Comparison of Vibration and Direct Reading Ferrographic Techniques in Application to High-Speed Gears Operating Under Steady and Varying Load Conditions©

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LUBRICATION ENGINEERING

This paper presents a comparison of results of vibration and direct reading (DR) ferrographic analysis of high-speed gears operating under conditions of steady and varying loads. Nine sets of gears were tested, four sets were subjected to a steady load and the other five to various forms of varying loads. Gears were lubricated either by splash lubrication or by a recirculating lubrication system. The results showed close correlation between these techniques, especially in the case of splash lubricated gears. Typical results are presented and discussed.

INTRODUCTION

The increasing application of the "on condition" approach to maintenance of modern machinery has led to the development of a vast number of machine condition-monitoring techniques. Such techniques usually fall into one of four categories, monitoring of operating variables (e.g. velocity, pressure), monitoring of friction-induced energy losses (e.g. noise, acoustic emission, temperature), monitoring of components and/or lubrication (e.g. vibration, displacement, lubricant supply, lubricant analysis), and, finally, monitoring of wear-induced material losses (e.g. spectrometric oil analysis, ferrography, particle counting).

Most of the techniques are best in detecting a single "symptom" of machine distress. For example, particle counting only provides information about size and size distribution of wear debris, spectrometric oil analysis only provides information about gross concentration of wear metals in a sample. The detection of machine distress and diagnosis, i.e. identification of the mode, location, and mechanism of the wear or damage process and its intensity, may be greatly enhanced by using a "syndrome" approach in which a combination of "symptoms" identified by individual techniques is used to identify the failure or wear problem. A relatively rare use of such an approach to condition monitoring is partly due to the increased cost of monitoring and partly due to the rather "sectarian" views of researchers and engineers involved in condition monitoring characterized by a strong preference for a particular technique of condition monitoring. Recent papers on condition monitoring have addressed this problem and some interesting results have become available (*1*), (*2*), and (*3*). The results of the study reported in this paper were obtained during a continuing machine condition-monitoring program sponsored by the Australian mining industry. One of the objectives of this program is to evaluate various machine condition monitoring techniques and determine the best mix of various techniques which will provide reliable detection, diagnosis and, eventually, prognosis of the state of mining machinery.

The first objective of the study reported in this paper was to evaluate various vibration and ferrographic techniques in detecting gear wear. The second objective was to obtain a comparison of the effectiveness of ferrographic and vibration techniques in the detection of wear of gears operating under steady or varying load conditions.

Tests on nine pairs of gears were carried out. To accelerate the tests, the gears were heavily loaded and, in some tests, gear damage was induced by lubrication starvation, contamination, or by inflicting damage to the gear teeth.

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TEST EQUIPMENT

A schematic representation of the test rig and instrumentation is shown in Fig. 1. The test rig consisted of a 5.6-kW (7.5-hp) 3-phase, 2865-rpm electric motor which was coupled by a flexible coupling to a single-stage parallel-shaft gearbox. The output shaft of the gearbox was coupled to a hydraulic gear pump. The pump flow was discharged at the pressure set by a relief valve. The test load was controlled by the relief valve setting which was adjusted either manually or, in some tests, automatically using a solenoid-operated relief valve and signal generator.

Test gears were commercially available spur gears manufactured from S1045 mild steel. The gears had not been heat treated. Teeth pressure angle was 20 degrees and shaft center distance was 44.45 mm. The gear shafts were sup-

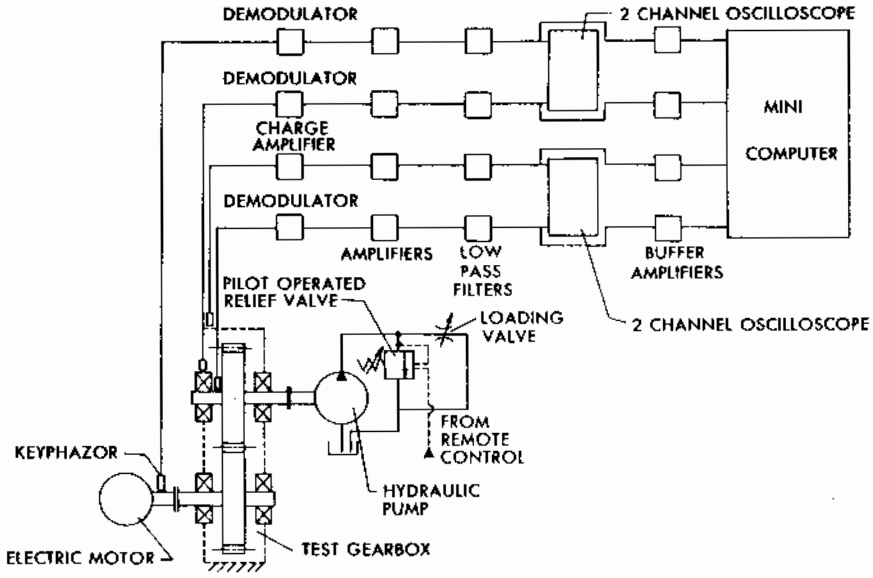

Fig. 1—Experimental test rig and instrumentation

ported by 6002 deep-groove ball bearings. These bearings have internal and external diameters of 15 mm and 32 mm, respectively, and load ratings of 5.59 kN (dynamic) and 2.5 kN (static). Details of gears used in each test are shown in Table 1.

LUBRICATION

The lubricant was a commercial GL-5 gear oil of the sulfur/phosphorus chemistry with extreme-pressure additives. The oil specified viscosity was 135 cSt at 40°C and 14.2 cSt at 100°C, viscosity index was 103.

Two types of lubrication were used during the tests. The first five tests were run with splash lubrication. The volume of lubricant in the gearbox was maintained constant by replacing the fluid lost during sampling. The remaining four tests were run with a recirculating lubrication system which consisted of a vane pump and full-flow, in-line filter. The lubricant was injected directly, under low pressure, into the contact zone of the mating gears. The paper filter element was rated, on the basis of a single-pass filter efficiency test carried out by the manufacturer, to retain above 90 percent of particles greater than 3 μm.

TEST PROGRAM

The details of the test program are listed in Table 2.

ANALYSIS—FERROGRAPHY

A description of analytical ferrographic (AF) and direct reading ferrographic (DR) techniques is given in (*4*).

Sample Processing

Oil samples were collected at time intervals specified in Table 2. The volume of each sample was 15 cc. Before analysis, each bottle containing a sample was thoroughly shaken using an ultrasonic bath and a mechanical shaker. When necessary, samples were diluted to maintain readings of DR ferrograph within linear range.

DR Trending Parameters

A number of trending parameters have been evaluated, the most effective were (*5*):

1. *Large Particle Count, DL* [1]

2. *Small Particle Count, DS* [2]

3. *Wear Rate Index,* $WR = DL + DS$ [3]

4. *Wear Intensity Index,* $WI = DL - DS$ [4]

5. *Wear Severity Index,* $SI2 = DL*(DL - DS)/DS$ [5]

   This index was a good indicator of the wear occurring in the splash-lubricated gears. Its usefulness was somewhat limited for gears using recirculating lubrication.

6. *Severity of Wear Index,* $SI = WR*WI$ [6]

Table 1—Details of Test Gears

Test No. 1	1	2	3	4	5	6	7	8	9
Number of teeth pinion/wheel	28/28	28/28	28/28	24/32	24/32	24/32	24/32	24/32	24/32
Face width (mm) pinion/wheel	12.7/12.7	6.3/6.3	12.7/4.0	6.3/6.3	6.3/6.3	5.0/5.0	5.0/5.0	5.0/5.0	5.0/5.0

Table 2—Test Program

Test No.	Type of Load	Sampling Rate h/ sample	Damage Induced
1.	steady (5.2 kW)	3	a. lubrication off at 45 h for 8 minutes b. lubrication off at 63 h for 25 minutes c. lubrication off at 78 h for 60 minutes d. tooth damaged at 96 h e. remove one tooth at 117 h
2.	steady	2	nil
3.	steady	2	nil
4.	steady	2	a. add 1 gm/l of ACTCD at 148 h b. add 2 gm/l of ACTCD at 156 h c. add 4 gm/l of ACTCD at 162 h
5.	load altered every 2 h	2	add 2 gm/l of ACTCD at 86 h
6.	load altered every 2 h	a. 2 h for 66 h b. one at 67 h c. 0.5 h	nil
7.	load altered every 2 h	a. 2 h for 92 h b. one at 93.5 h c. 0.5 h till 95.5 h d. one at 97.75 h	nil
8.	cyclic at 0.083 Hz	2	nil
9.	cyclic at 0.025 Hz	2	nil

In practice, this parameter has very large variations. The use of log or decibel values simplifies trending. Either the baseline value or $SI = 1$ can be used as a reference value (*6*). The *SIO* index was calculated using the initial (baseline) value of *SI* as a reference,

$$SIO = 20 \log[(WR*WI)/(WR_o*WI_o)] \quad [7]$$

where WR_o, WI_o are baseline values of *SI*, and
WR, *WI* are values of the current sample.

In addition to the parameters listed above, parameters proposed in the literature (*7*), (*8*) and others based on average or accumulative values of the above indices were also evaluated. All parameters were plotted against time and used for trending the condition of the gears. Figure 2 shows a comparison of trends of various DR indices for gear set 6. The wear trends were verified by inspections of the gears during tests and by analytical ferrographic analysis. The values of *DS* and *DL* used in the calculation of *SIO* for the splash-lubricated gears (tests 1 to 5) were corrected to compensate for dilution caused by replacement of the oil lost during sampling.

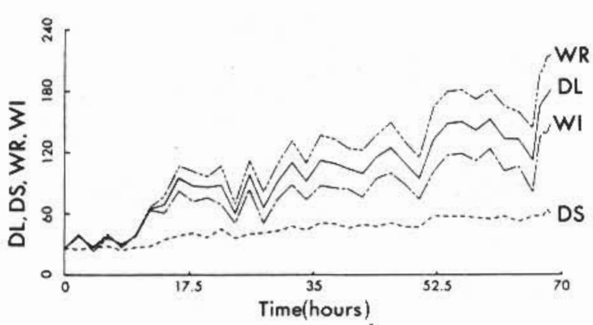

Fig. 2—Comparison of DR trends—Gear Set 6

ANALYSIS—VIBRATION

Sample Processing

Bearing acceleration, bearing to shaft relative displacements and keyphazor data were collected by a minicomputer and stored on a disk for further processing. These samples were collected at the same time as oil samples. Note: The keyphazor was a relative displacement transducer used in providing a once-per-revolution reference pulse off the shaft keyway. This pulse was subsequently used for determining the shaft rotational speed and in indexing the vibration time domain signal for time synchronous averaging. The signals were appropriately processed to prevent digital aliasing before storage. The upper frequency limit was 13.653 kHz per channel during the first three tests and 10.24 kHz during the following tests. The instrumental set up is shown in Fig. 1.

Vibration Trending Parameters

Only parameters obtained from acceleration signals are discussed here. Most of the time and spectral parameters used in our study were applied previously in a study of rolling element bearings (*9*). Cepstral parameters and parameters based on gear discrete frequencies were also investigated and discussed in detail in (*10*). The above and other studies, reported in (*11*), established that in the case of high-speed gears and bearings operating at a steady speed, the parameter known as the matched filter RMS was more sensitive and reliable in the detection of damage when compared with the more commonly used parameters such as RMS or peak levels. The matched filter RMS (MFO) based on the original spectrum is defined by

$$MFO = 10 \log\left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{As_i}{Ao_i}\right)^2\right] \quad [8]$$

where As_i is the amplitude of ith component of the sample frequency spectrum,

Ao_i is the amplitude of ith component of the original or baseline frequency spectrum, and

n is the number of frequency components in the vibration spectrum.

COMPARISON OF PARAMETERS

Of the wide array of analysis techniques employed in both vibration and ferrographic studies, the matched filter RMS, MFO and the wear severity index, SIO were chosen in order to make a comparison of their effectiveness in detecting and perhaps diagnosing abnormal wear and damage. The trends of parameters MFO and SIO were compared directly by plotting both parameters on a single graph. However, as changes of MFO values were smaller than the changes in values of SIO, a gain factor was introduced in some MFO trends for comparison purposes.

RESULTS

Gear Set 1

This gear set was run-in before sampling commenced. Gear damage was induced during the test by reducing the level of lubricant in the gearbox at 45, 63, and 78 hours. The MFO and SIO trends are compared in Fig. 3, MFO gain factor was 3.0. Both trends showed sharp, correlated increases at the time when lubrication was reduced at 45 hours and responded with downward trends when the correct lubricant level was restored. The oil sampling was stopped after 87 hours, thus no DR data are available on the effect of tooth damage at 96 and 117 hours. These events are clearly visible on the MFO plot.

Gear Set 2

No run-in was allowed during this test, a full steady load was applied as soon as the test commenced. Bearing failure at 68 hours was observed and verified using the AF technique. The MFO parameter (gain factor was 3.0) showed a gradual increase and then, after 18 hours, stabilized at about 48dB (actual 16dB), Fig. 4. The SIO showed a sharp increase by approximately 45 dB after only two hours of operation and, after peaking at 60 dB between 8 and 12 hours, decreased to approximately 40 dB at 56 hours. Both parameters increased again after bearing failure was observed at 68 hours and continued this trend until the end of the test.

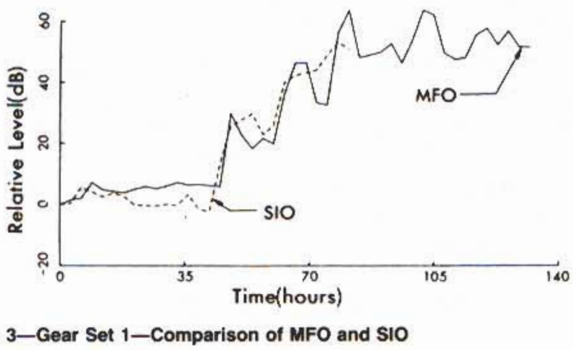

Fig. 3—Gear Set 1—Comparison of MFO and SIO

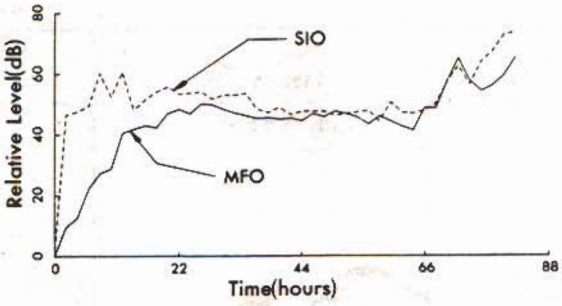

Fig. 4—Gear Set 2—Comparison of MFO and SIO

Gear Set 3

To accelerate this test, the width of the driven gear was reduced by approximately 30 percent in comparison with the width of gears used in the previous test. After 8 hours of operation, severe pitting and scoring of gears were observed, and the gears failed after 12 hours of operation. Both trends, shown in Fig. 5, were similar until 8 hours after which the vibration decreased slightly (MFO gain factor was 3.0). The AF analysis showed a large quantity of sliding and rubbing wear indicating that the gears were in failure mode early in the test, Fig. 6.

Gear Set 4

Conditions for this test were similar to those of gear set 2, with the exception of the gear ratio. Inspection of the gears showed gear scuffing and pitting early in the test. The AF analysis showed a similar wear pattern to that of gear set 2. Samples taken until 168 hours showed high levels of

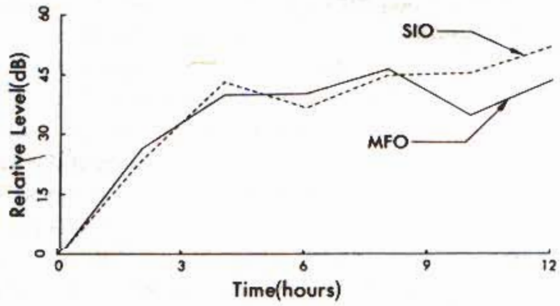

Fig. 5—Gear Set 3—Comparison of MFO and SIO

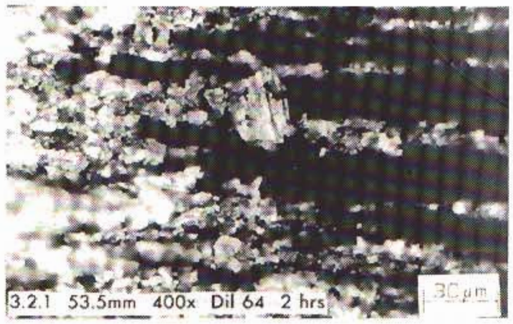

Fig. 6—Gear Set 3—Sliding and rubbing wear

fatigue and rubbing wear and low levels of sliding wear, Fig. 7. The initial SIO trend was very similar to trends observed in tests of gear sets 2 and 3. The MFO initial trend (gain factor of 4.0) showed a large increase unlike the previous tests, Fig. 8. After 72 hours, the MFO values showed a decreasing trend, whereas SIO was increasing marginally. Ingression of contaminant was simulated during this test by adding 1 g/l of air cleaner test coarse dust (ACTCD) at 148 hours. The SIO values increased, indicating the occurrence of abnormal wear, however the values of MFO decreased markedly probably due to the lapping effect of the dust on teeth surfaces. The effects of subsequent additions of dust at 156 and 162 hours are clearly shown on MFO and SIO plots. The pinion tooth fracture observed at 168 hours resulted in a sudden increase of MFO. However, the value of SIO decreased marginally. The plot of DL and DS parameters shown in Fig. 9 indicates that the decrease of SIO value was caused by a sudden decrease in the DL parameter. It appears that the tooth fracture generated large particles which did not stay in suspension and were not sampled.

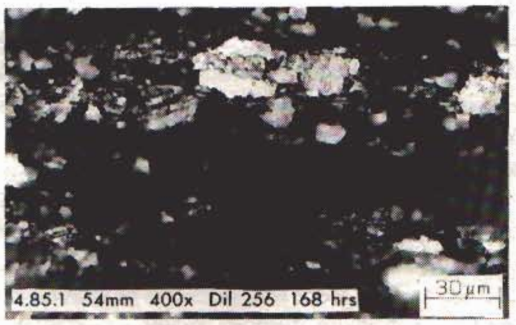

Fig. 7—Gear Set 4—Fatigue wear

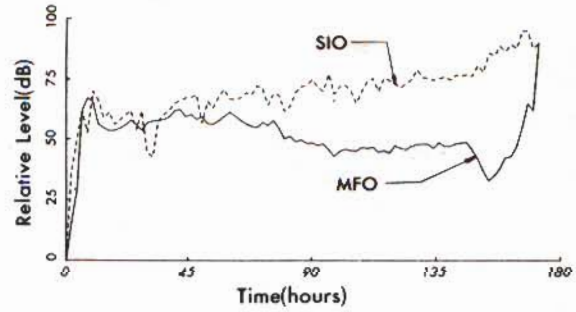

Fig. 8—Gear Set 4—Comparison of MFO and SIO

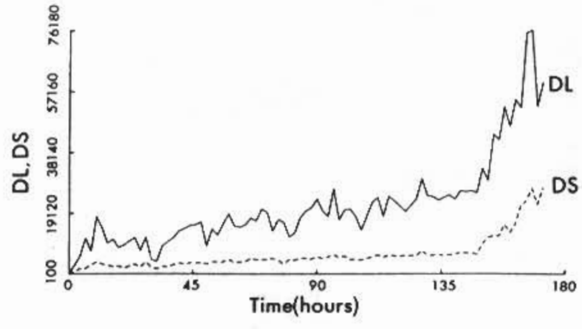

Fig. 9—Gear Set 4—Trend of WR and WI

Gear Set 5

This gear set was similar to the one used in the previous test. However, the load on the gears was not constant but was varied manually between samples. Figure 10 shows the variation of pump pressure during the test. The lubricant was contaminated with 2 g/l of ACTCD at 86 hours. The tooth failure was observed at 102 hours and the test was terminated after 109.5 hours. Similar sharply increasing trends of SIO and MFO (gain factor of 3.0) were recorded at the beginning of the test, Fig. 11. A gear examination showed that tooth pitting had already been initiated. The MFO trend remained essentially steady until the time when the contaminant was introduced to the system upon which it showed a decrease of about 10 to 20 dB (actual decrease of approximately 3–7 dB). The SIO parameter gradually decreased as the test progressed, again due to the decreasing values of the parameter DL, but as in previous tests responded sharply, by about 30 dB, to contamination. This test showed that a slow varying load did not have an obvious effect on the trends of either the MFO or SIO parameters.

Gear Set 6

This gear set was lubricated by a recirculating system. The gears were subjected to a varying load as in the previous test. The face widths of the gears in this and the following two tests were reduced by approximately 25 percent to increase tooth loading. The correlation of both techniques was remarkably good, Fig. 12. The initial increase of both SIO and MFO (gain factor of 2.0) parameters was due to pitting which was confirmed by AF analysis, Fig. 13. The gears were in a failure mode after only 18 hours of operation. The AF analysis of the sample taken at 58 hours

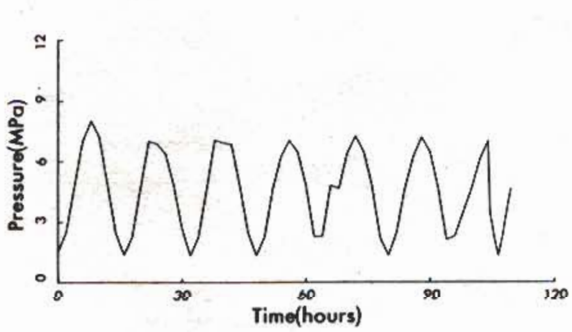

Fig. 10—Gear Set 5—Load pump pressure variations at sampling times

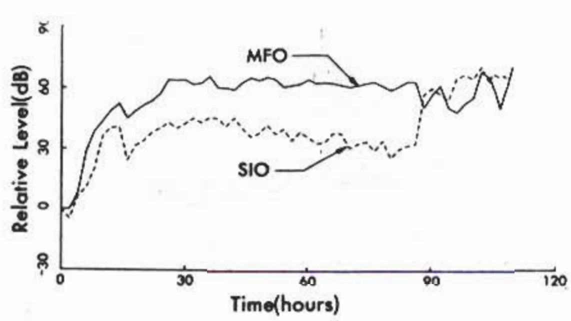

Fig. 11—Gear Set 5—Comparison of MFO and SIO

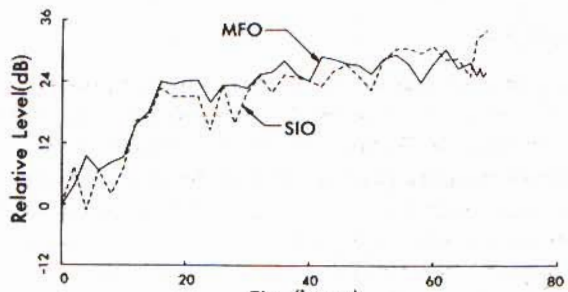

Fig. 12—Gear Set 6—Comparison of MFO and SIO

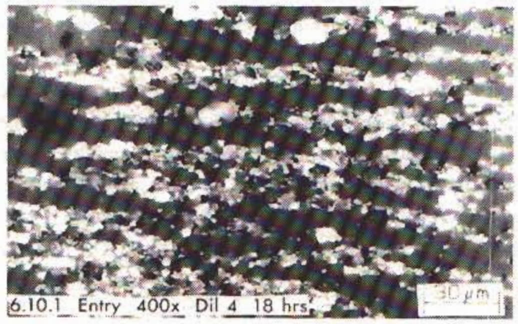

Fig. 13—Gear Set 6—Fatigue wear and spheres

showed large sliding wear particles, Fig. 14 and the presence of spheres indicating the fatigue mode of failure, Fig. 15. The trend of SIO and MFO values increased gradually over the duration of the test until the time of gear failure due to tooth breakage at 66 hours.

Gear Set 7

The gears used in this test were identical to those in the previous test and gear loading conditions were similar. The DR values for this test (and also for tests 6, 8, and 9) were much lower than those recorded for the tests with splash lubrication. The MFO was similar to those recorded during the previous tests; after an initial increase it stabilized at approximately the 15-dB level and did not significantly vary even when catastrophic failure of gears occurred at 95.75 hours, Fig. 16. The SIO parameter showed large variations and only a small increase over the time of the test. Early samples analyzed using the AF technique showed a large quantity of rubbing and fatigue wear almost immediately after commencement of the test and samples taken after 28 hours indicated that the gears were in an advanced failure mode. The DL and DS parameters showed large values at the start of the test, which gradually decreased until approximately 28 hours and then significantly increased. The DS showed a clear increasing trend and the ratio of DL to DS values decreased, indicating that failure was characterized by production of small particles. Comparison of values of DL, DS, and SIO in this and previous tests also showed that after the initial running-in (0 to 28 hours) the gears were in a failure mode.

Fig. 14—Gear Set 6—Severe sliding wear

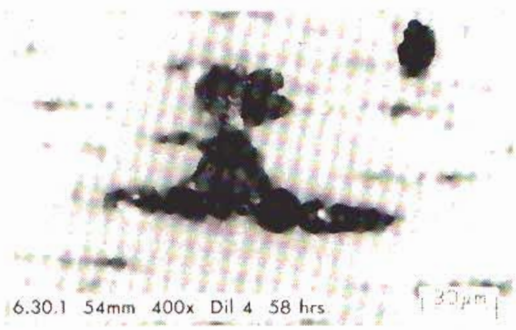

Fig. 15—Gear Set 6—Spheres

Gear Set 8

In this test, the load on the gears was cyclic at a frequency of 0.083 Hz and resulted in gear failure in only 16 hours. The MFO (gain factor of 2.0) trend showed a steady increase until the end of the test and reached the level at which, in tests 6 and 7, the gears were in failure mode, Fig. 17. The SIO parameter showed a large increase and reached its peak value at 6 hours. The trend of SIO decreased soon after due to the reduction of large particles and then started to increase again until failure of the gears at 16 hours. The values of DL and DS were well in excess of values recorded for tests 6 and 7 also indicating severe wear condition at approximately 4 hours. The decreasing ratio of DL/DS was

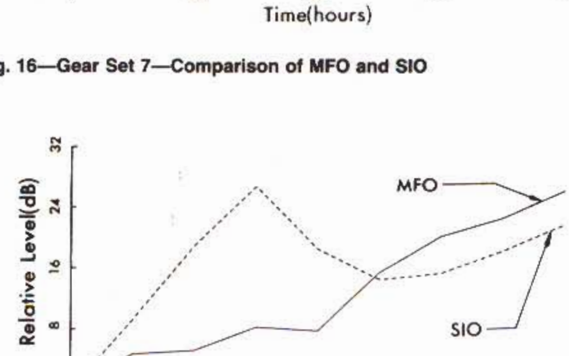

Fig. 16—Gear Set 7—Comparison of MFO and SIO

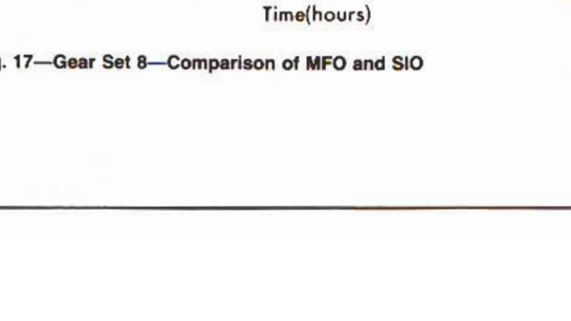

Fig. 17—Gear Set 8—Comparison of MFO and SIO

supported by AF analysis which showed an increasing proportion of relatively small particles which did not exceed 10 μm in size, Fig. 18.

Gear Set 9

To extend the duration of the test, the frequency of load variation was reduced to 0.025 Hz. The gears showed signs of moderate pitting after only a few hours of operation and were in an advanced failure mode at 32 hours. The MFO increased gradually throughout the test and reached a level corresponding to the failure mode in previous tests at about 55 hours, Fig. 19. The SIO trend showed the running-in period during which SIO values increased sharply soon after the commencement of the test. It reached a level corresponding to failure in test 8 after a few hours and then gradually decreased over the next 20 or so hours. Although SIO values fluctuated irregularly during the test, the increases in SIO values to the level of failure in previous tests indicated that the gears were in a failure mode at about 32 hours. This was confirmed by AF analysis which showed that the level of rubbing and fatigue wear remained more or less constant from this time on, and the levels of sliding and laminar particles increased sharply at 72 hours.

DISCUSSION

The MFO levels recorded for the tests with splash lubrication were higher than those recorded in the tests with the recirculating lubrication system by about 6 dB, Fig. 20. This was attributed to the much higher quantity of wear particles in the former tests. The MFO also showed an interesting downward trend in response to contamination. In most tests, SIO clearly showed periods of running-in, and responded

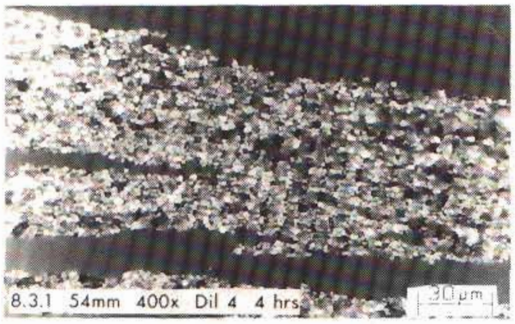

Fig. 18—Gear Set 8—Fatigue and rubbing wear

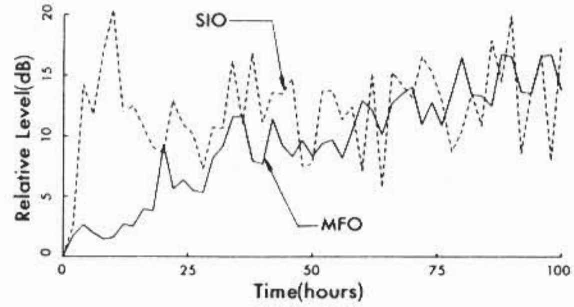

Fig. 19—Gear Set 9—Comparison of MFO and SIO

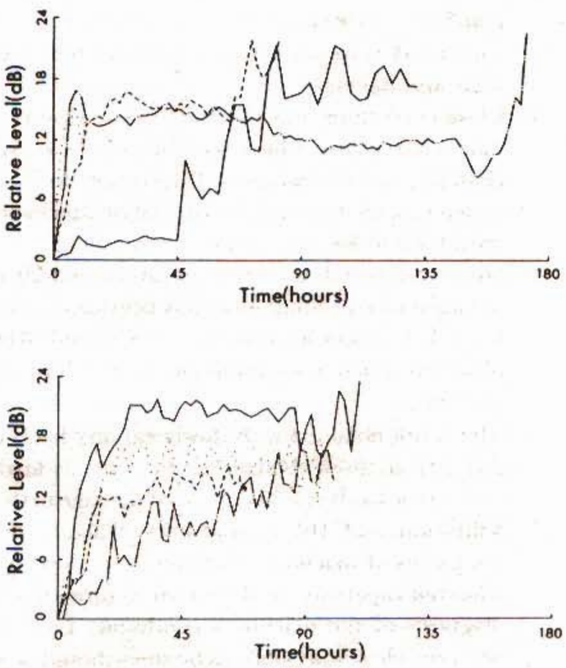

Fig. 20—Comparison of MFO trends
(a) _____ Gear Set 1, ------ Gear Set 2, ····· Gear Set 3, __.__ Gear Set 4.
(b) _____ Gear Set 5, ------ Gear Set 6, ····· Gear Set 7, --·-- Gear Set 8, __.__ Gear Set 9.

sharply to increased wear caused by contamination. The SIO values were much higher in the tests with splash lubrication in comparison to the tests which used the recirculating system. There was close correlation of MFO and SIO trends in tests 1 to 6. Although in the case of gears 7 to 9, the correlation between MFO and SIO trends appears to be less apparent. Plots of DL, DS, and SIO values showed that the gears were in a failure mode almost from the start of tests. The trends of SIO values in these tests were, to some extent, obscured by increasing concentration of large and small particles. Figure 21 shows plots of DL and DS in sequence for gears 6, 7, 8, and 9. As the lubricant and the filter element were not replaced between these tests, it was thought that lower than specified efficiency of the filter, increasing intensity of wear and short duration of tests, all prevented concentration of particles reaching an equilibrium.

CONCLUSIONS

1. The results of this investigation showed that both

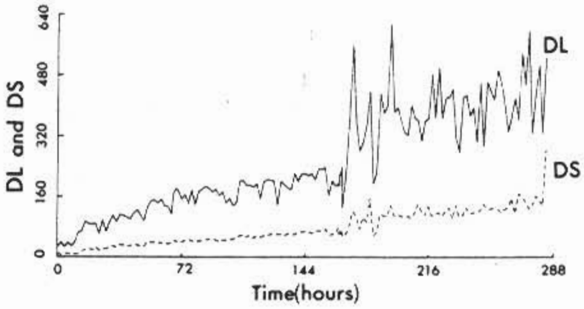

Fig. 21—Trends of DL and DS for tests 6 to 9

matched filter RMS and severity of wear index showed correlated responses which correctly indicated gear wear and damage.

2. Close correlation was obtained in the case of splash-lubricated gears, where samples correctly reflected changing wear conditions. Differences in results obtained in some tests using recirculating lubrication were attributed to less representative sampling.
3. Some results indicated that vibration analysis was less sensitive when sliding wear was prevalent, and significant differences in responses of SIO and MFO were observed when contamination in the lubricant was present.
4. The result obtained with slowly varying loads did not differ from those obtained under a steady load. However, cyclic loads resulted in rapid damage to the gears.
5. Vibration and DR ferrography evaluate different symptoms of machine condition, thus they have only a limited capability on their own to provide a reliable diagnosis of the machine's condition. To obtain the best possible results, both techniques should be applied in conjunction with each other, with AF ferrography and perhaps particle counting in a supporting role.

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