A preliminary study into the use of phase demodulation techniques for the analysis of gear vibration data / Étude préliminaire sur l'utilisation de techniques de démodulation de phase pour l'analyse des données vibratoires des engrenages

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A Preliminary Study in the Use of Phase Demodulation Techniques for the Analysis of Gear Vibration Data

J. Nicks, G. Krishnappa

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A PRELIMINARY STUDY INTO THE USE OF PHASE DEMODULATION TECHNIQUES FOR THE ANALYSIS OF GEAR VIBRATION DATA

ÉTUDE PRÉLIMINAIRE SUR L'UTILISATION DE TECHNIQUES DE DÉMODULATION DE PHASE POUR L'ANALYSE DES DONNÉES VIBRATOIRES DES ENGRENAGES

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Division of Mechanical Engineering
Technical Report

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ABSTRACT

This report presents a preliminary study of a vibration analysis method for the early detection of gear tooth damage. Using a phase demodulation technique, the condition of a gear based on the characteristics of the phase component of the vibration signal is evaluated. Vibration data from both a high-speed test rig and from a commercial aero-engine gearbox were examined. Preliminary findings indicate that this technique has the potential to be an effective diagnostic tool.

RÉSUMÉ

Le présent rapport traite de l'étude préliminaire d'une méthode d'analyse des vibrations visant à détecter rapidement les dommages aux dents d'engrenage. Cette méthode utilise une technique de démodulation de phase pour évaluer l'état de l'engrenage en se basant sur les caractéristiques des phases du signal vibratoire. Des données vibratoires provenant d'un banc d'essai à haut vitesse. et d'un carter d'engrenages de moteur d'avion commercial ont été étudiées. Les premiers résultats indiquent que cette technique pourrait s'avérer un outil de diagnostic efficace.

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A PRELIMINARY STUDY INTO THE USE OF PHASE DEMODULATION TECHNIQUES FOR THE ANALYSIS OF GEAR VIBRATION DATA

1.0 INTRODUCTION

The Engine Laboratory of the National Research Council Canada is currently involved in the field of condition monitoring of gas turbine engines. The assessment of component health by vibration analysis is an integral part of this monitoring.

One of the more recently developed gear health monitoring methods has involved analysis of the phase component of the vibration signal on the basis that defects can be detected earlier. This report presents the first study of this diagnostic method undertaken at the Engine Laboratory. It is intended that this preliminary work provide a firm basis for using this monitoring technique in the future.

2.0 ANALYTICAL METHOD

Most of the basic applications theory behind current phase demodulation analysis methodology has been previously published by McFadden and Smith[1] and by McFadden.[2,3] It is presented here to familiarize the reader with the background theory.

Under ideal conditions, the time-domain average of the vibration of a pair of gears should consist only of the fundamental and harmonics of the tooth mesh frequency. This is shown in the following equation:

$$x(t) = \sum_{m=0}^{M} X_m \cos(2\pi mTft + \theta_m) \tag{1}$$

where:

- f is the rotational frequency of the gear,
- T is the number of teeth on the gear,
- m is the mesh frequency harmonic (0,1,2,3...), and
- X_m is the vibration amplitude at the corresponding mesh frequency harmonic.

A discrete gear fault (such as a spall or fatigue crack) modifies this equation by introducing periodic amplitude or phase modulations into the vibration signal. The amplitude and phase-modulated vibration signal, y(t), can be written as:

$$y(t) = \sum_{m=0}^{M} X_m(1 + a_m(t)) \cos(2\pi mTft + \theta_m + b_m(t)) \tag{2}$$

where $a_m(t)$ is the amplitude modulation function and $b_m(t)$ is the phase modulation function at time t for each mesh harmonic. Amplitude and phase modulations produce sidebands about the mesh harmonics in the frequency domain.[4] In practice, numerous additional factors contribute to the content of the measured vibration signal. While the use of time-domain averaging eliminates non-synchronous vibration components from the measured signal, other parameters, such as transmission path effects, cannot be simply removed and may contribute to the masking of faults.

The vibration function $y_m(t)$ for any mesh frequency harmonic m can be approximated by bandpass filtering the time-domain averaged vibration signal. It is not possible to isolate this function completely, as there is a possibility of interference between higher-order sidebands of adjacent mesh harmonics. In addition, there may be other vibration components unrelated to the desired mesh harmonic within the passband. Assuming these factors are minimal, $y_m(t)$ can be accepted as a valid representation of the meshing vibration of a gearset. The filter bandwidth used in these preliminary studies was equal to the fundamental mesh frequency of each gear under study and centred on a mesh harmonic. Bandpass filtering of the time-domain averaged signatures was accomplished by performing a forward FFT and zeroing the frequency coefficients outside of the passband, then performing an inverse FFT. This method can be used effectively with synchronous signals, such as the time-domain average.

Although the measured function $y_m(t)$ is real-valued, it can be considered a projection of the complex-valued analytical function $z_m(t)$.[5] The function $z_m(t)$ can be represented by:

$$z_m(t) = y_m(t) + j\mathbf{H}(y_m(t)) \tag{3}$$

where $\mathbf{H}$ is the Hilbert transform function. The amplitude and phase components of the analytical signal can be seen more clearly if equation 3 is expressed in terms of the amplitude envelope function, $A_m(t)$, and the instantaneous phase function, $\phi_m(t)$[6]:

$$z_m(t) = A_m(t) \cdot e^{j\phi_m(t)} \tag{4}$$

The complex analytical signal (4) is derived by performing a forward Fourier transform on the real-valued time series $y_m(t)$ to produce $Y_m(f)$. The function $Y_m(f)$ is then filtered to obtain $Z_m(f)$ by multiplying the frequency coefficients by:

2 for $f > 0$,
1 for $f = 0$, and
0 for $f < 0$.

The inverse Fourier transform of $Z_m(f)$ produces the complex analytical time series $z_m(t)$. The amplitude envelope function, $A_m(t)$, and the instantaneous phase function, $\phi_m(t)$, are calculated from:

$$A_m(t) = |z_m(t)|, \tag{5}$$

$$\phi_m(t) = \arg(z_m(t)). \tag{6}$$

To extract the phase modulation function, the complex function $z_m(t)$ is multiplied by a unit length vector rotating at minus the mesh harmonic frequency *m*. This removes the frequency component of the harmonic itself. The resulting function represents the relative changes in the phase component produced by the sidebands of the meshing tone. The instantaneous phase modulation function, $\delta_m(t)$, is defined by:

$$\delta_m(t) = \arg(z_m(t) \cdot e^{-j\Theta}) \tag{7}$$

where $\Theta = 2\pi mTft + \theta_m$. The kurtosis or fourth statistical moment of the function $\delta_m(t)$ has often been a primary indicator used to quantify gear damage from the phase information. The unbiased kurtosis of a sampled data function is defined by:

$$Kurtosis = \frac{1}{(N-1)\sigma^4} \sum_{n=1}^{N} (x_n - \overline{x})^4 . \tag{8}$$

The kurtosis is sensitive to the impulsiveness of the data. The kurtosis of random or Gaussian noise is equal to 3.0, rising rapidly when impulsive events are present.

The three main sources of modulations in the phase trace are:

- phase modulations in the vibration signal;
- amplitude modulations in the vibration signal (any time that the amplitude envelope falls near zero, the phase can shift by any multiple of 90°); and
- toggling of the phase signal at the ±180° boundary of the phase function.

The general phase modulation function, $\delta(t)$, is constrained within the limits -180° to +180° ($-\pi$ to $+\pi$) by the arctan function, which is used in the calculations. When the phase function crosses either the +180° or -180° boundary, the result is an immediate phase shift of 360°. To eliminate this toggling of the phase trace at the ±180° limits, a phase unwrapping algorithm was implemented. This algorithm unwrapped the phase in steps of 360° every time an absolute point-to-point variation exceeding 275° was encountered. The unwrap point was selected by trial and error. The kurtosis of both the wrapped and unwrapped phase functions was calculated. In addition, the percent modulation of the phase modulation functions was quantified. The percent phase modulation was calculated using:

$$PM\ (\%\ modulation) = \frac{\max(\delta(t)) - \min(\delta(t))}{360^\circ} \cdot 100\% . \tag{9}$$

The time-domain vibration average and amplitude envelope, A(t), of a gear in good running condition is shown in Figure 1. The instantaneous phase modulation function, $\delta(t)$, of the same gear is shown in Figure 2. The average and amplitude envelope of an identical gear, with light surface damage and run at the same speed and load, is shown in Figure 3. The wrapped and unwrapped phase traces for this gear are shown in Figures 4 and 5, respectively.

3.0 DESCRIPTION OF TESTS

All gear vibration data used in this report had been acquired previously for analysis as part of other NRC test programs. The time-domain averaging of the gear vibration signals had been performed using a Stewart Hughes MSDA analyzer. The gear signatures were then transferred to a DEC MicroVAX for the phase demodulation analysis. Vibration data were originally obtained from two sources:

- a gear fatigue test rig at Pratt and Whitney Canada in Mississauaga [Fig. 6]; and
- a reduction gearbox for an Allison T56-A-14LFE gas turbine engine installed in test cell #2 of the Engine Laboratory [Fig. 7].

The PWC test rig has two parallel shafts coupled at the drive end by a pair of 40 tooth spur gears (the slave gears). The other end of the shafts are coupled by the test gears: either 20 tooth pitting gears or 80 tooth bending gears. The bending gears have a very narrow tooth profile with a large amount of backlash to permit tooth flex and induce bending fatigue. The pitting gears have a normal tooth profile. The test gears are loaded by twisting one of the two shafts with respect to the other (static torque preload). Since all of the gears used on the test rig have common multiples of tooth numbers, there is some interference between the mesh tones of slave gear and test gears.

The T56-A-14LFE reduction gearbox is a two-stage gearbox with a net reduction ratio of approximately 15.1:1. The first stage uses fixed axis gears and consists of a 32 tooth pinion gear driving a 100 tooth main drive gear. The second stage is an epicyclic with a fixed annulus. The 30 tooth sun gear, which is on the same shaft as the main drive gear, drives 5 planet gears (35 teeth). The output shaft is attached to the planet carrier. The annulus has 100 teeth.

The vibration data used in this report were obtained from:

- seeded fault trials on the PWC gear rig;
- normal endurance runs on the PWC gear rig; and
- normal test runs on the T56 engine.

Vibration data from two series of seeded faults were available: natural tooth faults on the pitting gears, and implanted and natural tooth faults on bending gears. The endurance runs on the PWC gear rig for which data were available had all been made using the bending gears.

4.0 RESULTS

4.1 Seeded Fault Trial Data

4.1.1 Pitting gear test series

Four trial runs had been made with the 20 tooth pitting gears on the PWC gear rig. All test runs were made with a nominal torque load of 1500 in-lb, at shaft speeds of 2500 and 3500 rpm. All gear faults had occurred during normal endurance runs on the test gears and represented a typical cross-section of the types of faults encountered with these gears. The four runs consisted of:

- baseline with unused gear faces;
- light damage with very light scoring, some pitting in dedendum, and a few small spalls;
- intermediate damage with light scoring, pitting in dedendum, a few small spalls, and one large spall; and
- severe scoring.

Previous analysis of this data had identified faults in the intermediate damage and scoring test conditions only. It had not been possible to identify the light damage gears as faulty.

Phase demodulation was performed about the first three mesh harmonics (bands 1, 2, and 3). These harmonics were clearly defined in the spectra of the 2500 rpm baseline data [Fig. 8]. When the rig was run at 2500 rpm, the fundamental mesh frequency fell near with a system structural resonance centred at about 800 Hz, resulting in strong excitations of the lower-order mesh harmonics. At 3500 rpm this influence was removed, and the second and third mesh harmonics were much less clearly defined [Fig. 9]. The slave gear mesh harmonics were not identifiable, as they coincided with even-numbered harmonics of the test gear.

Analysis results are given in Tables 1 through 4. For each test condition, five gear averages were analyzed. The phase modulation (PM) values presented are from the unwrapped phase functions. The kurtosis values presented were also derived from the unwrapped phase, with the values from the original (wrapped) phase functions given in brackets where they differed. These results are also presented graphically in Figures 10 through 13. The maximum kurtosis value given in Figures 10 and 12 is the maximum of the average wrapped and unwrapped kurtosis values for each analysis point. All of the baseline averages, with the exception of band 3 data at 3500 rpm, produced stable and repeatable kurtosis and PM results.

At 2500 rpm, only the intermediate damage and scoring test conditions returned fault indications. The effects of the rig's structural resonance appeared to reduce the ability to detect faults using phase demodulation. Band 1 data showed no significant changes from the baseline. Band 2 and 3 results were mixed, but did indicate problem conditions.

At 3500 rpm, all fault conditions were identified. Band 3 results were quite variable, however the extremely high PM for intermediate damage and scoring indicated problems. Band 1 results showed large changes in both kurtosis and PM for all fault conditions. Band 2 results showed large changes in the PM results for all fault conditions and in the kurtosis results for scoring only.

The kurtosis of the unwrapped phase data showed a tendency to fall more often than rise when the unwrapped PM exceeded 100%. Some of the changes in the kurtosis values were significant. However, in these cases the increase in the PM values over the baseline were significant and were a reliable fault indicator on their own.

4.1.2 Bending gear test series

Seven trial runs had been made using the 80 tooth bending gears. The nominal torque load was 1000 in-lb, and the rig was run at shaft speeds of 3000, 4000, and 5000 rpm. The gear faults were a mix of implanted faults and natural faults that had occurred during normal endurance runs. The seven test runs were:

- baseline with unused gear faces;
- single tooth spalled (implanted);
- partial tooth removed (implanted);
- full tooth removed (implanted);
- single tooth loss (natural);
- multiple tooth loss (natural); and
- severe scoring (natural).

When these test run data had been analyzed previously, only the more developed of the gear faults had been detected. This had been accomplished primarily through changes in the overall vibration levels and by the effects of the test rig's structural resonances.

Phase demodulation was performed about the first two mesh harmonics (bands 1 and 2). Baseline spectra are shown in Figures 14 through 16. The mesh frequency fundamental is well defined in all of the baseline spectra, but the second harmonic is distinct only in the 3000 rpm data. With the bending gears installed, the mesh harmonics of the slave gears became quite visible (at multiples of 40 times the shaft speed). When the rig was running at 4000 rpm, the mesh harmonic of the slave gears (40 teeth) closely coincided with a 2800 Hz structural resonance.

Analysis results are given in Tables 5 through 11 and are shown graphically in Figures 17 through 22. For each test condition, five gear averages were analyzed. Unlike the results for the pitting gears, the bending gears analysis results were quite poor.

In the baseline data, only the 4000 rpm, band 1 data showed any degree of repeatability. Results at other speeds and in other frequency bands showed large variations among the five gear averages. Analysis results for the faulted gears were highly variable as well. It was not possible to identify the gear faults under most of the test conditions used. The inability of phase demodulation analysis to detect faults in these tests may have been due to the following factors:

- the teeth on the bending gears are designed to induce bending fatigue. This was done by reducing the tooth profile to such an extent that the backlash is about the same as the width of the tooth. This large amount of backlash permits the teeth to flex a great deal during running. The effects on the phase modulation due to the gear tooth flex may have been greater than the effects of the faults - causing the flaws to be masked; and

- although the bending gears were run up to their normal test speed of 5000 rpm, the torque preload may have been too low. Poor meshing action can result from insufficient speed or load on a pair of gears.

4.2 Normal Endurance Run Data

A large amount of gear vibration data were available from normal endurance runs using the bending gears on the PWC gear fatigue rig. Vibration data had originally been recorded throughout the running life of the test gears, with the exception of one short post-failure run. All gears were originally run at 5000 rpm and at loads of between 1500 and 2000 in-lb. A timed recording schedule was used to allow the monitoring of the progression of fault development, if possible. This data had been previously analyzed and assessed, and from the available pool of gear vibration data some typical test results were selected. One gear average was analyzed for each test point in these runs, except for gears 098/099, where three averages were used. The following data from five of the endurance runs were analyzed:

- gears 114/115: 2000 in-lb load, failure by tooth breakage, gear faults previously detected;
- gears 116/117: 1500 in-lb load, failure by scoring, gear faults previously detected;
- gears 110/111: 1800 in-lb load, failure by tooth breakage, faults not detected;
- gears 104/105: 2000 in-lb load, failure by tooth breakage, faults not detected; and
- gears 098/099: 1650 in-lb load, failure by multiple tooth breakage, data used for analysis was recorded after gears failed, gear faults previously detected.

As with the bending gear seeded fault data (Section 4.1.2), phase modulation analysis was performed on the first two mesh harmonics. A typical baseline signature for the endurance runs is shown in Figure 23. The mesh frequency fundamental can be clearly identified in the endurance run data. The second mesh harmonic was not very distinct overall. Analysis results are presented in Tables 13 through 17.

Phase modulation analysis of data from these gear tests did not produce good results. Analysis on all gear tests, except those for gears 098/099, were essentially the same. Band 2 results were highly variable and unreliable. Band 1 results were quite repeatable within a test and showed no faults.

An interesting phenomena occurred in the data for gears 104/105 [Table 17]. These results showed a significant change in the band 1 results beginning at 11% of gear life. The kurtosis and PM results increased at this time. By 50% gear life, the values had fallen back to a range similar to those at the beginning of the test. This variation may have been part of the gears' running in process.

Data for gears 098/099 were obtained after a tooth had failed. At the first test point, at 99+% gear life, one tooth was known to have been lost; at the second point, 100% life, as many as three teeth may have been lost. Band 2 PM results for these gears ranged slightly higher than for the other endurance tests. The major difference was in the results for band 1. Band 1 produced high PM values for both test points and high kurtosis values for the first test point. It was possible to identify a well-developed fault with these test gears. This was, however, a fairly extreme fault condition. Phase demodulation is intended to detect faults early. It appeared that the load and speed were high enough to produce stable results for at least band 1 data. The failure to detect developing faults may have been due to the masking effects of excessive tooth flex, as discussed in Section 4.1.2.

4.3 T56 Reduction Gearbox Data

Unlike the gear data available from the PWC test rig, the data from the T56 reduction gearbox represented a gear system in good working order only. All of the T56 vibration data can be considered baseline. This data had previously been analyzed as part of a component visibility investigation of the T56 gas turbine engine and reduction gearbox system. The data from the T56 gearbox were used in phase modulation analysis to see if this technique had potential for use in condition monitoring of this gearbox. No faults had been identified during previous analyses of this gearbox.

The T56 data provided vibration information recorded at six power settings from high-speed ground idle (2000 ft-lb load) to full military power (23400 ft-lb). Normal operating load for this engine/gearbox system (in actual use) is in the 18000 ft-lb range. Vibration signals from three accelerometers were used for this analysis. The planet gears, sun gear, and main drive gear were assessed at all three transducer locations; the pinion input gear at location 3 only. The annulus signatures were not used for phase modulation analysis. The reason for this is discussed in Section 5. Examples of the vibration signatures of each of the gears are given in Figures 24 through 27. The first three mesh harmonics of each gear were used for analysis. Only one signature was available for analysis at each test point.

The results of this analysis indicate it may be possible to apply phase modulation analysis to the T56 gearbox. The PM values from the runs at 15000 and 18000 ft-lb loads were typically the lowest of the six test conditions. The other test conditions did not return consistently low PM values. On most of the gears, the 23400 ft-lb load condition returned acceptable PM values. Results from the three lower load conditions varied a great deal among the different gears and analysis bands. The analysis could have been extended to include higher harmonics of the planet and main drive gears. The sun gear band 3 analyses were poor.

5.0 DISCUSSION

The kurtosis values derived from the phase modulation functions tend to rise and then fall as gear damage becomes progressively worse. The fall in the kurtosis is primarily due to saturation of the phase modulation signature by the numerous and large-scale shifts in phase, which occur as the gear condition deteriorates. The kurtosis appears to be most reliable in the very early stages of fault development, since the values drop as the gear condition worsens.

Sudden phase shifts in the order of 90°, 180°, 270°, and 360° can occur whenever the amplitude of the signal envelope falls near zero. These discontinuities in the phase signal are one of the factors in changes in the kurtosis. Too many phase shifts and the kurtosis values fall. Gear averages that produce highly modulated amplitude envelopes are probably unsuitable for phase analysis. An example of this would be the average of an annulus gear from an epicyclic system.

The phase modulation parameter, PM, appeared to be a reliable fault indicator. This parameter tended to rise and remain high as the condition of a gear deteriorates. PM performed well with baseline modulation levels of up to 50%. When the PM value for a good gear was in the order of 100% or more, the sensitivity of this parameter was reduced and would only react to well-developed faults. The kurtosis (either wrapped or unwrapped) values obtained when PM was initially high were highly variable and unreliable.

The relationships observed between the parameters tested (wrapped and unwrapped PM and kurtosis) follow:

- for values of PM below 100%, there should be no effective difference between analysis results from wrapped and unwrapped data. However, a PM value occasionally falls when unwrapped. When the fall is significant, it indicates that a phase toggle condition was most likely the dominant factor. A phase toggle condition occurs most when the phase trace crosses a ±180° boundary and toggles back and forth between -180° and +180°. This will make the PM values calculated from the wrapped phase traces approach 100%, while the unwrapped PM can fall as low as 50%. Kurtosis values obtained from the wrapped data are unreliable when a phase toggle condition is present;

- for values of PM greater than 100% and less than approximately 200%, the unwrapped kurtosis values are typically lower than the wrapped values. This difference can be significant. However, PM values that are this high can also indicate a defect; and

- for values of PM greater than 200% (approximately), the unwrapped kurtosis values are again typically lower than wrapped values. Both wrapped and unwrapped kurtosis values tend to be low (less than 3) when PM values are this high.

A combination of kurtosis and unwrapped modulation (PM) appear to give reliable fault detection rates. The maximum kurtosis value (of wrapped and unwrapped phase traces) should be used, except when PM falls significantly with unwrapping. In these cases, the wrapped kurtosis is unlikely to reflect accurately the gear condition, and the unwrapped kurtosis should be used.

To successfully monitor gear condition using phase modulation analysis methods, the time-domain averaged vibration signal must be sufficiently stable to produce reliable results. An attempt has been made to establish applications criteria for using phase modulation analysis. This analysis method should first be tested on gears in known good condition to establish if phase analysis would be feasible:

- mean PM values should be quite low (several sample gear averages are needed), although good results have been obtained with means as high as 50%. The standard deviation of the average PM results should be below 5;

- the mean kurtosis values should be below 3 to 4 for a gear in good condition; standard deviation should be below 1; and

- the amplitude envelope should not fall close to zero at any point as this will cause sudden shifts in the phase signature. This will raise PM values and can skew the kurtosis results.

- the spectrum of the signal average can provide a rough indication as well. The mesh harmonic should be the dominant frequency component within the filter passband, typically 20 dB or so higher than the average background vibration level. The presence of sidebands about the mesh tone may not have any effect on the analysis results and can often be ignored, even when they are of a level comparable to their mesh harmonic. Other strong tones within the analysis passband will adversely affect the results.

Any mesh harmonic within the vibration spectra can be a candidate for phase demodulation. As with other analysis techniques, operating conditions (such as speed and load) can significantly alter phase modulation results.

The filter settings used in these tests were (arbitrarily) selected so that the filter cutoff points were midway between adjacent mesh harmonics. All frequency components within the band were passed. This worked well in these tests. If other mesh harmonics or strongly defined tones were present in the bandwidth, the filters would have to be adjusted to remove these tones. In the analyses on the PWC gear rig data, it was not possible to isolate the mesh harmonics from slave and test gears as they shared common frequency multiples. This interference did not appear to influence results for the pitting gears but may have hampered fault detection with the bending gears.

6.0 CONCLUSIONS

Phase modulation analysis can provide very early and reliable detection of faults in gears. It is important that the analysis procedure be performed on a gear when it is in good condition to establish an acceptable baseline. Any mesh harmonic may be demodulated about, providing that stable baseline analysis results can be obtained. This analysis method appears to be more suited for trend monitoring, to obtain the earliest possible fault warning, rather than single-shot assessment. The analysis parameter most widely used with phase demodulation has been kurtosis. This parameter was not always reliable. Combining the percent modulation of the unwrapped phase function (PM) with the maximum kurtosis of the wrapped and unwrapped phase functions resulted in more reliable diagnosis of faults.

Very good results were obtained with the pitting gears on the PWC gear fatigue rig. The phase demodulation technique successfully detected faults on all defective gears. This had not been accomplished during previous analysis work on these gears using other analysis methods. The best results were obtained with demodulation about the first two mesh harmonics.

Very poor results were obtained with the bending gears on PWC rig and are a strong argument for the establishment of reliable baseline analysis results. The possible causes for this include:

- the bending gear's thin tooth profile (with large backlash) cause excessive tooth flex. This was a design feature intended to promote bending fatigue. The high degree of flex may mask fault visibility until damage is great enough to be seen, above the background noise caused by tooth flex; and

- the mesh harmonics typically had a lower overall level than for those encountered with the pitting gears. This was especially apparent when demodulating about the second mesh harmonic. Data from the seeded fault trials were the most severely affected; data from the normal endurance runs did not show this problem as much. This appears to be related to running speed and load.

Initial trials on the T56 reduction gearbox data appear promising. The best results were obtained at the higher test load conditions. Test results at the lower power settings do not appear as reliable. Further work will be necessary for this gearbox.

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Table 1. Seeded fault data - pitting gear, baseline run.

RPM	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2500						
Mean	10	2.5	20	2.1	21	2.6
Std	0.6	0.2	1.9	0.1	1.5	0.2
3500						
Mean	11	2.3	56	1.6	136	3.7 (4.9)
Std	0.5	0.1	0.9	0.0	11	2.6 (0.6)

Table 2. Seeded fault data - pitting gear, light damage.

RPM	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2500						
Mean	13	2.3	17	2.6	22	1.7
Std	0.4	0.1	0.8	0.3	0.4	0.1
3500						
Mean	80	5.6 (5.5)	144	2.2 (2.6)	105	2.7 (4.6)
Std	36	2.9 (1.0)	56	0.4 (0.6)	45	0.4 (1.5)

Table 3. Seeded fault data - pitting gear, intermediate damage.

RPM	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2500						
Mean	13	2.7	27	2.9	35	6.0
Std	0.5	0.1	1.1	0.2	1.6	0.5
3500						
Mean	48	4.6	546	1.8 (1.8)	657	1.9 (1.8)
Std	0.9	0.1	29	0.3 (0.3)	39	0.2 (0.0)

Numbers in brackets are kurtosis values before phase unwrapping.

Table 4. Seeded fault data - pitting gear, severe scoring.

RPM	Band 1		Band 2		Band 3	
	PM	Kurtosis	PM	Kurtosis	PM	Kurtosis
2500						
Mean	16	2.2	136	3.3 (4.0)	25	2.3
Std	3.0	0.4	31	1.5 (0.2)	1.5	0.2
3500						
Mean	144	4.3 (3.7)	151	3.0 (3.9)	526	1.9 (2.5)
Std	20	3.1 (1.0)	11	1.8 (0.4)	24	0.1 (0.1)

Table 5. Seeded fault data - bending gear, baseline.

RPM	Band 1		Band 2	
	PM	Kurtosis	PM	Kurtosis
3000				
Mean	129	3.0 (3.6)	97	3.0 (3.7)
Std	67	0.8 (1.4)	121	1.9 (3.8)
4000				
Mean	20	3.5	344	2.3 (2.0)
Std	2.3	0.4	119	1.2 (0.2)
5000				
Mean	114	3.9 (7.5)	240	2.7 (3.6)
Std	12	3.4 (1.5)	51	1.6 (0.9)

Numbers in brackets are kurtosis values before phase unwrapping.

Table 6. Seeded fault data - bending gear, single spall (implanted).

RPM	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis
3000				
Mean	142	6.3 (6.0)	37	4.0
Std	75	6.3 (3.5)	33	1.9 (2.7)
4000				
Mean	12	1.8	511	2.4 (2.9)
Std	1.9	0.6	225	1.0 (0.6)
5000				
Mean	86	3.9 (7.3)	233	2.8 (3.7)
Std	33	1.5 (2.5)	121	0.6 (0.6)

Table 7. Seeded fault data - bending gear, tooth chip (implanted).

RPM	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis
3000				
Mean	118	8.0 (5.3)	47	4.3 (5.8)
Std	64	5.9 (2.6)	38	1.3 (3.2)
4000				
Mean	15	3.1	259	1.9 (2.7)
Std	1.5	0.3	97	0.3 (0.6)
5000				
Mean	114	2.1 (7.4)	277	2.8 (3.8)
Std	5.1	1.0 (0.7)	127	1.4 (1.6)

Numbers in brackets are kurtosis values before phase unwrapping.

Table 8. Seeded fault data - bending gear, tooth removed (implanted).

RPM	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis
3000				
Mean	207	3.7 (5.6)	113	3.1 (12.0)
Std	43	1.9 (1.2)	28	3.7 (2.6)
4000				
Mean	22	2.6	520	1.8 (2.1)
Std	2.1	0.2	130	0.4 (0.5)
5000				
Mean	147	2.4 (5.8)	343	1.9 (3.8)
Std	37	0.8 (0.4)	177	0.5 (0.8)

Table 9. Seeded fault data - bending gear, single tooth broken.

RPM	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis
3000				
Mean	14	2.2	272	2.4 (3.9)
Std	2.7	0.4	115	0.3 (2.7)
4000				
Mean	32	2.7	431	2.0 (2.1)
Std	1.1	0.1	78	0.4 (0.5)
5000				
Mean	33	2.9	321	2.6 (3.0)
Std	4.0	0.1	120	1.2 (0.1)

Numbers in brackets are kurtosis values before phase unwrapping.

Table 10. Seeded fault data - bending gear, multiple tooth loss.

RPM	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis
3000				
Mean	519	2.1 (2.8)	746	2.0 (2.2)
Std	84	0.6 (0.7)	206	0.6 (0.7)
4000				
Mean	154	1.7 (6.2)	297	2.6 (2.0)
Std	40	0.2 (1.5)	41	1.0 (0.4)

Table 11. Seeded fault data - bending gear, severe scoring.

RPM	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis
3000				
Mean	23	1.9	18	2.8
Std	1.5	0.2	2.7	0.4
4000				
Mean	24	3.1	381	3.9 (2.6)
Std	4.6	0.2	163	1.9 (0.4)
5000				
Mean	61	3.0 (3.9)	146	2.8 (5.2)
Std	44	1.0 (1.7)	73	0.7 (1.2)

Numbers in brackets are kurtosis values before phase unwrapping.

Table 12. Bending gear endurance run - gears 114/115.

% life	Band 1 PM	Band 1 Kurtosis	Band 2 PM	Band 2 Kurtosis
3	24	2.4	545	2.5 (2.0)
15	33	2.0	167	2.4 (3.4)
28	40	2.2	231	1.8 (3.1)
40	38	1.8	130	1.6 (2.6)
53	37	1.9	85	2.3 (3.6)
65	36	1.8	209	2.3 (1.7)
78	37	1.9	161	3.0 (2.3)
90	33	1.6	297	1.6 (1.9)
100	28	1.8	234	2.2 (2.4)

Table 13. Bending gear endurance run - gears 116/117.

% life	Band 1 PM	Band 1 Kurtosis	Band 2 PM	Band 2 Kurtosis
10	12	2.2	201	3.8 (2.9)
40	16	2.4	260	2.9 (2.6)
60	18	2.4	378	1.6 (2.7)
70	23	3.1	169	5.4 (1.5)
80	22	2.8	307	3.0 (2.4)
90	17	2.9	371	2.6 (2.5)
100	22	3.2	178	3.8 (3.0)

Table 14. Bending gear endurance run - gears 110/111.

% life	Band 1 PM	Band 1 Kurtosis	Band 2 PM	Band 2 Kurtosis
<1	23	2.5	166	1.4 (3.1)
32	26	1.9	164	5.2 (3.3)
36	18	1.9	388	1.8 (2.5)
68	19	2.0	445	1.9 (2.0)
98	17	2.5	437	1.7 (2.5)

Numbers in brackets are kurtosis values before phase unwrapping.

Table 15. Bending gear endurance run - gears 098/099.

% life	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis
99+	323	1.5 (7.2)	866	2.0 (2.4)
	231	2.3 (7.1)	554	1.6 (2.7)
	240	2.4 (5.0)	439	2.1 (2.8)
100	426	1.5 (2.7)	182	2.3 (1.9)
	600	2.4 (2.0)	504	1.9 (1.9)
	699	2.2 (2.5)	506	2.3 (1.8)

Table 16. Bending gear endurance run - gears 104/105.

% life	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis
1	31	1.7	164	4.1 (2.2)
6	30	1.6	217	1.6 (3.4)
11	128	1.5 (3.8)	124	2.0 (2.9)
16	120	2.1 (3.1)	250	1.6 (1.9)
20	133	1.6 (3.8)	301	1.8 (1.7)
25	131	1.5 (3.7)	188	2.2 (1.8)
30	126	1.8 (3.4)	185	2.4 (2.0)
35	64	2.4	359	1.6 (2.8)
40	42	1.7	167	2.9 (2.4)
45	43	1.9	241	2.2 (2.5)
49	32	1.7	238	8.5 (3.5)
59	25	1.5	204	1.8 (2.4)
69	24	1.6	248	2.0 (3.0)
78	24	1.6	237	2.9 (3.2)
88	22	1.6	220	2.2 (3.0)

Numbers in brackets are kurtosis values before phase unwrapping.

Table 17. T56 gearbox - planet gears, location #1.

Load (ft-lb)	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2000	4	2.6	19	3.2	19	2.0
5000	6	3.4	11	3.5	24	2.0
10000	27	2.8	11	3.3	9	2.7
15000	5	2.6	11	2.6	7	3.0
18000	4	2.6	20	4.2	10	3.0
23400	4	3.1	27	2.7	8	3.9

Table 18. T56 gearbox - planet gears, location #2.

Load (ft-lb)	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2000	30	4.9	153	5.2 (5.4)	41	2.8
5000	40	3.3	26	4.4	45	2.8
10000	13	2.5	8	4.0	10	3.6
15000	9	2.2	13	4.3	20	4.0
18000	9	2.4	7	2.3	18	2.6
23400	28	2.7	9	3.0	28	3.9

Table 19. T56 gearbox - planet gears, location #3.

Load (ft-lb)	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2000	17	4.0	18	2.5	56	2.8
5000	16	2.7	8	2.1	31	3.4
10000	15	2.5	9	2.1	68	3.8 (11.7)
15000	6	2.3	5	3.0	13	3.7
18000	12	2.4	4	3.0	8	2.9
23400	8	2.5	4	1.8	13	2.5

Numbers in brackets are kurtosis values before phase unwrapping.

Table 20. T56 gearbox - sun gear, location #1.

Load (ft-lb)	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2000	3	2.3	28	3.3	30	2.0
5000	6	3.0	31	1.7	798	1.9 (2.4)
10000	105	8.7 (3.1)	42	1.8	149	1.7 (2.6)
15000	8	2.1	29	1.8	233	2.8 (2.8)
18000	7	3.0	50	4.3	997	1.8 (2.2)
23400	6	3.3	48	2.1	35	1.8

Table 21. T56 gearbox - sun gear, location #2.

Load (ft-lb)	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2000	132	1.4 (4.3)	148	1.4 (3.9)	203	2.2 (4.7)
5000	143	1.8 (4.1)	72	4.5	139	8.3 (3.2)
10000	229	2.2 (7.0)	29	3.8	61	2.6
15000	33	3.6	19	2.2	739	1.8 (4.3)
18000	24	4.0	19	2.5	637	1.7 (4.2)
23400	82	5.5	13	2.3	44	2.5

Table 22. T56 gearbox - sun gear, location #3.

Load (ft-lb)	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2000	44	3.1	43	3.7	231	2.4 (1.5)
5000	887	1.8 (2.5)	26	2.6	132	5.2 (6.3)
10000	594	1.5 (4.2)	18	2.8	146	1.9 (3.5)
15000	15	1.7	10	2.9	25	2.8
18000	19	2.7	7	2.9	28	2.7
23400	18	2.2	7	3.2	39	2.3

Numbers in brackets are kurtosis values before phase unwrapping.

Table 23. T56 gearbox - main drive gear, location #1.

Load (ft-lb)	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2000	399	1.1 (2.0)	1048	2.0 (3.5)	794	1.7 (2.9)
5000	7	2.9	1318	2.0 (2.4)	660	2.1 (4.0)
10000	6	2.7	54	5.0	40	3.7
15000	8	2.9	801	2.2 (3.5)	23	2.6
18000	8	2.4	1244	1.6 (2.1)	17	3.4
23400	10	3.6	131	1.4 (8.4)	12	3.8

Table 24. T56 gearbox - main drive gear, location #2.

Load (ft-lb)	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2000	142	5.7 (4.5)	167	3.9 (4.4)	1139	2.4 (3.1)
5000	6	3.1	164	1.3 (3.6)	148	6.7 (8.5)
10000	9	3.9	15	3.3	23	2.3
15000	11	2.4	14	2.8	22	2.6
18000	14	2.6	14	3.1	13	2.8
23400	23	4.0	32	3.3	13	2.6

Table 25. T56 gearbox - main drive gear, location #3.

Load (ft-lb)	Band 1 PM	Kurtosis	Band 2 PM	Kurtosis	Band 3 PM	Kurtosis
2000	20	4.1	163	4.6 (6.3)	734	1.8 (2.5)
5000	6	3.0	360	8.0 (4.7)	274	2.1 (5.3)
10000	5	2.8	183	1.3 (5.6)	27	3.2
15000	5	2.3	27	2.8	15	3.2
18000	5	2.5	18	3.4	10	2.6
23400	10	1.9	10	3.1	10	2.5

Numbers in brackets are kurtosis values before phase unwrapping.

Table 26. T56 gearbox - pinion input gear, location #3.

Load	Band 1		Band 2		Band 3	
(ft-lb)	PM	Kurtosis	PM	Kurtosis	PM	Kurtosis
2000	18	1.8	136	7.0 (5.6)	145	1.9 (2.3)
5000	9	1.6	252	1.6 (3.5)	173	1.3 (3.6)
10000	8	1.7	141	1.2 (8.7)	73	6.4
15000	10	1.8	374	4.8 (5.6)	31	2.4
18000	7	1.4	14	2.3	15	2.6
23400	7	1.8	8	2.1	10	1.9

Numbers in brackets are kurtosis values before phase unwrapping.

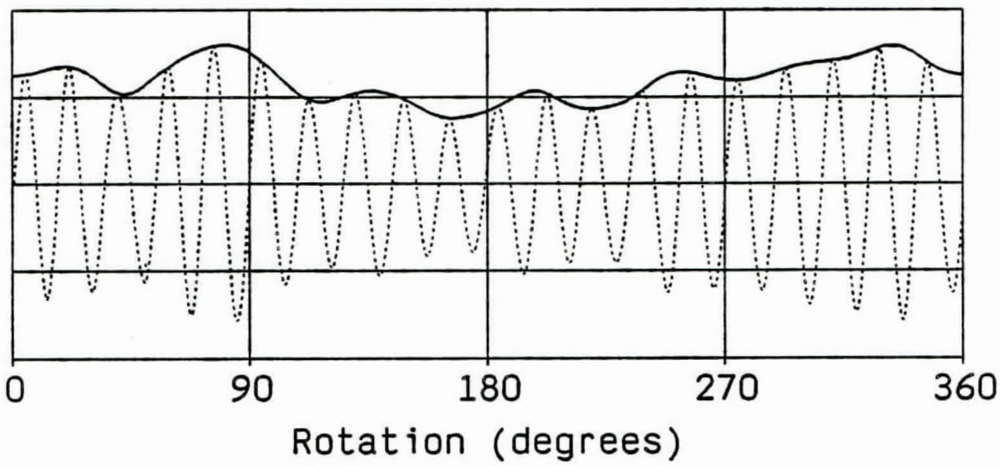

Figure 1. Filtered vibration signal and amplitude envelope of an undamaged gear.

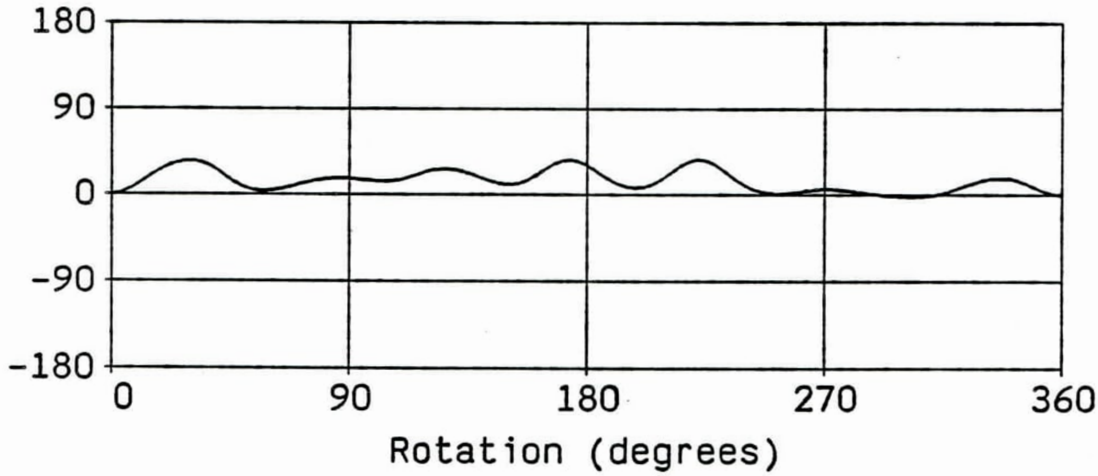

Figure 2. Demodulated phase trace of an undamaged gear.

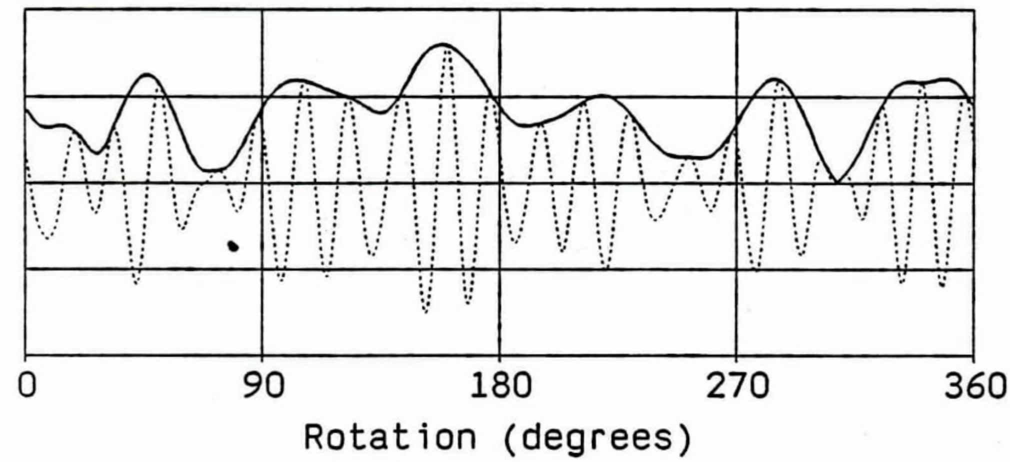

Figure 3. Filtered vibration signal and amplitude envelope of a gear with light surface damage.

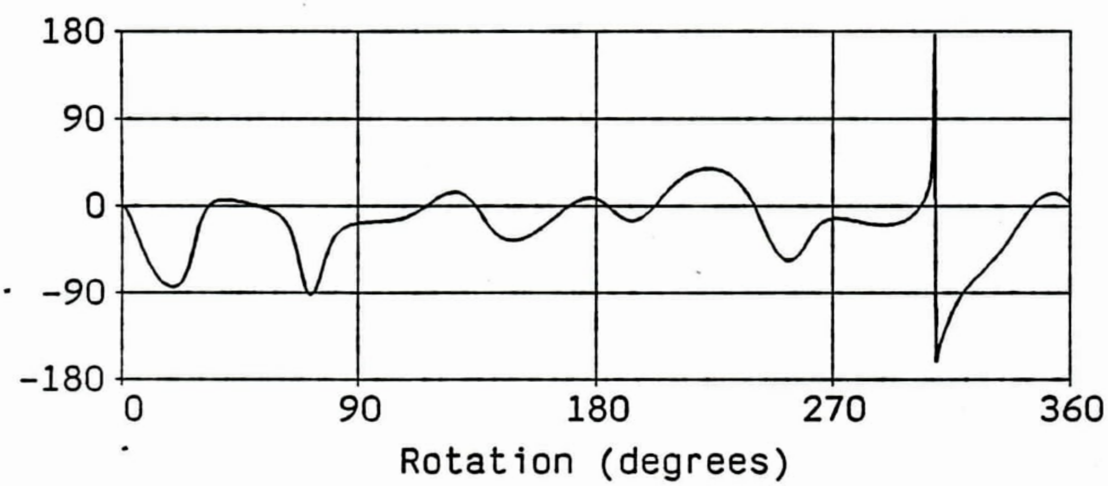

Figure 4. Demodulated phase trace of a gear with light surface damage.

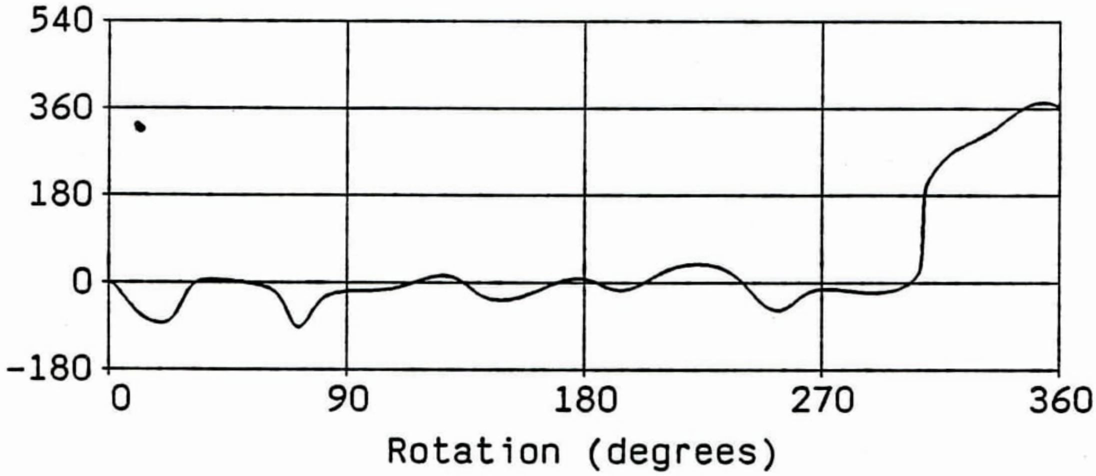

Figure 5. Unwrapped phase trace of a gear with light surface damage.

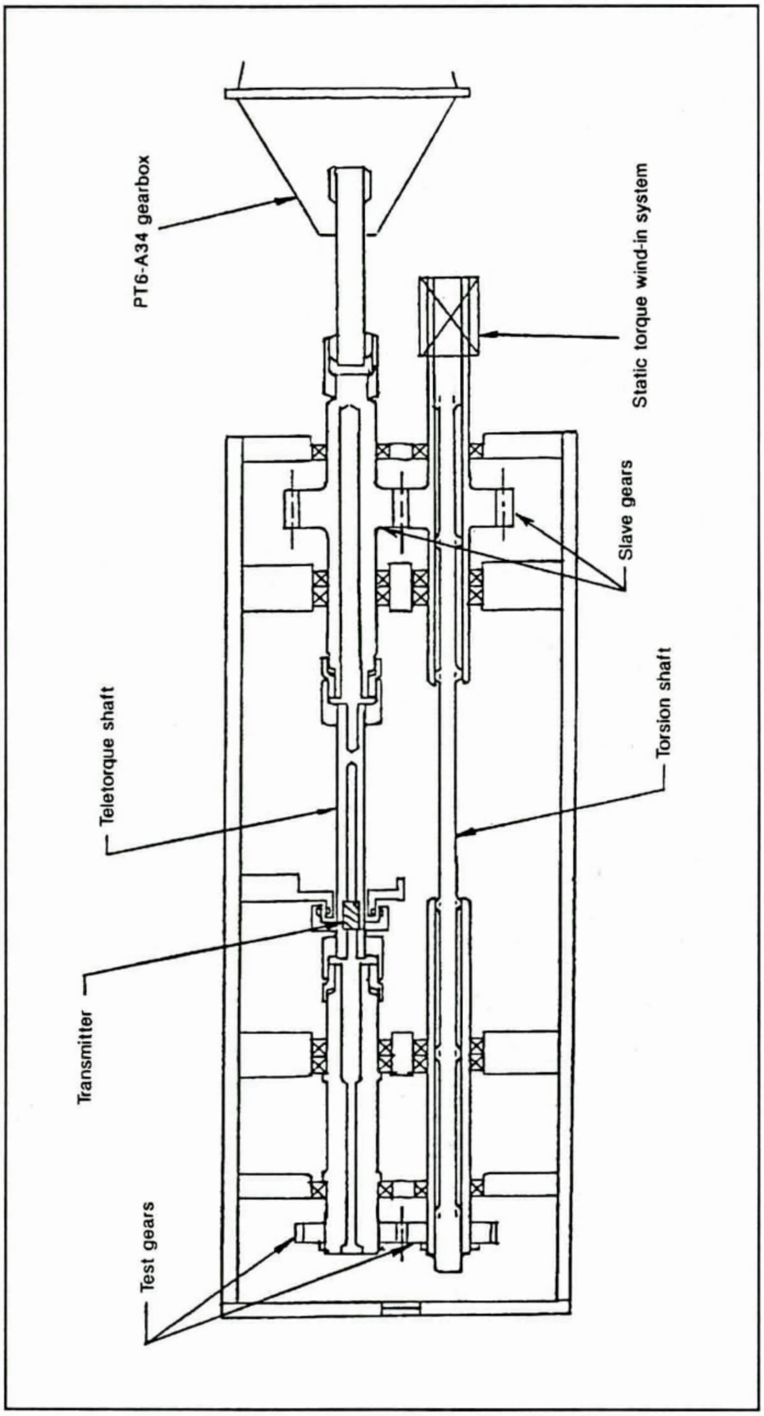

Figure 6. PWC gear fatigue rig - functional diagram.

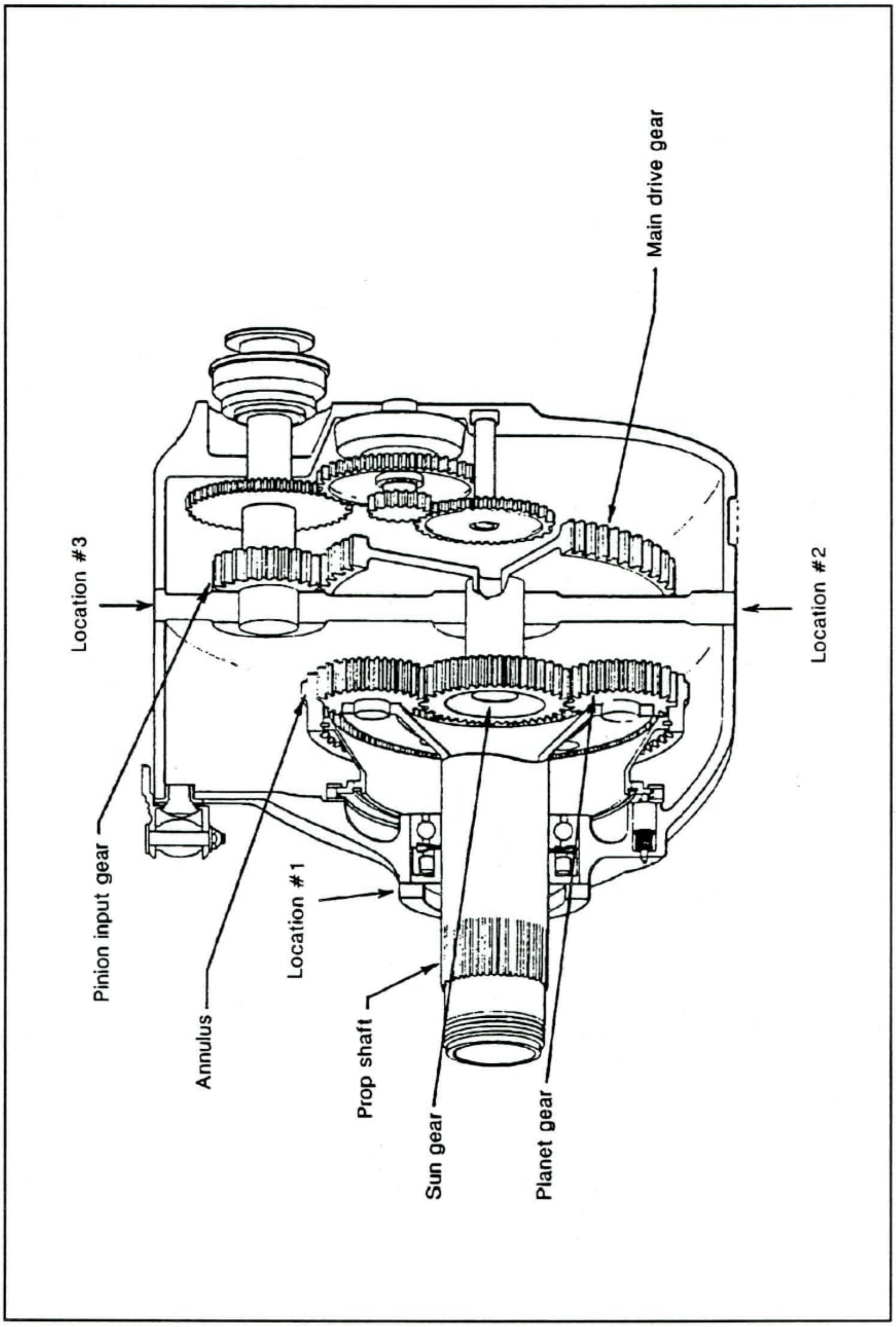

Figure 7. T56-A-14LFE reduction gearbox.

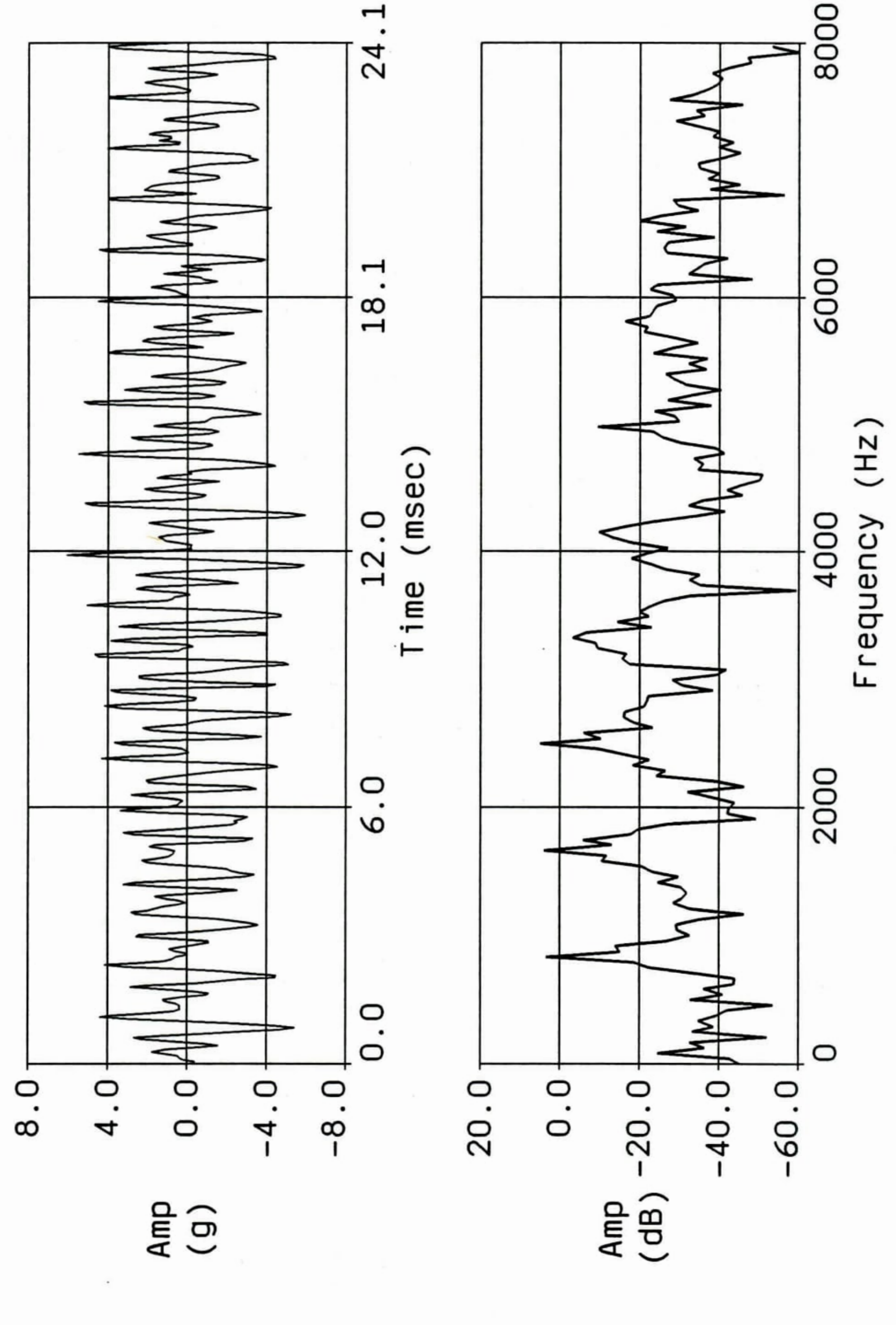

Figure 8. Seeded faults trials - pitting gear baseline, 2500 RPM.

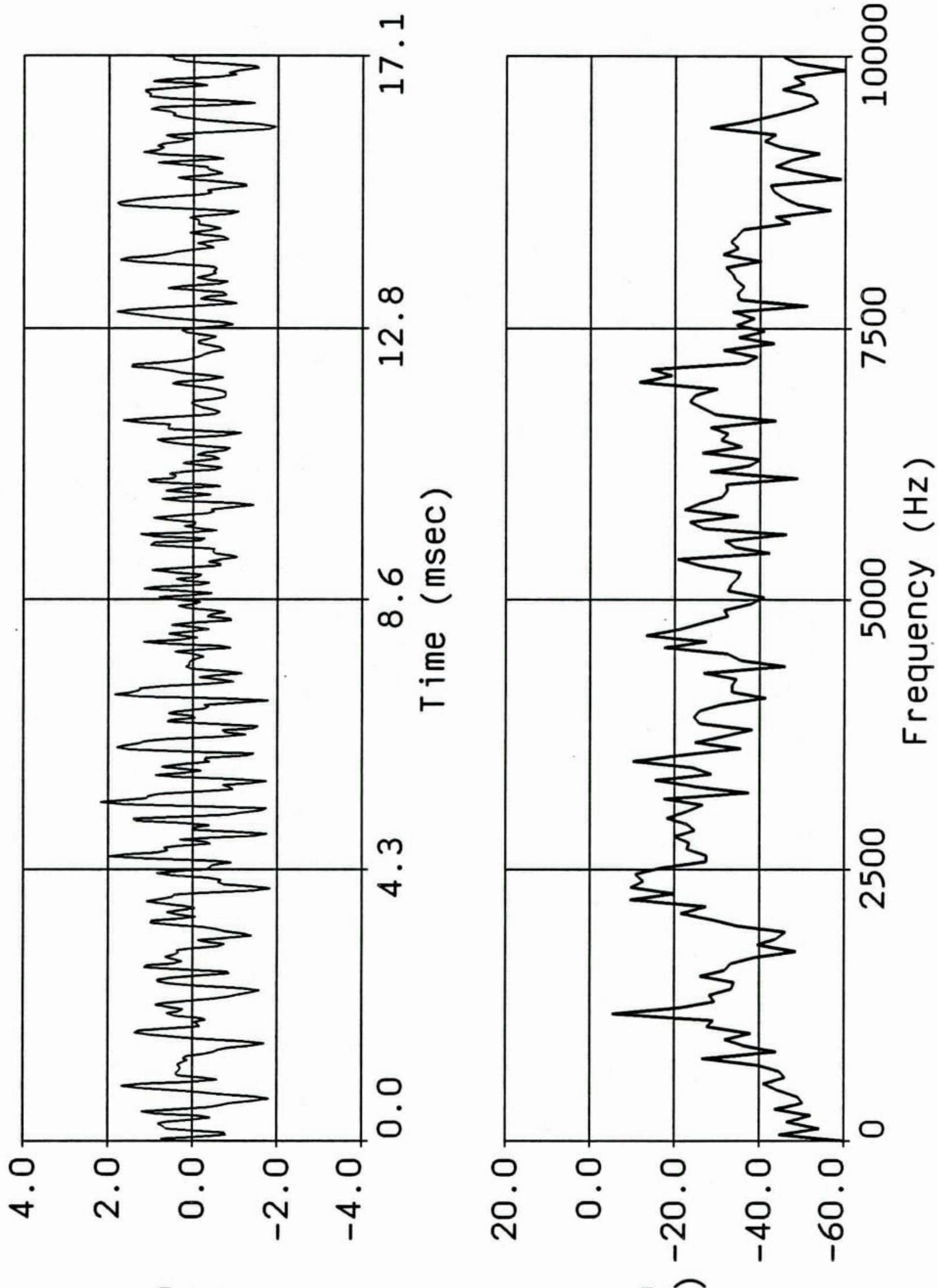

Figure 9. Seeded fault trials - pitting gear baseline, 3500 RPM.

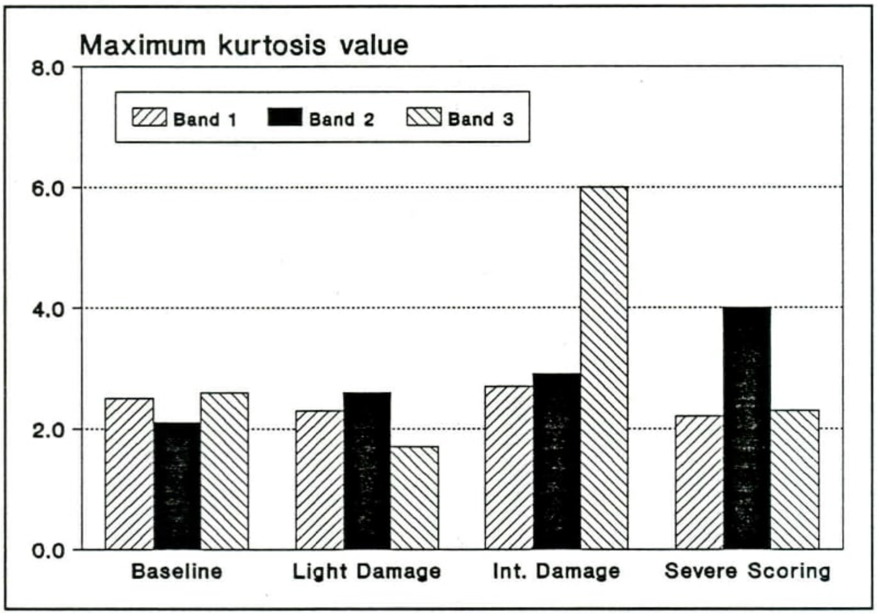

Figure 10. Seeded faults - pitting gears, 2500 RPM, maximum kurtosis.

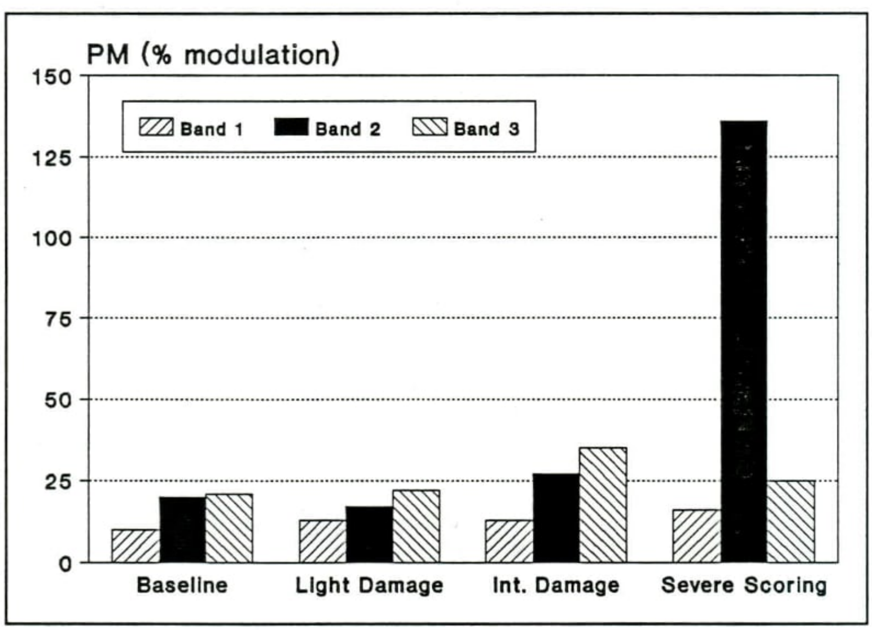

Figure 11. Seeded faults - pitting gears, 2500 RPM, percent modulation.

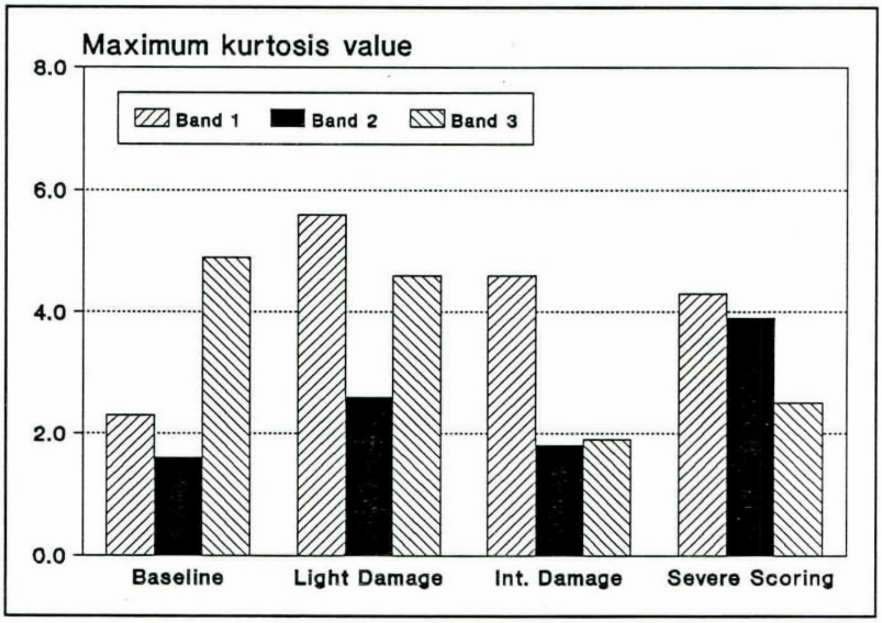

Figure 12. Seeded faults - pitting gears, 3500 RPM, maximum kurtosis.

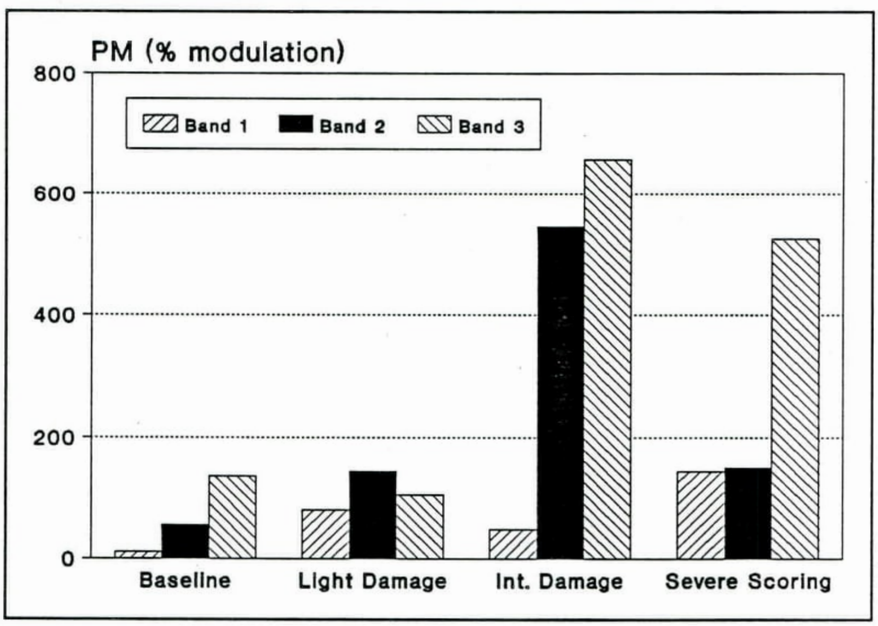

Figure 13. Seeded faults - pitting gears, 3500 RPM, percent modulation.

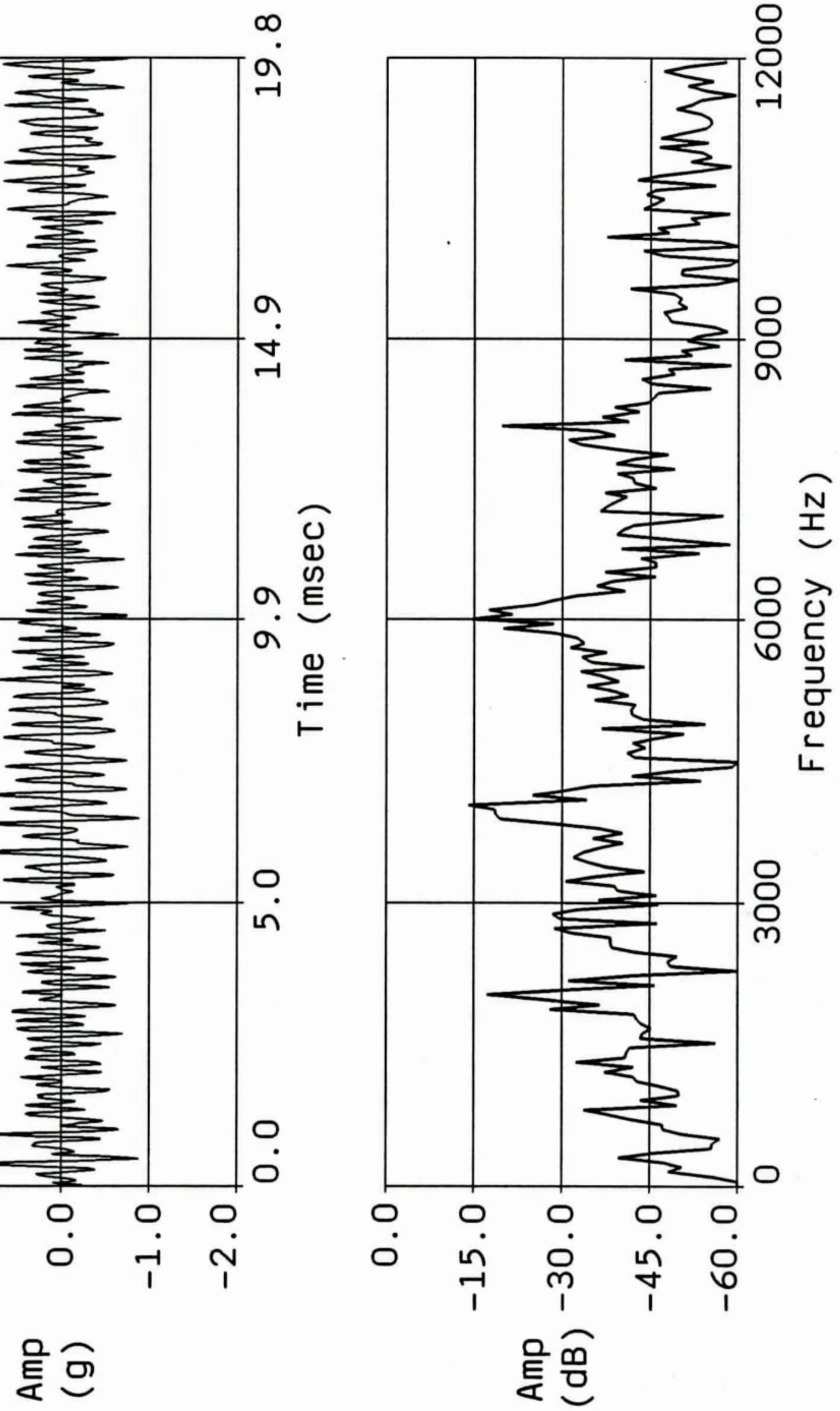

Figure 14. Seeded fault trials - bending gear baseline, 3000 RPM.

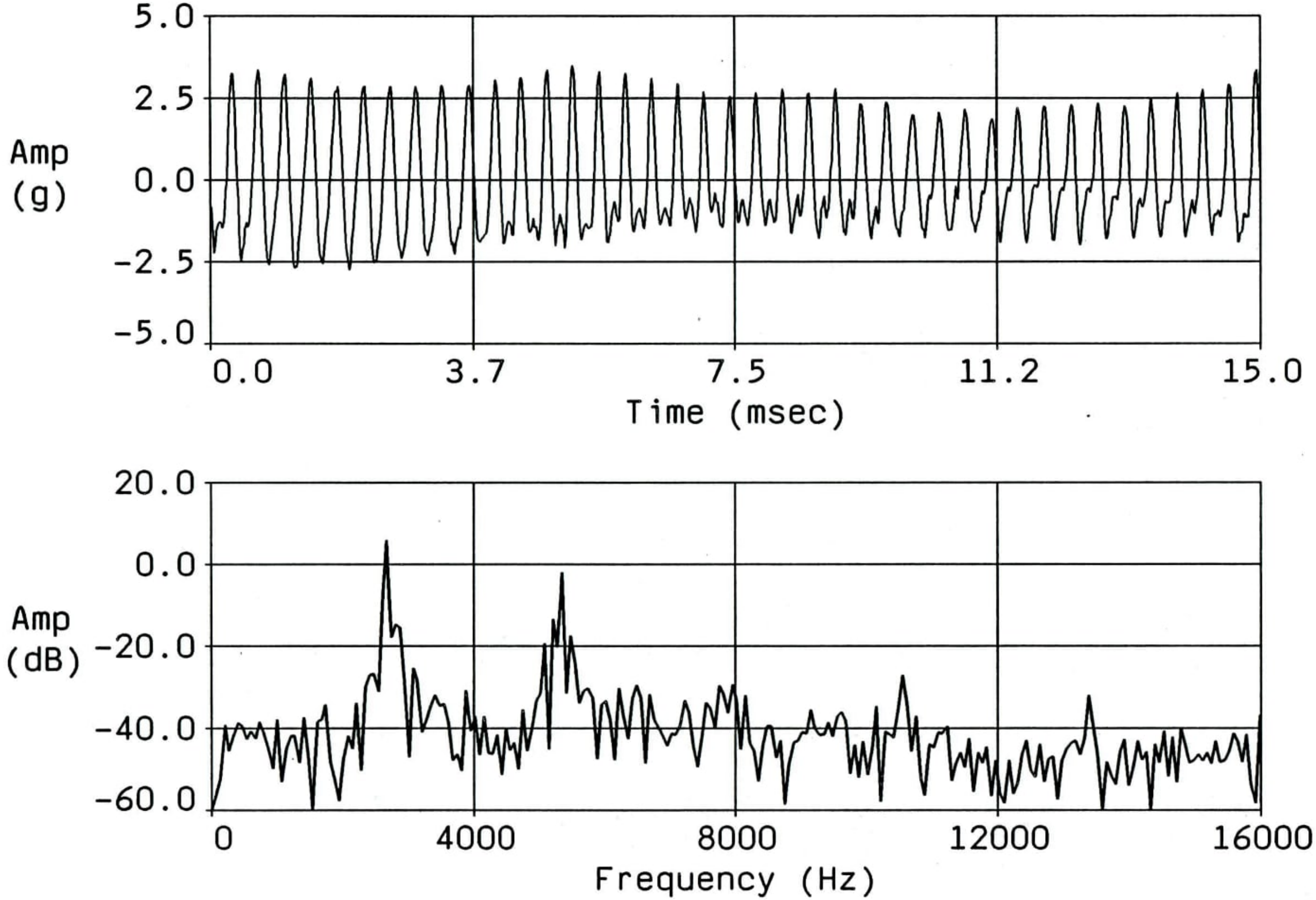

Figure 15. Seeded fault trials - bending gear baseline, 4000 RPM.

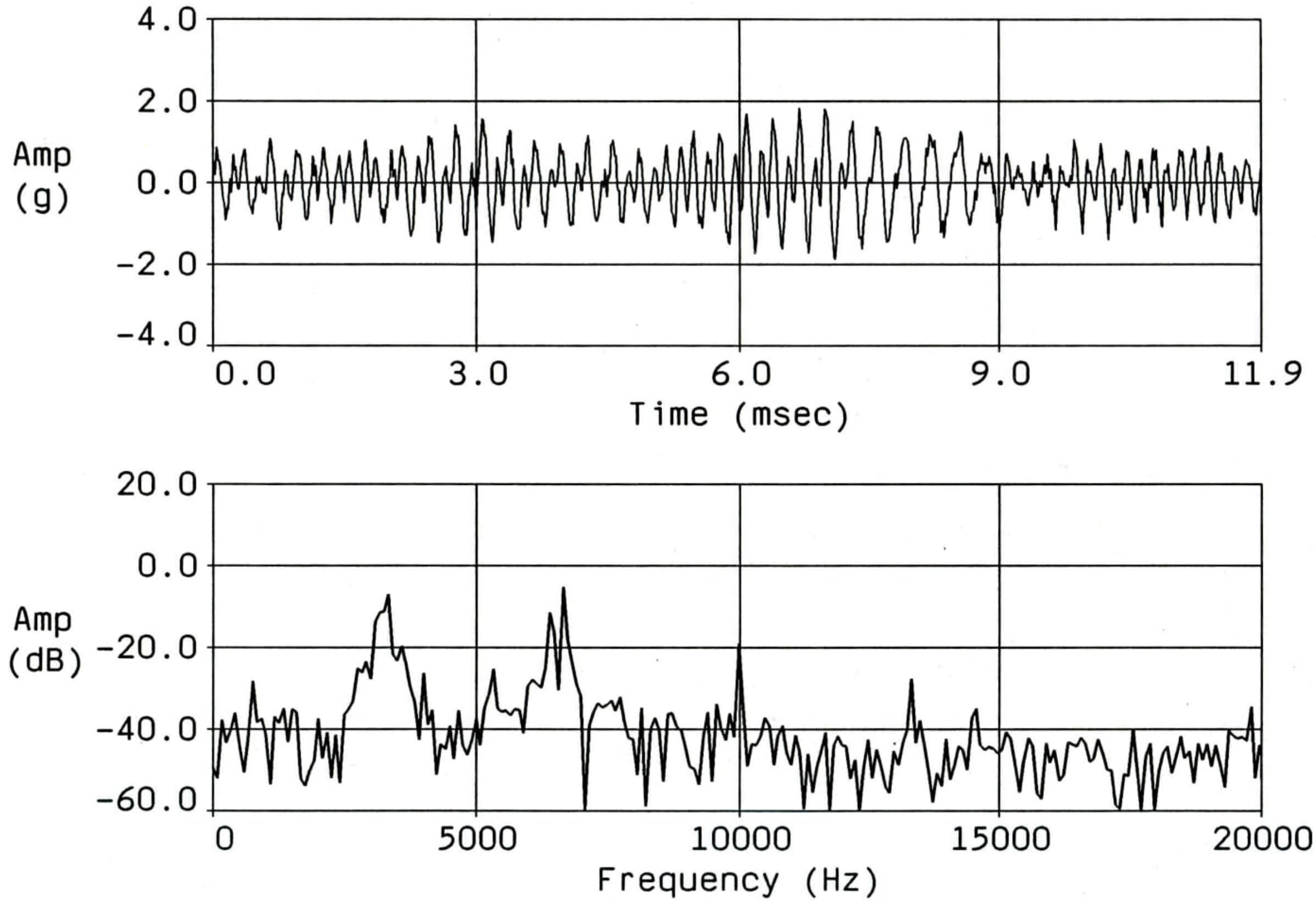

Figure 16. Seeded fault trials - bending gear baseline, 5000 RPM.

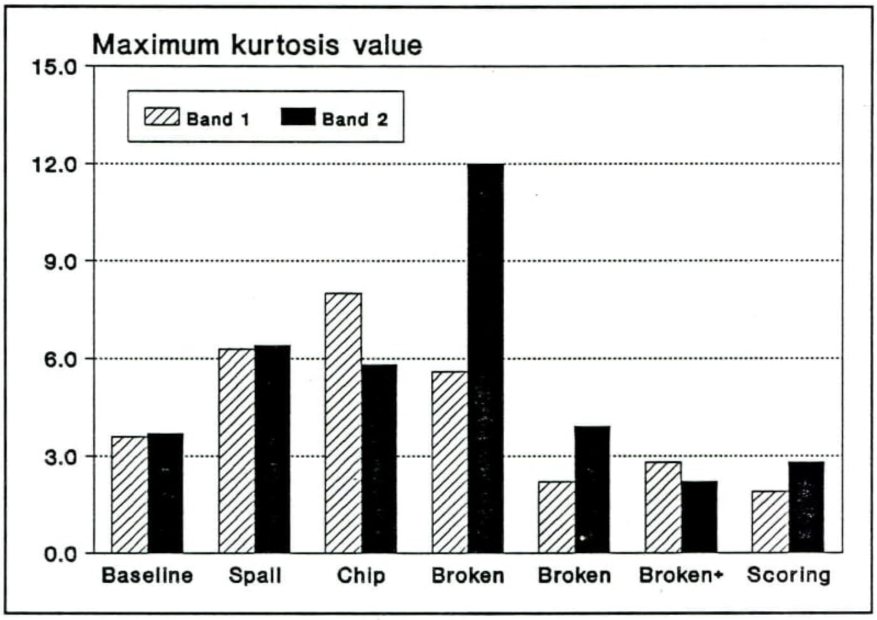

Figure 17. Seeded faults - bending gears, 3000 RPM, maximum kurtosis.

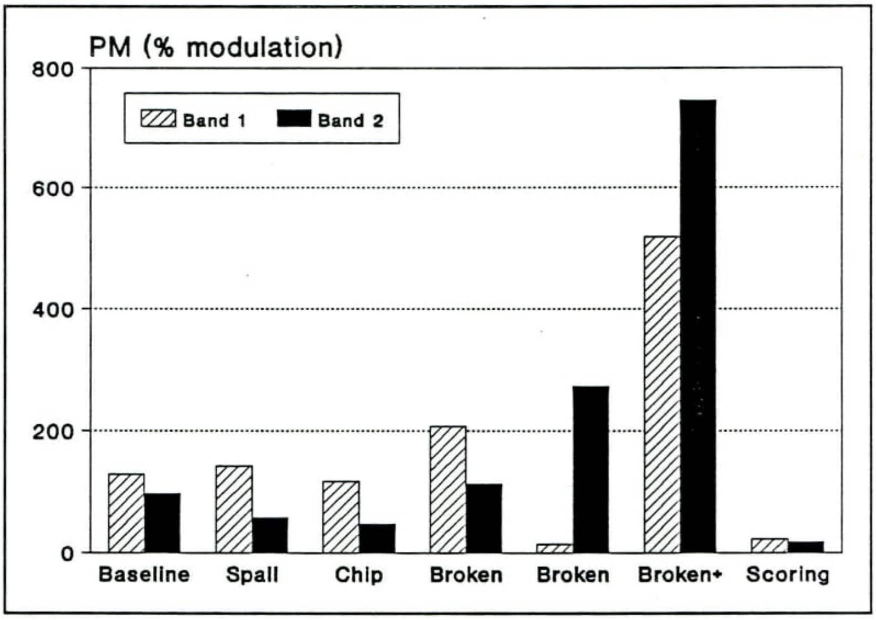

Figure 18. Seeded faults - bending gears, 3000 RPM, percent modulation.

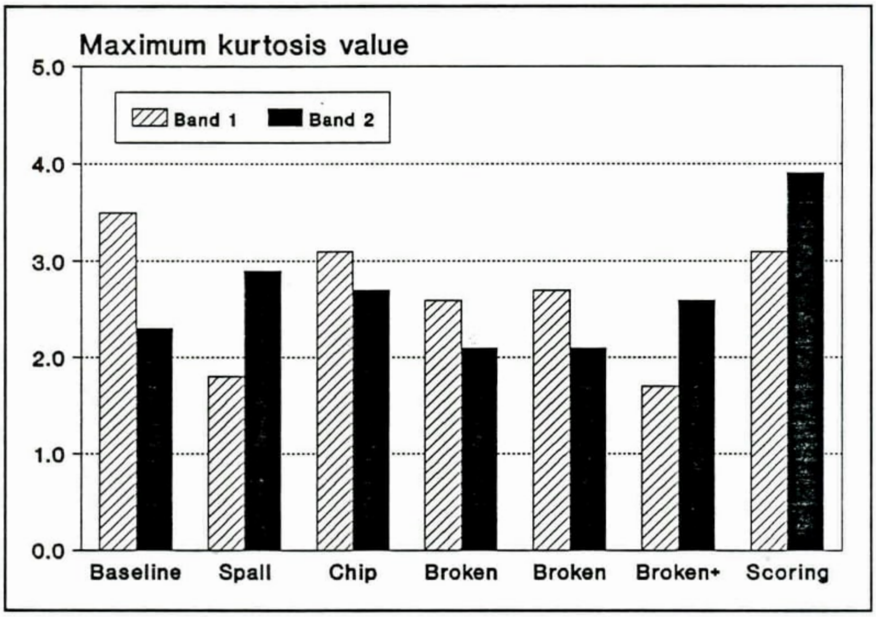

Figure 19. Seeded faults - bending gears, 4000 RPM, maximum kurtosis.

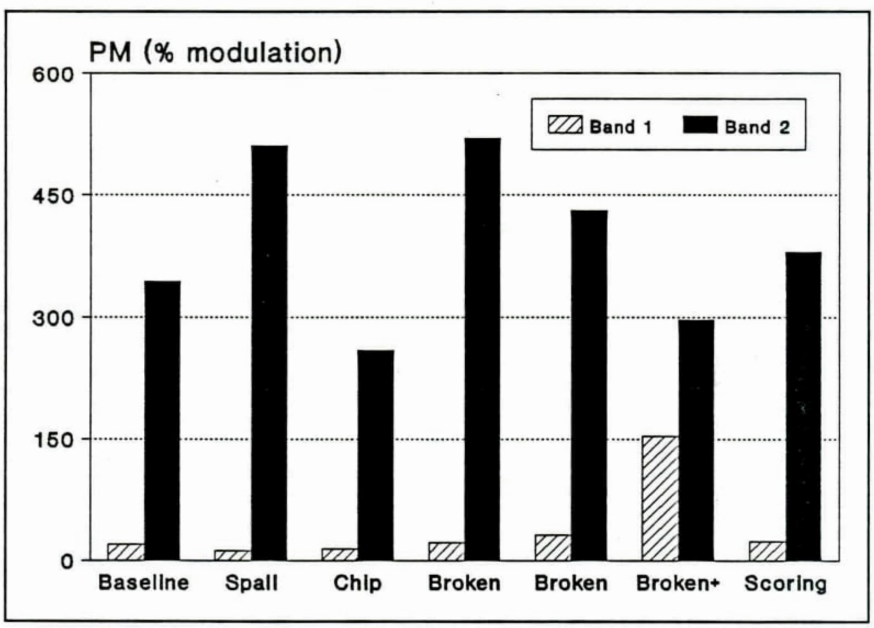

Figure 20. Seeded faults - bending gears, 4000 RPM, percent modulation.

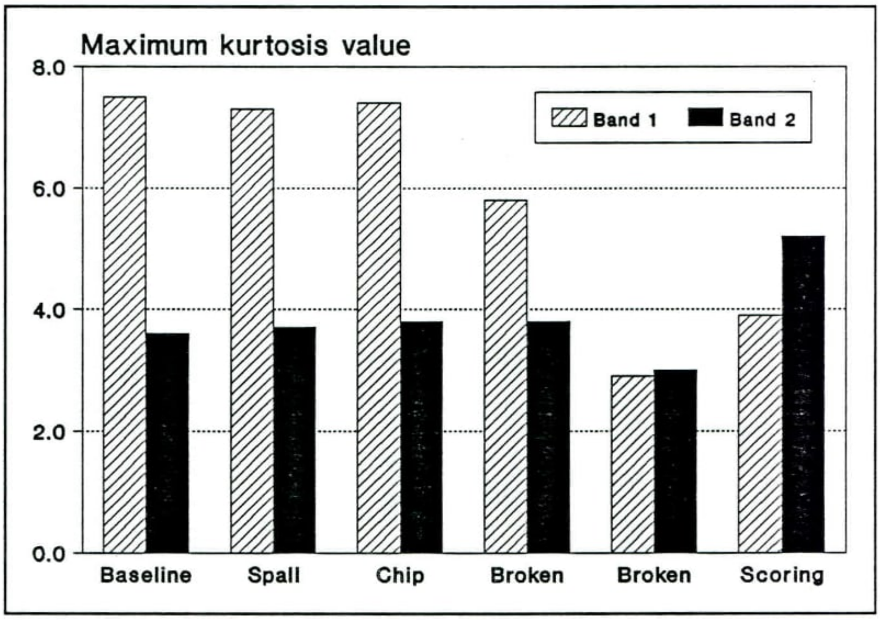

Figure 21. Seeded faults - bending gears, 5000 RPM, maximum kurtosis.

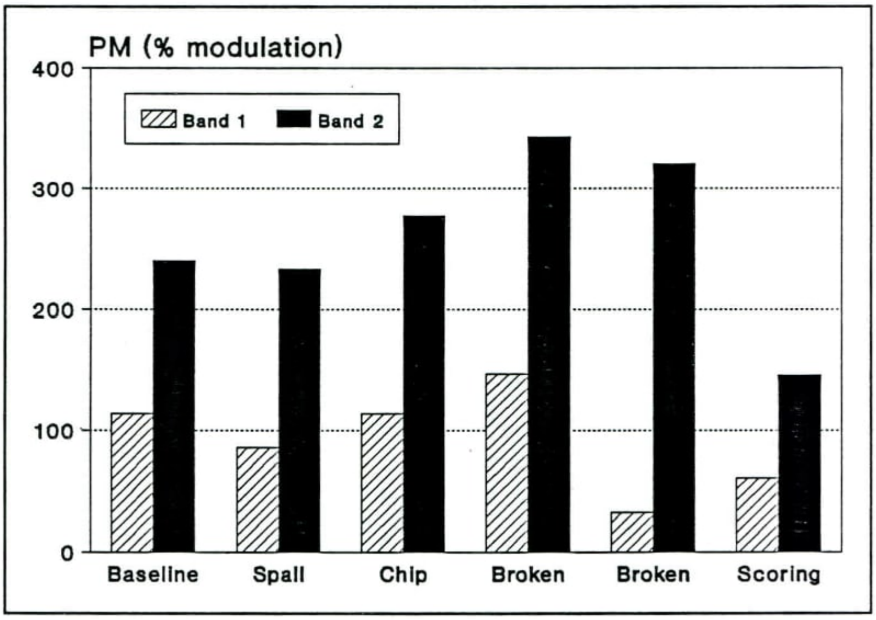

Figure 22. Seeded faults - bending gears, 5000 RPM, percent modulation.

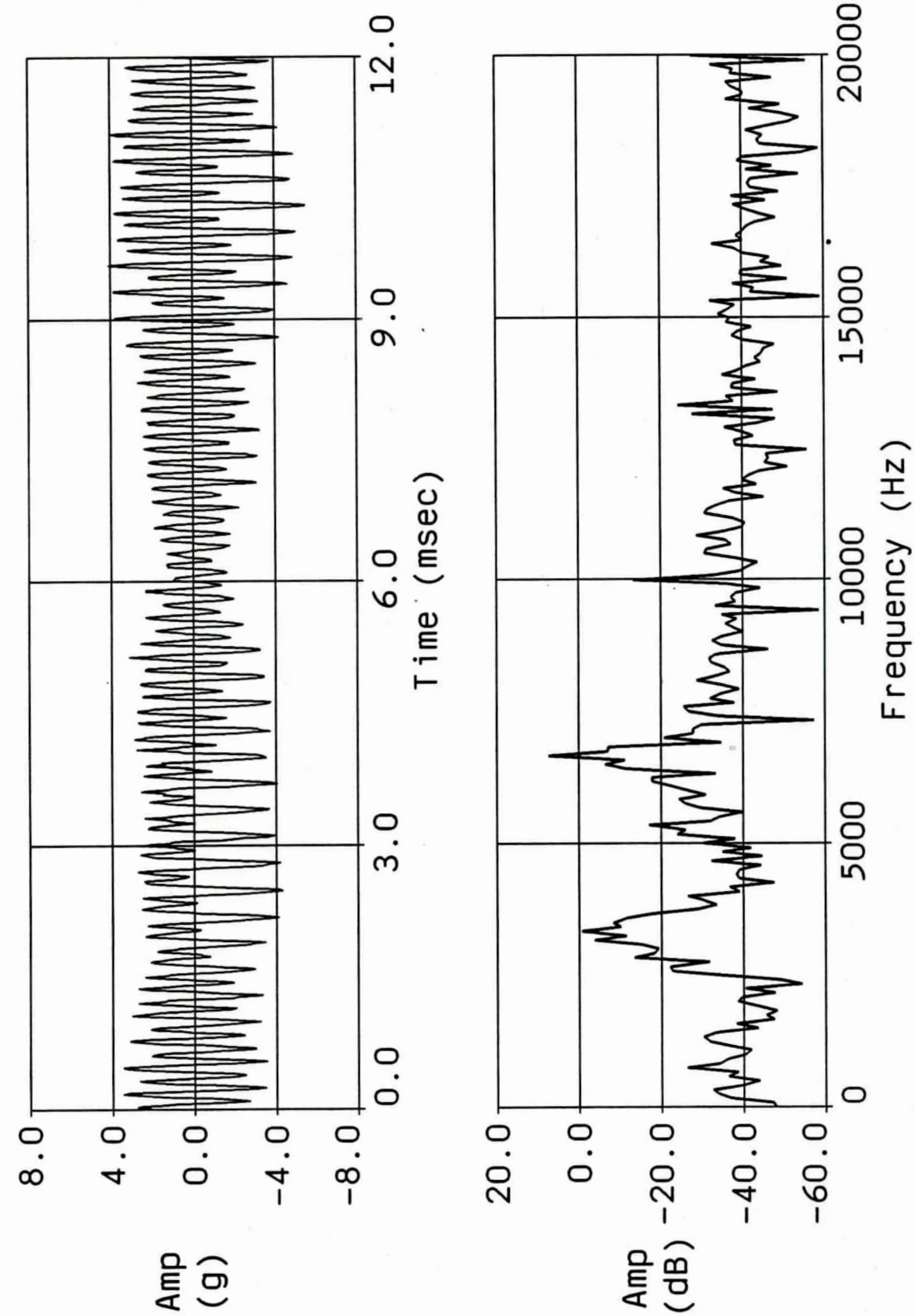

Figure 23. Bending gear endurance run - gears 110/111, baseline.

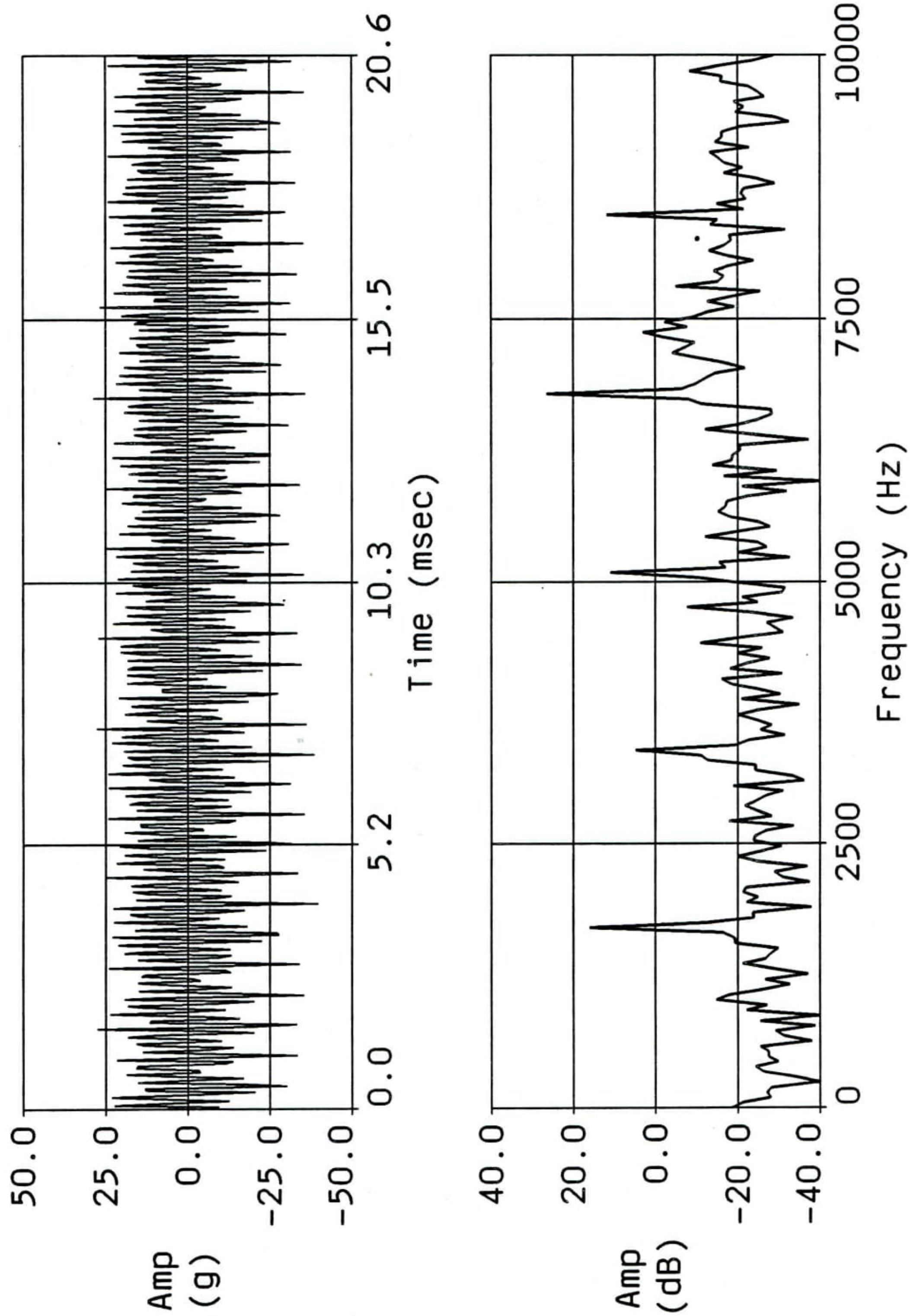

Figure 24. T56 gearbox - planet gears, 18000 ft-lb load.

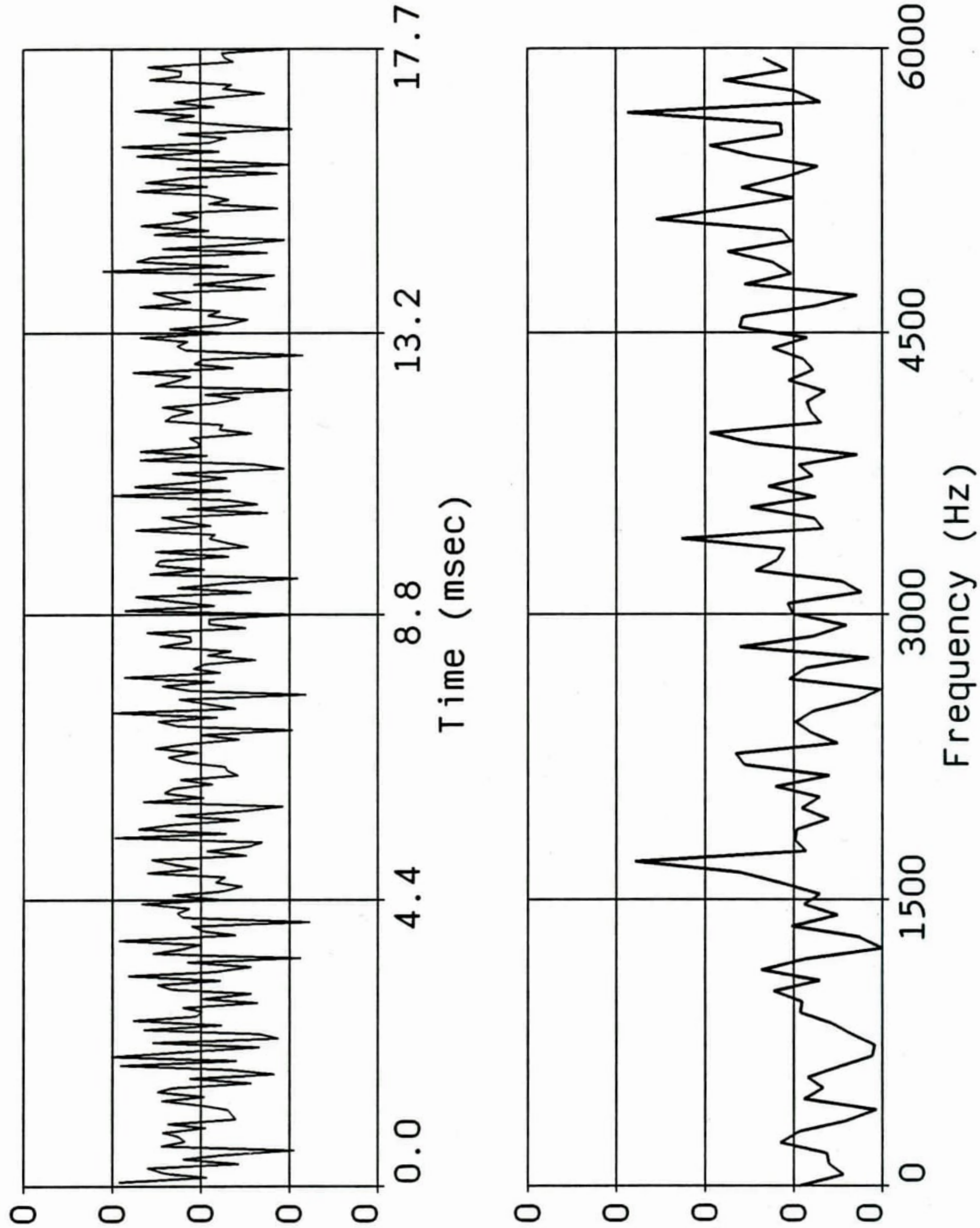

Figure 25. T56 gearbox - sun gear, 18000 ft-lb load.

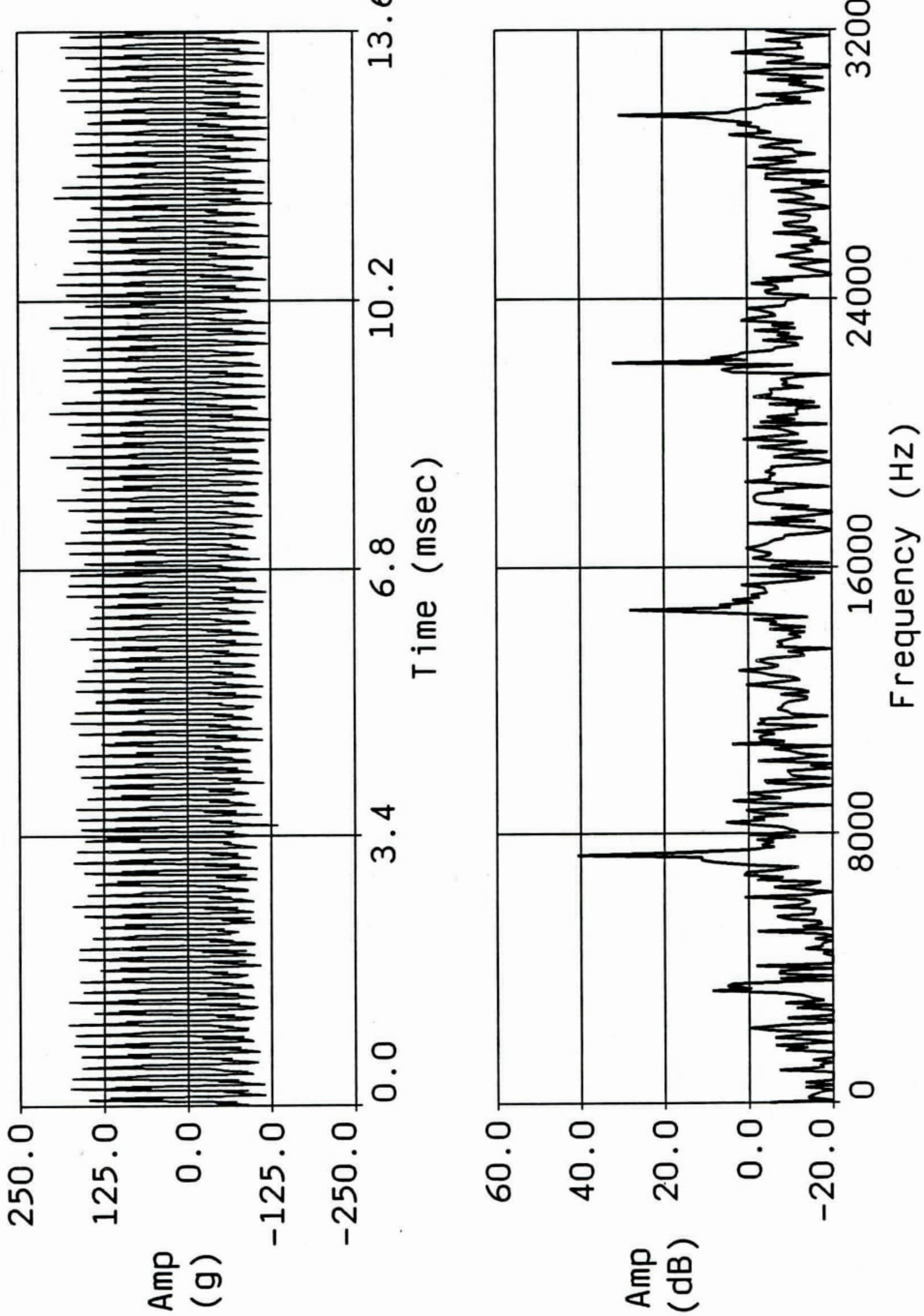

Figure 26. T56 gearbox - main drive gear, 18000 ft-lb load.

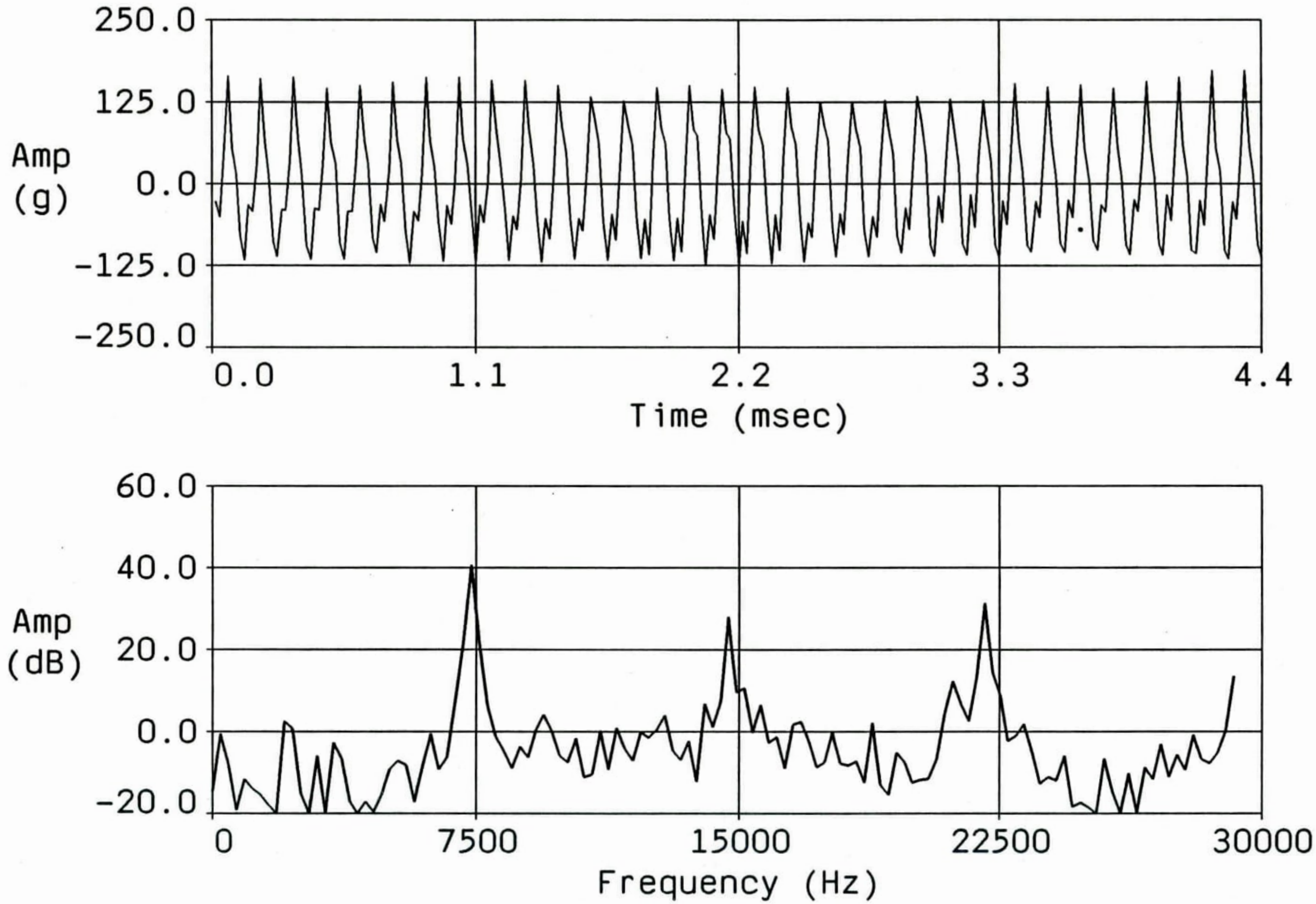

Figure 27. T56 gearbox - pinion input gear, 18000 ft-lb load.

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4 A Preliminary Study into the Use of Phase Demodulation Techniques for the Analysis of Gear Vibration Data

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SUMMARY/SOMMAIRE

A preliminary study into the use of phase modulation analysis techniques for gear condition monitoring is presented. Initial findings and application guidelines are presented.

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