
	B	58	39	31	20	31	0	90
	C	59	41	44	20	30	1	90
	D	63	39	34	18	28	0	90
	E	59	38	31	16	30	0	90
	F	52	36	30	15	26	0	90
9	A	54	35	28	12	23	0	92
	B	57	38	28	13	27	0	92
	C	90	39	27	13	29	0	92
	D	56	38	29	16	23	0	93

	E	56	38	27	10	24	0	93
	F	59	36	31	17	31	3	93
10	A	65	38	38	12	40	0	90
	B	63	38	37	10	27	0	90
	C	63	38	31	9	32	0	90
	D	48	33	26	10	31	0	90
	E	46	34	26	10	23	0	90
	F	61	35	31	11	28	0	90
11	A	80	56	77	32	71	29	92
	B	80	56	75	30	68	28	92
	C	77	52	64	20	58	14	92
	D	68	43	26	0	31	0	90
	E	69	44	44	2	39	0	90
	F	65	39	36	0	29	0	90
12	A	65	43	43	3	38	0	92
	B	59	38	38	0	38	0	92
	C	65	39	45	0	32	0	96
	D	65	40	29	0	34	0	96
	E	63	38	26	0	26	0	90
	F	63	38	27	0	24	0	92
13	A	77	45	31	0	40	0	89
	B	74	47	42	5	46	1	89
	C	78	46	32	0	50	0	89
	D	75	46	38	3	27	0	89
	E	72	43	28	0	29	0	89
	F	74	44	39	0	34	0	89
	Average	65	41	35	7	35	1	92
	Median	64	40	31	5	31	0	92
	Maximum	93	56	77	32	71	29	96
	Minimum	43	31	20	0	11	0	89
Bearing	**Test**	**4k PH**	**4k AV**	**30k PH**	**30k AV**	**40k PH**	**40k AV**	**Temp**