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Detecting Gear Tooth Fracture in a High Contact Ratio Face Gear Mesh

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RESEARCH LABORATORY

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ABSTRACT

This paper summarizes the results of a study in which three different vibration diagnostic methods were used to detect gear tooth fracture in a high contact ratio face gear mesh. The NASA spiral bevel gear fatigue test rig was used to produce unseeded fault, natural failures of four face gear specimens. During the fatigue tests, which were run to determine load capacity and primary failure mechanisms for face gears, vibration signals were monitored and recorded for gear diagnostic purposes. Gear tooth bending fatigue and surface pitting were the primary failure modes found in the tests. The damage ranged from partial tooth fracture on a single tooth in one test to heavy wear, severe pitting, and complete tooth fracture of several teeth on another test. Three gear fault detection techniques, FM4, NA4*, and NB4, were applied to the experimental data. These methods use the signal average in both the time and frequency domain. Method NA4* was able to conclusively detect the gear tooth fractures in three out of the four fatigue tests, along with gear tooth surface pitting and heavy wear. For multiple tooth fractures, all of the methods gave a clear indication of the damage. It was also found that due to the high contact ratio of the face gear mesh, single tooth fractures did not significantly affect the vibration signal, making this type of failure difficult to detect.

INTRODUCTION

Drive train diagnostics is one of the most significant areas of research in rotorcraft propulsion. The need for a reliable health and usage monitoring system for the propulsion system can be seen by reviewing rotorcraft accident statistics. An investigation of serious rotorcraft accidents that were a result of fatigue failures showed that 32 percent were due to engine and transmission components [1]. In addition, governmental aviation authorities are demanding that in the near future the safety record of civil helicopters must match that of conventional fixed-wing jet aircraft. This would require a thirtyfold increase in helicopter safety. Practically, this can only be accomplished with the aid of a highly reliable, on-line Health and Usage Monitoring (HUM) system. A key performance element of a HUM system is to determine if a fault exists, as early and reliably as possible. Research is thus needed to develop and prove various fault detection concepts and methodologies.

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For rotorcraft transmissions, a critical element of a reliable HUM system is the accurate detection of gear tooth damage. A number of fault detection methods have been applied to spur gear fatigue data [2] and spiral bevel gear fatigue data [3], with gear tooth surface pitting as the primary failure mode. This paper extends the research by applying gear fault detection methods to fatigue data from high contact ratio face gears in a test rig. The methods applied to the face gear experimental data include method FM4, developed by Stewart [4] to detect isolated damage on gear teeth, and methods NA4* and NB4, both recently developed at NASA Lewis [2,3,5] to detect general damage on gear teeth. Verification of these detection methods with experimental face gear fatigue data along with a comparison of their relative performance is an integral step in the overall development of an accurate means to detect gear tooth damage.

In view of the above, it becomes the object of the research reported herein to determine the relative performance of the detection methods as they are applied to experimental data from a face gear fatigue rig at NASA Lewis. The vibration signal from four face gear fatigue tests were monitored and recorded for gear diagnostics research. Gear tooth bending fatigue and surface pitting were the primary failure modes found in the tests. The damage ranged from partial tooth fracture on a single tooth in one test to heavy wear, severe pitting, and complete tooth fracture of several teeth in another test. Results of each method are compared, and overall conclusions are made regarding the performance of the methods.

THEORY OF FAULT DETECTION METHODS

All of the methods in this investigation utilized vibration data that was processed as it was collected. The vibration data was converted to digital form and time synchronously averaged to eliminate noise and vibration incoherent with the period of revolution of the face gear. The averaged data was then resampled by linear interpolation to provide exactly 1024 samples over two complete revolutions of the face gear. This was done to optimize the frequency resolution when converting the data to the frequency domain. This averaged and resampled data was used as the input to the three diagnostic methods discussed below.

FM4 was developed to detect changes in the vibration pattern resulting from damage on a limited number of teeth [4]. A difference signal is first constructed by removing the regular meshing components (shaft frequency and harmonics, primary meshing frequency and harmonics along with their first order sidebands) from the time averaged signal. The fourth normalized statistical moment (normalized kurtosis) is then applied to this difference signal. For a gear in good condition the difference signal would be primarily Gaussian noise, resulting in a normalized kurtosis value of 3 (non-dimensional). When one or two teeth develop a defect (such as a crack, or pitting) a peak or series of peaks appear in the difference signal, causing the normalized kurtosis value to increase beyond the nominal value of 3.

NA4 is a method developed at NASA Lewis Research Center to detect the onset of damage, and also to continue to react to the damage as it increases [2,3]. Similar to FM4, a residual signal is constructed by removing regular meshing components from the original signal, however, for NA4, the first order sidebands stay in the residual signal. The fourth statistical moment of the residual signal is then divided by the current run time averaged variance of the residual signal, raised to the second power. This operation normalizes the kurtosis in NA4, however it is normalized using the variance of the residual signal averaged over the run up to the current time record, where NA4 is being calculated. With this method, the changes in the residual signal are constantly being compared to a weighted baseline for the specific system in "good" condition. This allows NA4 to grow with the severity of the fault until the average of the variance itself changes. NA4*, a modified version of NA4, allows the parameter to continue to grow further by "locking" the value of the averaged variance when the instantaneous variance

exceeds predetermined statistical limits [5]. As with FM4, NA4 and NA4* are dimensionless, with a value of 3, under nominal conditions.

NB4 is another parameter recently developed at NASA Lewis. NB4 is similar to NA4 in that it uses the same operation to normalize the kurtosis. The major difference is that instead of using a residual signal, NB4 uses the envelope of a bandpassed segment of the signal. NB4 is a demodulation technique, in which the signal is first band-pass filtered about the dominant (primary) meshing frequency. For the face gear tests, a bandwidth of +/- 50 sidebands was used. Using the Hilbert transform, a complex time signal is then created in which the real part is the band-pass signal, and the imaginary part is the Hilbert transform of the signal. The envelope is the magnitude of this complex time signal, and represents an estimate of the amplitude modulation present in the signal due to the sidebands. Amplitude modulation in a signal is most often due to periodically reoccurring transient variations in the loading. The theory behind this method is that a few damaged teeth will cause transient load fluctuations unlike the normal tooth load fluctuations, and thus be observed in the envelope of the signal. NB4 is also dimensionless, with a value of 3 under nominal conditions.

APPARATUS AND GEAR DAMAGE REVIEW

The damage on the face gears shown in figures 1 through 4 were a result of a series of face gear fatigue tests conducted on a gear test rig at NASA Lewis Research Center. The face gear fatigue tests were part of an Advanced Rotorcraft Transmission (ART) program that was initiated to develop advanced transmission technologies for future military and civil rotorcraft [6]. The overall objective of the face gear tests was to determine the feasibility of using face gears in aerospace applications. Each test was allowed to progress beyond the pitting and heavy wear stages until a tooth fracture occurred. The load in some tests, after running at 100 % load for a period of time, was gradually increased to a maximum of 200% load, in order to precipitate failure. During the tests, vibration data from an accelerometer mounted on the pinion shaft bearing housing was captured using an on-line program running on a personal computer with an analog to digital conversion board and anti-aliasing filter. The 107 tooth face gear meshes with a standard 28 tooth spur pinion rotating at a nominal speed of 19,107 rpm. This transmits 136 kW (182 Hp) at 100 % design load to the face gear, rotating at 5,000 rpm. The face gear/pinion mesh has an effective contact ratio of 2.1, meaning that at least two gear teeth are in contact at all times.

Figure 1 illustrates the tooth damage resulting from face gear run #1. During the last 7 hours of the test all of the teeth on the face gear experienced heavy wear damage, with some developing severe pitting and surface fatigue cracks as well. One tooth broke off at approximately 18 minutes before the end of the test, and the test was terminated when the second tooth broke off. Both were complete tooth fractures, as shown in the figure.

Figure 2 illustrates the damage resulting from face gear run #2. After about 25 hours into the run, the load was incrementally increased over a period of 5 hours to 200%. The test continued at 200% load until 3 teeth broke off. Almost one complete tooth broke off along with a majority of an adjacent tooth, as seen in this figure. The third tooth, positioned approximately 120 degrees from the two shown in figure 2, also experienced a partial tooth fracture of over 50% of the tooth.

Figure 3 illustrates the tooth damage resulting from face gear run #3. During the last 3 hours of the run several teeth on the face gear experienced gradual pitting damage on the tooth surface. This resulted in the pitting-induced single tooth fracture at the end of the test. As seen in figure 3, nearly 75% of the tooth broke off. In addition, the tooth adjacent to the fractured tooth has extensive pitting damage, and a fatigue crack across most of the tooth width.

Figure 4 illustrates the damage resulting from face gear run #4. As seen in this figure, the damage was limited to a single tooth fracture. Approximately 75% of the tooth broke off during the test.

DISCUSSION OF RESULTS

Results of applying the various diagnostic methods to face gear run #1, 2, 3, and 4 are illustrated in figures 5, 6, 7, and 8, respectively. In addition, figures 9, 10, 11, and 12 plot the time synchronous averaged vibration signal for the test face gear at the start (a) and end (b) of face gear run #1, 2, 3, and 4, respectively. The time averaged vibration signals shown in these figures are for two complete revolutions of the face gear.

Based on the results, all of the gear diagnostic methods investigated reacted significantly to the multiple tooth fracture damage experienced in face gear runs #1 and 2. As seen in figure 5, all of the parameters clearly indicated the multiple tooth fracture damage at the end of run #1. One tooth, or a portion of a tooth, broke off at approximately 18 minutes before the end of the test, which may account for the "knee" seen in the resulting plots at approximately the same point in time. Table 1 lists the results of the methods for the last 30 minutes of run #1. From the graphs in figure 5, it appears that the indications from the methods are nearly instantaneous. However, as seen in table 1 there is a gradual increase in FM4, NA4*, and NB4 over the last 24 minutes. At the end of run #1, FM4 reaches a value of 7.0, NA4* reaches 549, and NB4 reaches 1213, all relative to the nominal value of 3.0. Similarly, as seen in figure 6, all of the parameters clearly reflect the multiple tooth fracture damage at the end of run #2. Table 2 lists the results of the methods for the last 24 minutes of run #2. Again, the damage indications from the methods are not instantaneous, but gradually increases over the last 21 minutes of the test. As seen in this table, at the end of run #2, FM4 reaches a value of 6.7, NA4* reaches a value of 142, and NB4 reaches a value of 369.

Single tooth damage, as experienced in face gear runs #3 and 4, was more difficult to detect using the methods investigated. As seen in figure 7, only FM4 and NA4* reacted to the gradual pitting damage and single tooth fracture experienced in run #3. The final values of these two parameters are much lower than that experienced in the runs with multiple tooth fracture damage. NB4 did not show any indications of the damage in this run. As seen in figure 8, none of the parameters give any indications of the single tooth fracture damage experienced in run #4. For both run #3 and run #4, the tooth fracture damage was similar, i.e. approximately 3/4 of one tooth broke off, however only run #3 had some damage detection success. This may be due to the fact that the tooth adjacent to the fractured tooth in face gear run #3 had extensive pitting damage and a large fatigue crack. Even though this adjacent tooth did not break off in run #3, it was damaged enough to act similarly as if it were partially fractured.

The difficulty in detecting single tooth fracture in a high contact ratio gear mesh is a direct result of the nature of high contact ratio gearing. The contact ratio of the test face gear and pinion mesh in the tests was 2.1. Because the contact ratio is greater than 2, at least two pairs of teeth will be in contact at all times. Thus if one tooth becomes damaged, another tooth is available to carry the total mesh force. Theoretically this should change the vibration pattern, however, it will not change it as much as if the same damage was on a tooth in a low contact ratio gear mesh. For a contact ratio greater than 1 but less than 2, each tooth carries the total mesh load for a portion of the mesh cycle, and thus no other tooth is available to take up the load if that tooth is damaged. As seen in figures 9 and 10, the time averaged vibration signal at the end of runs #1 and 2 clearly indicate an impulsive event at the point of multiple tooth fracture. This impulsive signal is easy to detect with the methods used. As seen in figures 11 and 12, the time averaged vibration signal indicates very little impulsive event for the single tooth damage in

run #3 (figure 11), and no real change in the signal for the single tooth damage in run #4 (figure 12). It is apparent from these results that single tooth damage is difficult to detect in a high contact ratio gear mesh.

Method NA4* was able to detect more than just pitting and tooth fracture damage. As seen in figure 5b, only NA4* reacted significantly to the heavy wear damage experienced by the face gear during the last 7 hours of face gear run #1. As in previous tests [2,3], NA4* was shown to be capable of reacting to a number of different failure modes. In these series of face gear tests, NA4* was able to detect gear tooth pitting, heavy wear, and fracture damage. NA4* is however, sensitive to load and speed changes. For example, as the load was gradually changed from 100% to 200% of design load between the run time of 26 and 31 hours during run #2, NA4* gave a false indication of damage, as seen in figure 6b. These false reactions by NA4*, in this case, are much lower in magnitude than its reaction to the actual tooth fracture damage at the end of run #2.

Although method NB4 gave no reaction to the runs with single tooth damage, it did give the most robust reaction to the runs with multiple tooth fracture damage (runs #1 and 2). As seen in figure 5c and table 1, NB4 stays near the nominal value of 3.0 until near the end of run #1, where NB4 increases to over 400 times the nominal value. Similarly, as seen in figure 6 and table 2, NB4 stays relatively close to the nominal value until near the end of run #2, where NB4 increases to over 120 times the nominal value. In addition, NB4 does not appear to be as sensitive to load and speed changes as method NA4*.

SUMMARY AND CONCLUSIONS

A study was conducted in which three different vibration diagnostic methods were used to detect gear tooth fracture in a high contact ratio face gear mesh. The NASA spiral bevel gear fatigue test rig was used to produce unseeded faults, natural failures of four face gear specimens. Based on the results of applying the diagnostic methods FM4, NA4*, and NB4 to the vibration signals from the fatigue tests, the following conclusions can be made.

1) All of the methods investigated gave strong reactions to multiple tooth fractures. The impulsive behavior of multiple tooth fractures dominate the time synchronous vibration signal of the damaged gear.

2) Single tooth fractures are difficult to detect in a high contact ratio gear mesh. Due to the nature of high contact ratio gearing, single tooth fractures may not significantly affect the vibration signal.

3) Of all the methods, NA4* is the only one capable of detecting gear tooth fractures, surface pitting, and heavy wear. Method NA4*, however, is affected by load and speed changes to a higher degree than methods FM4 and NB4.

4) Method NB4, although not able to detect single tooth fracture, does give the most robust reaction to multiple tooth fracture damage.

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4) Stewart, R.M.: Some Useful Data Analysis Techniques for Gearbox Diagnostics. Report MHM/R/10/77, Machine Health Monitoring Group, Institute of Sound and Vibration Research, University of Southampton, July 1977.

5) Decker, H.J.; Handschuh, R.F.; Zakrajsek, J.J.: An Enhancement to the NA4 Gear Vibration Diagnostic Parameter. Proceedings of the 18th Annual Meeting of the Vibration Institute, Hershey, PA, 1994, pp. 259 - 268, (NASA Technical Memorandum 106553).

6) Heath, G.; Bossler, R.: Advanced Rotorcraft Transmission (ART) Program - Final Report. NASA CR 191057, ARL-CR-14, January, 1993.

TABLE 1.— LAST 30 MINUTES OF FACE GEAR RUN #1

Run Time (Hour)	FM4	NA4*	NB4
17.30	3.6	64.	3.1
17.35	3.7	61.	2.5
17.40	3.8	66.	4.0
17.45	3.9	115.	18.
17.50	4.2	130.	58.
17.55	4.6	153.	78.
17.60	4.7	162.	78.
17.65	4.7	147.	42.
17.70	4.8	133.	37.
17.75	5.1	223.	81.
17.80	7.0	549.	1213.

TABLE 2.— LAST 24 MINUTES OF FACE GEAR RUN #2

Run Time (Hour)	FM4	NA4*	NB4
46.35	2.6	15.	4.4
46.40	2.7	20.	7.0
46.45	3.6	36.	24.
46.50	4.0	48.	44.
46.55	4.7	67.	79.
46.60	5.5	98.	222.
46.65	5.8	113.	277.
46.70	6.7	142.	369.
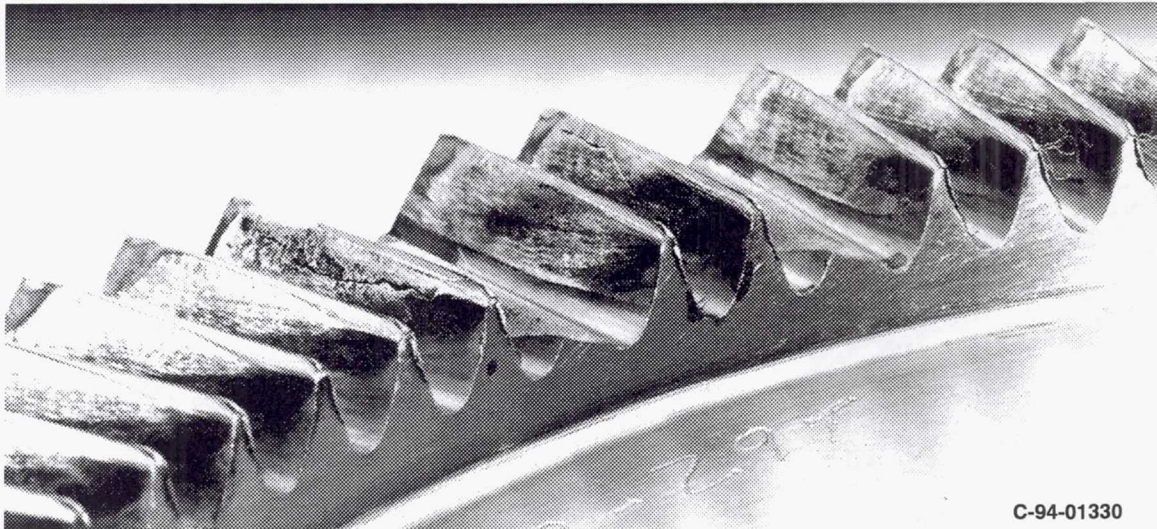
C-94-01330

Figure 1.—Gear tooth damage at end of face gear run #1.
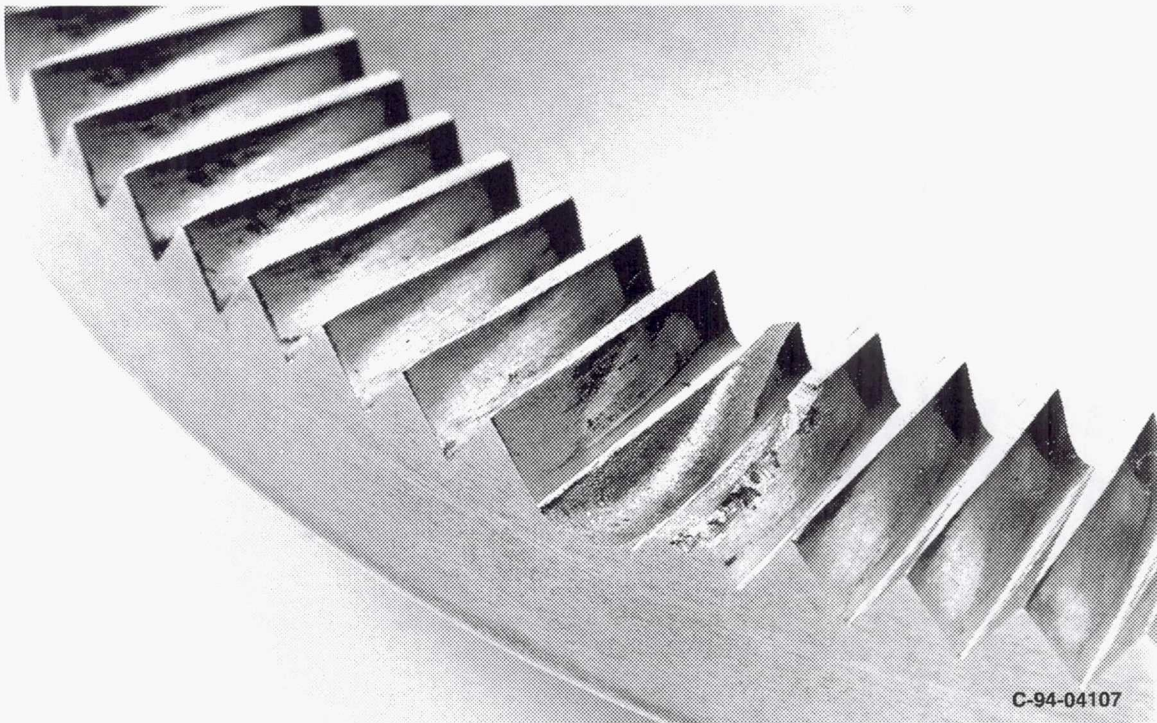
C-94-04107

Figure 2.—Gear tooth damage at end of face gear run #2.

C-94-01329
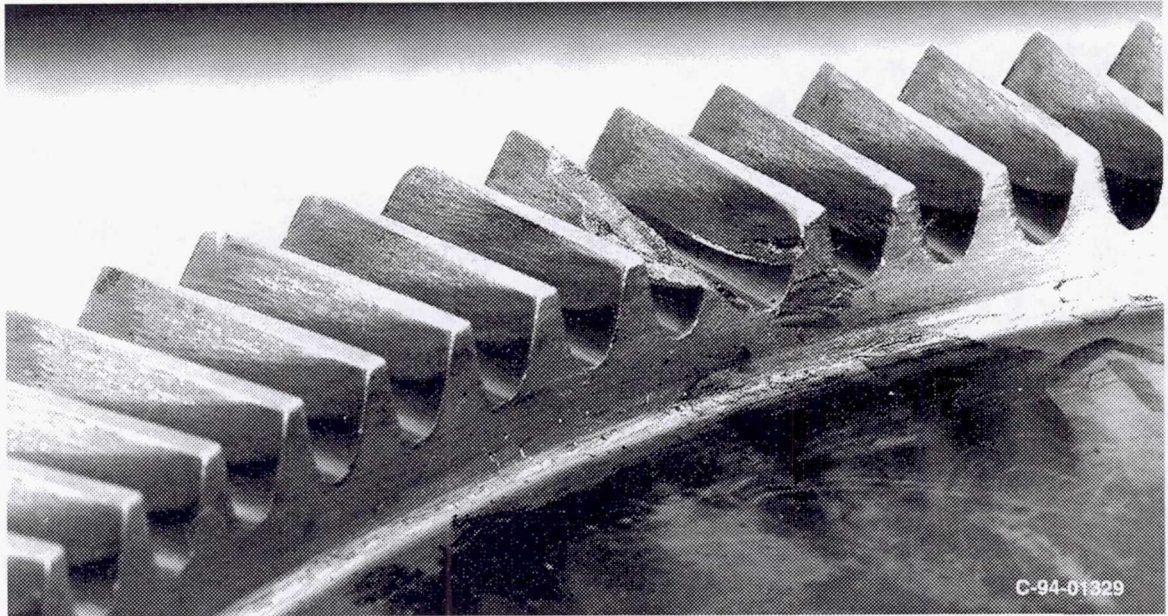
Figure 3.—Gear tooth damage at end of face gear run #3.

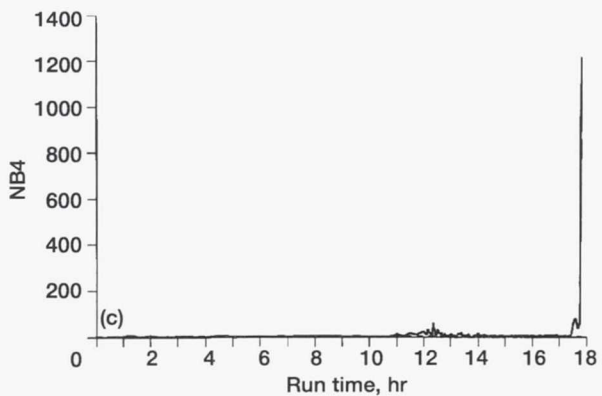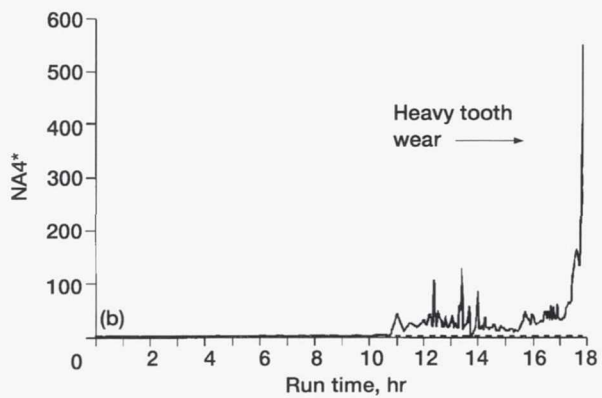

C-94-04111
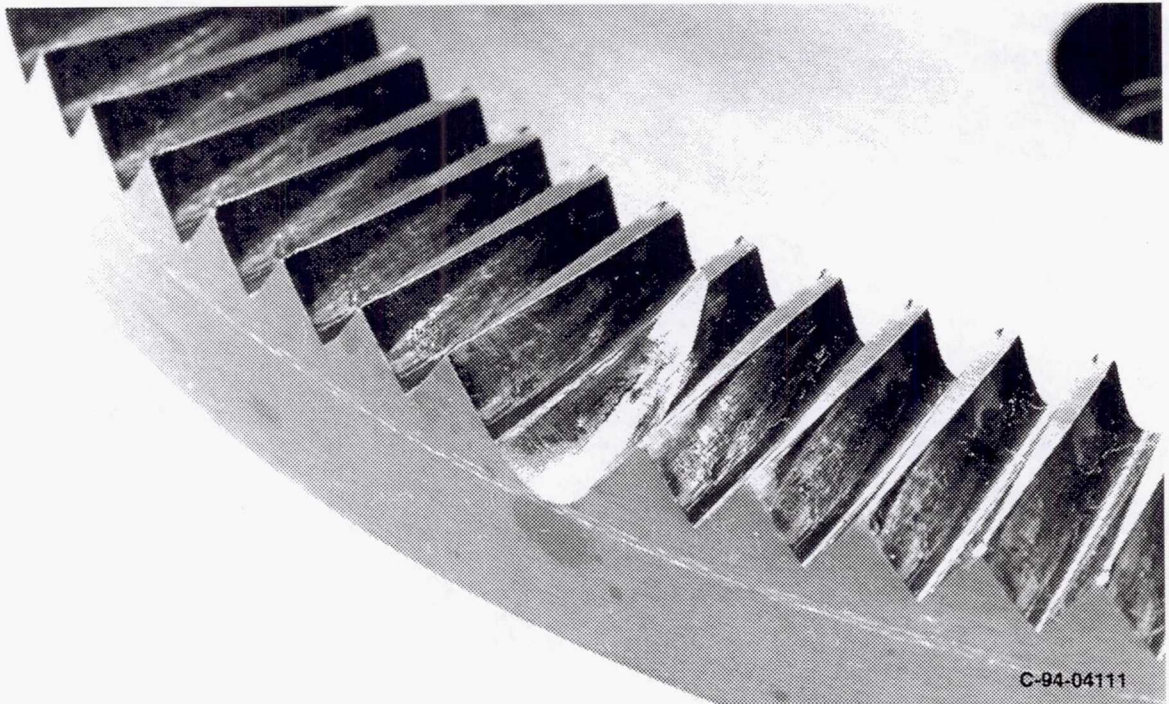
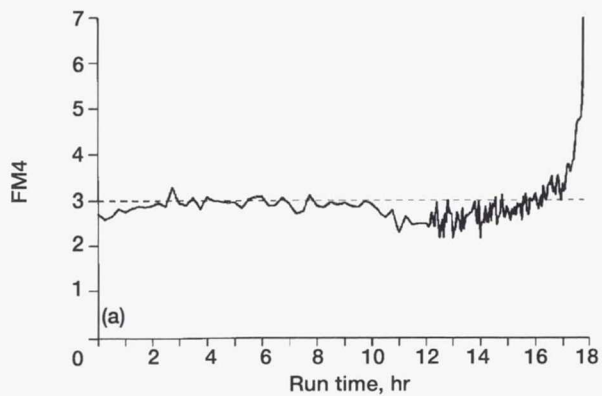Figure 4.—Gear tooth damage at end of face gear run #4.

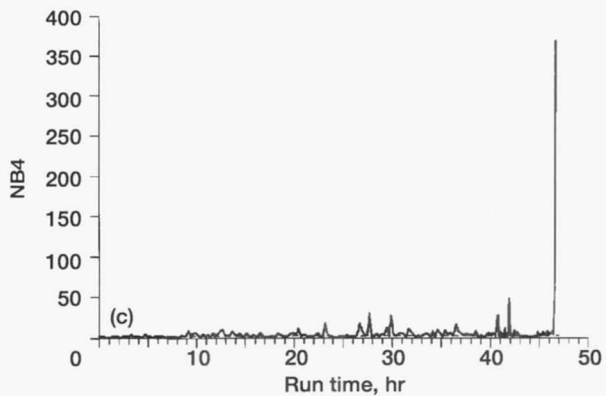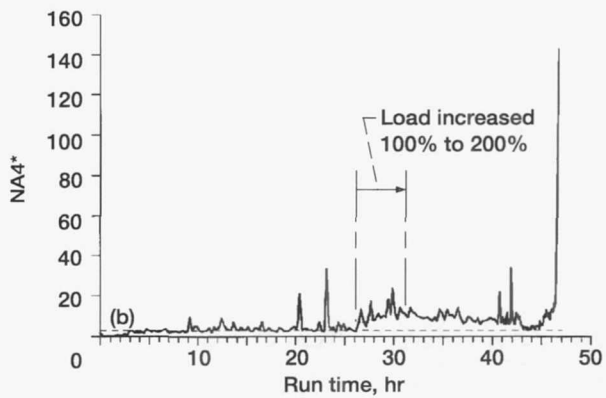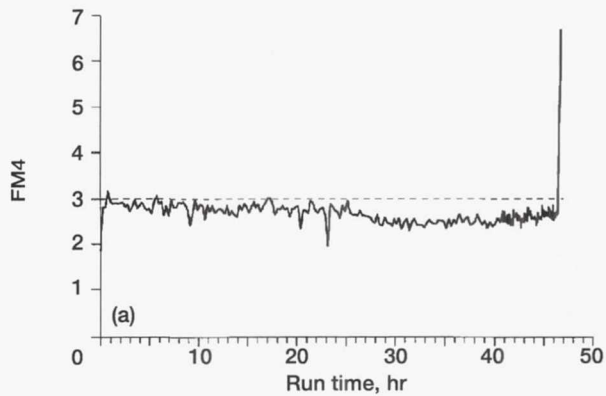Figure 5.—Face gear run #1 results. (a) FM4. (b) NA4*. (c) NB4.

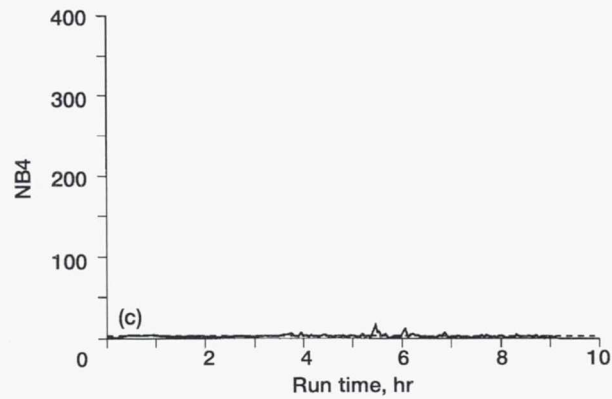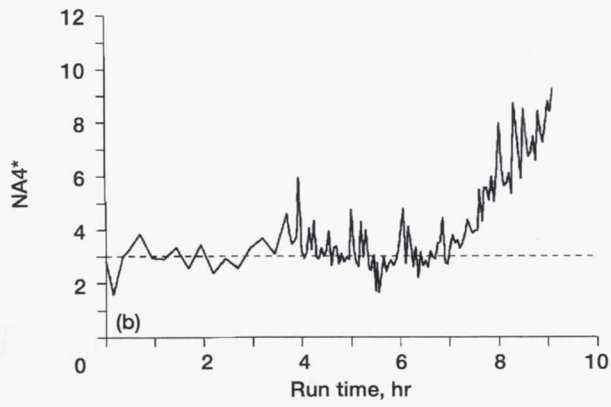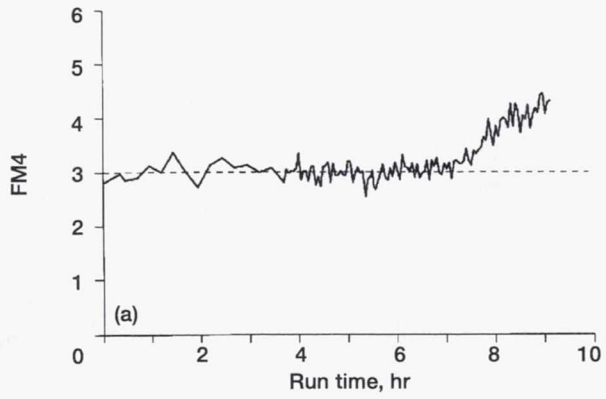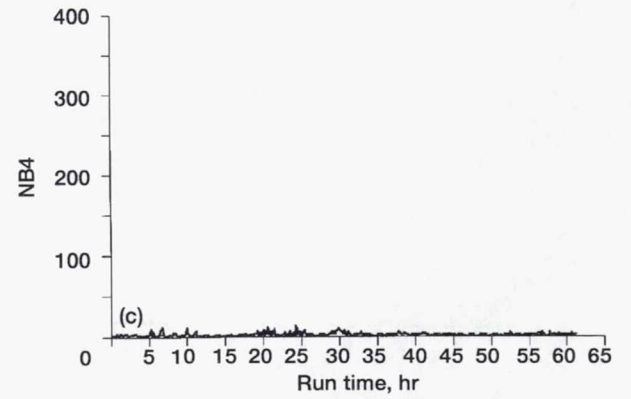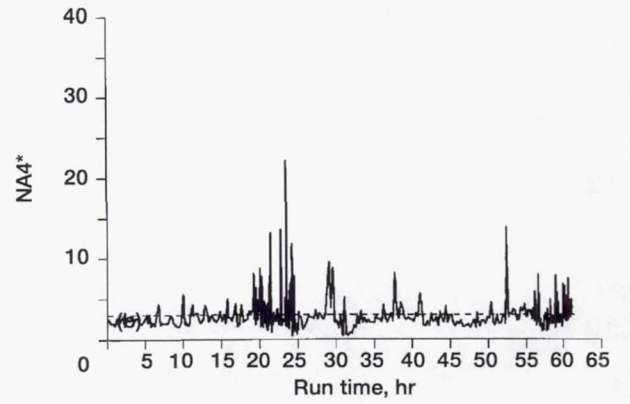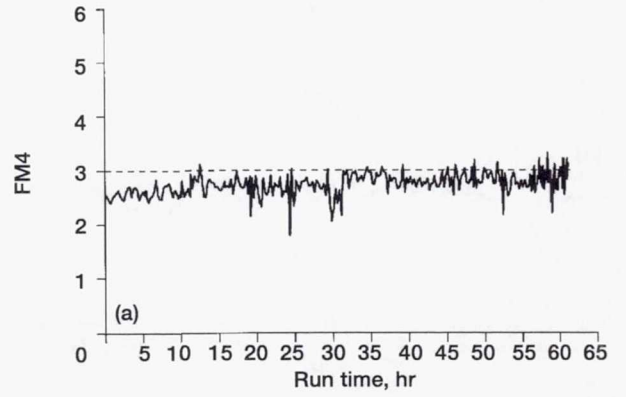Figure 6.—Face gear run #2 results. (a) FM4. (b) NA4*. (c) NB4.

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Figure 7.—Face gear run #3 results. (a) FM4. (b) NA4*. (c) NB4.
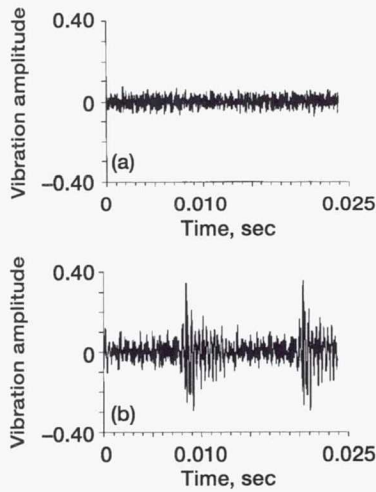
Figure 8.—Face gear run #4 results. (a) FM4. (b) NA4*. (c) NB4.

Figure 9.—Time averaged vibration
signal for face gear run #1.
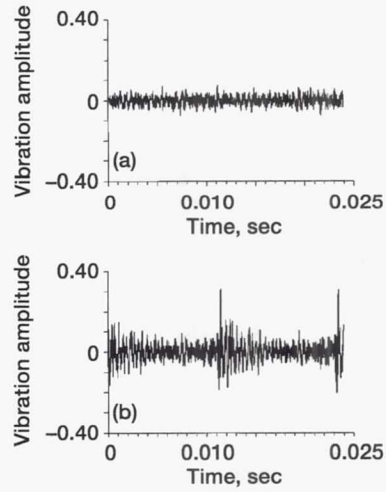(a) At start. (b) At end of test.

Figure 10.—Time averaged vibration
signal for face gear run #2.
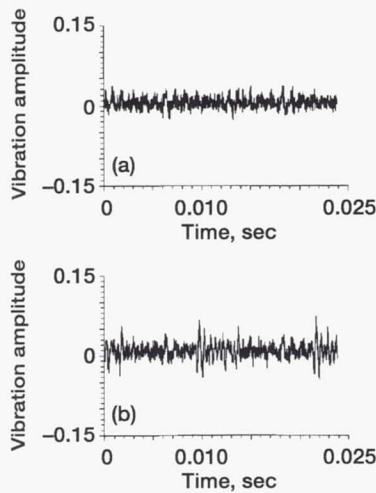(a) At start. (b) At end of test.

Figure 11.—Time averaged vibration
signal for face gear run #3.
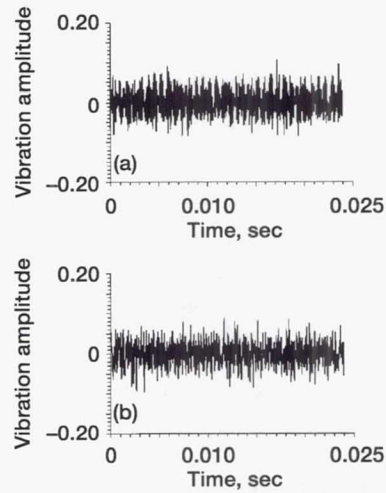(a) At start. (b) At end of test.

Figure 12.—Time averaged vibration
signal for face gear run #4.
(a) At start. (b) At end of test.

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