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Quantifying Oil Filtration Effects on Bearing Life

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SUMMARY

Rolling-element bearing life is influenced by the number, size, and material properties of particles entering the Hertzian contact of the rolling element and raceway. In general, rolling-element bearing life increases with increasing level of oil filtration. Based upon test results, two equations are presented which allow for the adjustment of bearing L_{10} or catalog life based upon oil filter rating. It is recommended that where no oil filtration is used catalog life be reduced by 50 percent.

INTRODUCTION

It has long been recognized that lubricant contamination can affect bearing life, reliability, and performance. It is the number, size, and material properties of particles entering the Hertzian contact of the rolling element and raceway that impact bearing life. The nature of the particles in the oil is a function of several processes:

1. Manufacturing processes (swarf, chips, grit)
2. Internal generation, including wear debris and chemical attack of surfaces
3. Ingression from the environment (sand, dust)
4. Maintenance activities (making/breaking fittings, new oil)
5. Lubricant breakdown products (sludges, precipitates, coke)

Along with selected test contaminants, typical particle size distributions from a variety of mechanical systems are shown in figure 1. The greater number of smaller particles in each of the lubrication systems is due in part to wear mechanisms that generate smaller particles, and, in part, to removal processes that tend to remove larger particles. For comparison purposes two AC Test Dusts are shown which represent mineral derived contaminants such as silica sand. In addition to wear generated particles, Steele (1983) reported a wide range of particulate levels in unused turbine oils.

Hirano and Yamamoto (1958) reported that contaminants added to various lubricants could initiate scuffing in rubbing contacts. Dalal et al. (1974, 1975) reported that ball bearing lives in excess of 50 times AFBMA calculations (catalog value) were achieved by operating with prefiltered ultraclean lubricant in which the only source of metallic contamination was the test bearing itself. However, Dalal et al. (1974, 1975) did not run a control test lot of bearings without filtration to determine the exact life improvement attributable to filtration. They later induced raceway damage in their test bearings with a hardness indenter in an attempt to simulate contaminant caused indentations in service; although reduced from the ultraclean values, the fatigue lives were still longer than the AFBMA calculations.

Fitzsimmons and Clevenger (1976) carried out an extensive test program with tapered roller bearings using a variety of lubricants and contaminants with controlled particle sizes, types, and concentrations. They noted that two-body wear occurs when a hard, rough surface plows a series of grooves in an opposing softer surface. They stated that solid contaminants in lubricants are conducive to three-body abrasive wear, which occurs when particles are introduced between sliding surfaces and abrade material off both surfaces.

They added the caveat that a certain amount of abrasive wear may be tolerable, depending on the application. As an example, noise in gears which results from looseness in the bearing system rather than from surface failure may constitute cause for "failure" of the application.

In tapered roller bearings wear normally occurs on the surfaces where there is combined rolling and sliding contact, for instance between the roller ends and the cone large-end flange. Fitzsimmons and Clevenger (1976) found wear of these surfaces increased linearly with the concentration of hard contaminant particles. In their discussion of this work, Kirnbauer and Ferris (Fitzsimmons and Clevenger, 1976) report that 3 μm filtration prevents circulation of the hard particles that cause abrasive wear.

The objective of this paper is to develop a method for calculating bearing L_{10} or catalog life to account for the effects of particle size on bearing fatigue failure.

NOMENCLATURE

E_x	particle removal efficiency, $1 - 1/\beta_x$
FR	filter rating, μm
h_c	central or average elastohydrodynamic (EHD) film thickness, μm
L_{10}	bearing 10 percent or catalog life or the operating time which is exceeded by 90 percent of a group of bearings of a given type
L_{50}	bearing 50 percent or median life or the time which is exceeded by 50 percent of a group of bearings of a given type
LF	life adjustment factor for effect of filtration in bearing L_{10} life
ND_x	average number of particles downstream of the filter whose particle sizes are greater than x μm

NU_x average number of particles upstream of the filter whose particle sizes are greater than x μm

x particle size μm

β filtration factor, NU_x/ND_x

Λ lubricant film parameter, h_c/σ

σ composite surface roughness, $\left(\sigma_1^2 + \sigma_2^2\right)^{1/2}$, μm

σ_1, σ_2 root mean square (rms) surface roughness of contacting bodies, μm

1 body 1 or ball or roller

2 body 2 or bearing raceway

OIL FILTRATION

Oil filtration is a means to control and eliminate particle contamination from the lubrication system. Figure 2 shows the spectra of efficiencies (β) for various filter ratings as a function of particle size, where

$$\beta = \frac{NU_x}{ND_x} \tag{1}$$

NU_x and ND_x are the average number of particles upstream and downstream of the filter, respectively, whose particle size is greater than x μm. The data of figure 2 were generated using AC Fine Test Dust. A 3 μm filter is defined as $\beta_3 \geqq 200$. Similarly, a 25 μm filter is defined as $\beta_{25} \geqq 200$.

The removal efficiency E_x of any particle size x can be related to the β factor as follows:

$$E_x = 1 - \frac{1}{\beta_x} \tag{2}$$

From this relationship it becomes apparent that there is a large particle size above which essentially nothing passes. There is an intermediate particle size for which a reasonable fraction of the particles are captured and the rest pass downstream. Finally, there is a smaller size particle below which particles freely pass and accumulate to copious quantities, in recirculating lubrication systems. As an example, the 3 μm and 25 μm filters will filter 99.5% of all particle sizes over 3 μm and 25 μm, respectively.

The distribution of filtration factor β measured on a test stand is not necessarily the same as that obtained from operating machinery in the field. However, experience shows (fig. 1) that this rating (fig. 2) qualitatively predicts differences in contamination levels in actual machine operation. As an example, the 3 μm filter used for the T-56 gas turbine engine will keep the lubrication system approximately two orders of magnitude cleaner than a 40 μm filter. Additionally, the T-700 gas turbine engine used in the Blackhawk and Seahawk helicopters with 3 μm lubrication filters has no scheduled oil changes for its 2000 hr time between removal. By inhibiting catalytic induced oil oxidation by fine metallic wear particles, finer filters inhibit the blockage of oil passages and coating of heat exchanger surfaces by deposits of varnish, resins, and coke (oil oxidation products), and minimize chemical attack of bearing surfaces by organic acids found through oxidation.

LIFE EFFECTS

There were two independent investigations to determine the effect of oil filtration on rolling-element bearing life. These were those of Loewenthal et al. (1978, 1979, and 1982) at NASA Lewis Research Center, Cleveland, Ohio and Bhachu et al. (1981) at the Imperial College, London, England.

Bhachu et al. (1981) used a gear test machine to generate wear debris. The gear wear debris, verified by ferrography to be representative of that found in helicopter gearboxes, was used as the contaminant. Rolling-element fatigue tests were conducted with 25-mm bore roller bearings having a 2957 N (665 lb) radial load. For each test series, gear oil flow was passed through one of four possible filters of different ratings from 2.5 to 40 μm or through an electromagnetic separator, and continuously supplied to a parallel roller bearing fatigue tester. Elastohydrodynamic film thickness and Λ ratios during test are shown in table 1. Significantly, tests run with 40 μm filtration for only 30 min before switching to 3 μm filtration showed substantially the same lives as if all running had been with a 40 μm filter. Apparently the early damage could not be healed, at least in these small roller bearings. The test results are also shown in table 1. These results show that life increased with improved filtration where it is suggested from these data that

$$LF = 3.5(FR)^{-0.55} \tag{3}$$

Using equation (3), the predicted L_{10} lives for the roller bearings are presented in table 1 for comparison purposes.

The post-test inner-raceway measurements for 40 μm filtration showed greater out-of-roundness than in the unrun bearing. Less out-of-roundness was observed with finer filtration down to the 8 μm rating. Virtually no out-of-roundness was observed when the 3 μm filter was used. Below the 3 μm level the measurement was similar to that of the unrun bearing. Bhachu et al. (1981) suggested that particles smaller than 3 μm were too small to have any effect on roundness and merely passed through the contacts of the rollers and raceways.

There is a strong suggestion from these data, that the lack of contamination contributes to improvement in bearing raceway surface finish during operation. There appears to be a correlation between the lubricant film parameter Λ after testing and rolling-element fatigue life as evidenced by the data of table 1.

Loewenthal et al. (1978, 1979, and 1982) performed a series of tests to measure the quantitative effects of filtration on rolling-element fatigue life. Four levels of filtration were investigated using full-flow filters rated at 3, 30, 49, and 105 μm. The 3 μm filter used for these tests had been developed to replace the original 40 μm filter for a helicopter gas turbine lubrication system. The new filter elements were not only found to provide a much cleaner lubricant with less component wear, but contrary to prior belief, to greatly extend the time between filter and oil changes as discussed by Loewenthal et al. (1978, 1979, and 1982).

The test bearings were 65-mm deep groove ball bearings run at 15 000 rpm under a radial load of 4580 N (1030 lb) which produced a maximum Hertz stress of 2410 MPa (350 000 psi). The lubricant contaminant rate was 0.125 gram per hour per bearing. The test environment was designed to simulate an aircraft lubrication system containing multiple bearings, pumps, and other components commonly found in such systems. Test temperature was 347 K (165 °F). The test lubricant was a MIL-L-23699 type which produced a Λ ratio of 3.3. The test contaminant was similar to particulate matter found in the lubricant filters of 50 JT8D commercial engines (Jones and Loewenthal, 1980). Because this engine has a number of carbon-graphite bearing sump seals, replication of oil contaminants in engines with "windback" type labyrinth seals may demand a slightly different composition.

The results of these tests are summarized in table 2. As with the work of Bhachu et al. (1981), improved filtration increased bearing life. However, for the contaminated tests, there appears to be no statistical difference in life obtained between the 3 and 30 μm filters. Due to the severe wear obtained, the contaminated 105 μm filter test series was suspended after 448 hr on each bearing. No fatigue failures were encountered, because of the gross wear of the bearing races. Based upon the test results between the 3 and 49 μm filters the following life relation is suggested from these data:

$$LF = 1.8(FR)^{-0.25} \tag{4}$$

Using equation (4), the predicted L_{10} lives of ball bearings are presented in table 2 for comparison purposes.

Table 3 compares equation (3) with equation (4) for various filter ratings. The resultant life adjustment factors can be used to adjust the calculated bearing L_{10} or catalog life to account for filtration level in the lubricant system. Based upon the data of Loewenthal et al. (1978, 1979, and 1982), it is not recommended to use a life adjustment factor less than 0.5 even when no filter is used. Further, equation (4) appears to give more conservative results than equation (3). These two equations may reflect the differences in the effect of particle damage between roller and ball bearings.

The technology for improved oil filtration is commerically available. By minimizing the number of harmful particles entering a rolling-element bearing, oil filtration can substantially extend bearing life. In addition to machine generated wear debris, the comparatively high contamination of new oil also demands good filtration.

No reported testing has been performed comparing grease lubrication which entraps wear debris with the same bearings being oil lubricated with or without oil filtration. It is suggested that for long term application, grease lubrication be considered the same as oil lubrication for bearings without filtration where no periodic regreasing of the bearing occurs.

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TABLE 1. – EFFECT OF OIL FILTRATION ON THE ROLLING-ELEMENT FATIGUE LIFE OF 25-mm BORE ROLLER BEARINGS

[Radial load, 2975 N (665 lb); original raceway surface finish, 0.38 μm.] (Bhachu et al., 1981).

Test filter rating (where $\beta \geq 200$), μm	Composite surface roughness, σ after testing, μm	Calculated film thickness, μm	Film parameter, Λ after testing	Experimental life, millions of inner-race revolutions				Weibull slope	Predicted L_{10} life from eq. (3), millions of inner-race revolutions
				10-percent life, L_{10}	90-percent confidence limits	50-percent life, L_{50}	90-percent confidence limits		
40	0.41	0.58	1.4	1.5	1.0 to 2.0	2.1	1.9 to 2.3	5.8	1.9
25	.36	↓	1.6	2.5	2.0 to 3	3.0	2.9 to 3.1	9.4	2.5
6	.32	↓	1.8	4.5	3.4 to 5.8	5.9	5.4 to 6.3	7.0	5.5
3	.26	↓	2.2	8.0	5.5 to 11.6	12.0	10.7 to 13.5	4.7	8[a]
2.5	.22	↓	2.6	6.5	3.6 to 11.8	12.4	9.9 to 15.5	2.9	8.8
Magnetic	.20	↓	2.9	5.0	2.9 to 8.5	10.0	8.3 to 12.0	3.2	–––
40	0.41	0.99	2.4	1.8	–––––––––	3.3	–––––––––	3.1	2.2
3	.26	.99	3.8	9.3	–––––––––	16.2	–––––––––	3.4	9.3[a]
40/3	.41	.99	2.4	1.7	–––––––––	3.1	–––––––––	3.3	2.2

[a]Life prediction normalized to 3 μm filter.

TABLE 2. – COMPARISON OF BALL BEARING FATIGUE LIFE RESULTS WITH AN ULTRACLEAN LUBRICANT AND WITH DIFFERENT LEVELS OF FILTRATION IN A CONTAMINATED LUBRICANT

[Radial load, 4580 N (1030 lb); speed, 15 000 rpm; temperature, 347 K (165 °F); test lubricant, MIL-L-23699 type; film parameter, Λ, 3.3] (Loewenthal et al., 1978, 1979, and 1982).

Test series (lubricant condition)	Test filter rating (where $\beta \geq 200$), μm	Experimental life, hr		Weibull slope	Failure index[a]	Confidence number,[b] percent		Predicted L_{10} life from eq. (4), hr
		10-percent life, L_{10}	50-percent life, L_{50}			L_{10}	L_{50}	
Ultraclean	3	1099	1741	4.1	5 out of 9	—	—	1099[d]
Clean (baseline)	49	672	2276	1.5	9 out of 32	76	—	547
Contaminated	3	505	993	2.8	10 out of 16	93	99	505[d]
Contaminated	30	594	857	5.1	11 out of 16	96	99	284
Contaminated	49	367	533	5.1	20 out of 32	99	99	251
Contaminated	105[c]	–––	–––	–––	–––––––––	—	—	208

[a]Number of fatigue failures out of number of bearings tested.
[b]Probability (expressed as a percentage) that bearing fatigue life in a given test series will be inferior to the life obtained with ultraclean lubrication. A 90 percent or greater confidence number is considered statistically significant.
[c]Test series was suspended after 448 test hours on each of the test bearings due to excessive bearing wear. No fatigue failures were encountered.
[d]Life prediction normalized to 3 μm filter.

TABLE 3. - LIFE ADJUSTMENT FACTOR BASED ON FILTER RATING

Filter rating (where β ≥ 200), FR	Life factor, LF	
	Roller bearing equation (3)	Ball bearing equation (4)
3	1.9	1.4
6	1.3	1.2
8	1.1	1.1
10	1	1
12	0.9	1
25	.6	0.8
40	.5	.7
49[a]	.4	.7
60[a]	.4	.6
105[a]	.3	.6

[a]For filter ratings exceeding 40 μm or with no filtration it is not recommended to use a life adjustment factor less than 0.5.

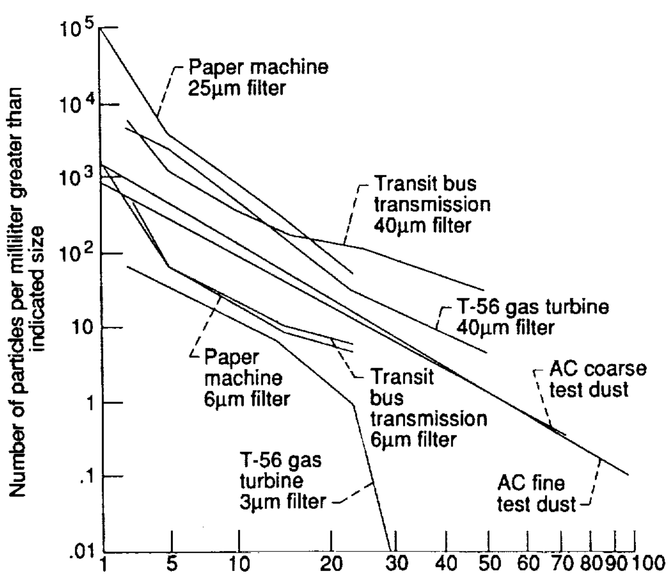

Figure 1.—Effect of oil filtration on particle contamination for mechanical systems.

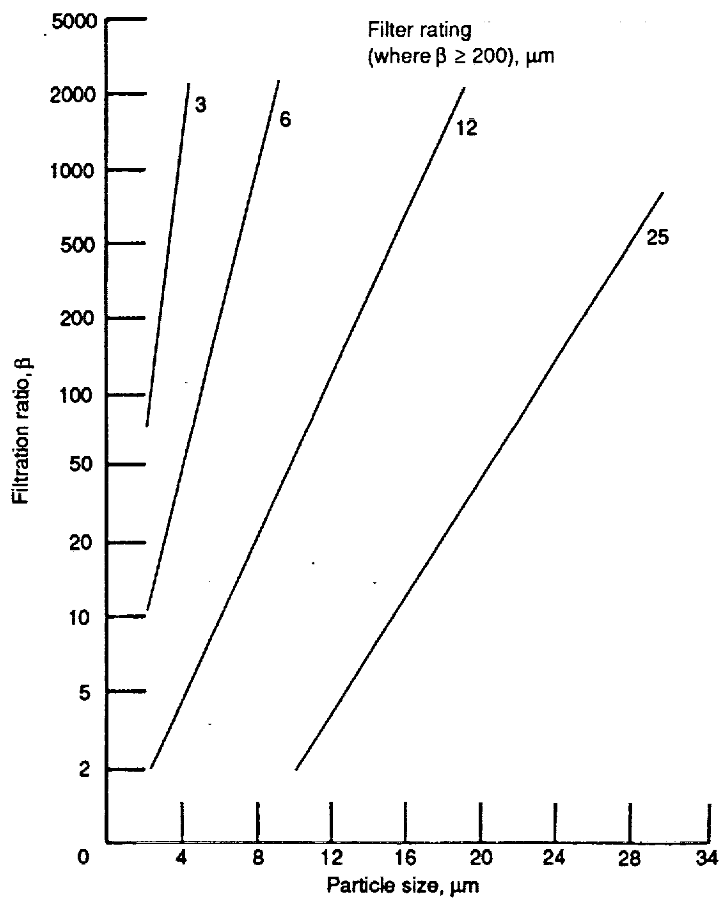

Figure 2.—Particle size as a function of filtration ratio β for different filter ratings.

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16. Abstract

Rolling-element bearing life is influenced by the number, size, and material properties of particles entering the Hertzian contact of the rolling element and raceway. In general, rolling-element bearing life increases with increasing level of oil filtration. Based upon test results, two equations are presented which allow for the adjustment of bearing L_{10} or catalog life based upon oil filter rating. It is recommended that where no oil filtration is used catalog life be reduced by 50 percent.

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