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Detecting Tooth Damage in Geared Drive Trains

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Summary

This paper describes a method that was developed to detect gear tooth damage that does not require a priori knowledge of the frequency characteristic of the fault. The basic idea of the method is that a few damaged teeth will cause transient load fluctuations unlike the normal tooth load fluctuations. The method attempts to measure the energy in the lower side bands of the modulated signal caused by the transient load fluctuations. The method monitors the energy in the frequency interval which excludes the frequency of the lowest dominant normal tooth load fluctuation and all frequencies above it.

The method reacted significantly to the tooth fracture damage results documented in the Lewis data sets which were obtained from tests of the OH-58A transmission and tests of high contact ratio spiral bevel gears. The method detected gear tooth fractures in all four of the high contact ratio spiral bevel gear runs. Published results indicate other detection methods were only able to detect faults for three out of four runs.

Introduction

Because helicopter transmission failure is a critical safety problem, there is an important need for on-board transmission health and usage monitoring systems (HUMS) to warn the aircrew of imminent danger or apprise ground personnel of specific conditions that warrant maintenance.

An important challenge in HUMS design is the detection of specific faults. If a fault exists in a gearbox, the offending component is expected to induce a characteristic frequency signature. Determination of the signature, however, requires high computational throughput in real time to decipher the vibration data, and the detection of the fault also depends on the use of a priori engineering knowledge of the gearbox design and frequency generating process. In view of these difficult requirements, the design of an on-board HUMS requires design trade-offs to arrive at a workable solution.

In an effort to obtain further insight into analysis techniques for HUMS use, several studies were conducted utilizing data from NASA Lewis Research Center. The Lewis data were considered to be particularly salient for this purpose because they represented time series records of actual transmissions or transmission components exhibiting observable tooth damage.

In this paper a promising approach is presented for detecting tooth damage faults which requires minimum consideration of the underlying transmission design and its frequency generating process.

The Lewis Data Sets

Two sets of vibration data generated at NASA Lewis Research Center (LeRC) are examined herein. These are time-series records obtained from several high contact ratio face gear component meshes, and similar records obtained from an OH-58A model transmission. The data were recorded originally for separate experimental purposes, but now serve as a valuable framework for understanding the generality of computational methods.

In the first data set, face gear fatigue tests were conducted in the Spiral Bevel Gear Fatigue Rig (ref. 1). During four experimental runs, test meshes were allowed to progress beyond the pitting and heavy wear stages until tooth fracture occurred. Each mesh was composed of a 28-tooth pinion spur gear, rotating at a nominal speed of 19,107 rpm, which was fitted to a 107-tooth face gear that was imparted a rotation speed of 5000 rpm. During the test runs, time-series vibration data were recorded from an accelerometer mounted on the pinion shaft bearing housing. The raw vibration signal and a once-per-revolution time synchronous tachometer pulse were recorded. These records were separated by 20-minute intervals. For each record, the vibration data were sampled at a rate of 125 kHz and passed through an anti-aliasing filter set at 20 kHz, converted to digital form, and time synchronously averaged to eliminate noise and vibration that was not coherent with the period of revolution of the face gear. The digitized data were then linearly interpolated to produce a 1024-point vector for two contiguous revolutions.

In the second data set, OH-58A model transmission vibration tests were conducted in LeRC's 500 horsepower transmission test rig. Several faults were seeded[1] by cutting file marks on nine alternate teeth of the input spiral bevel pinion gear, which has a total of 19 teeth. The transmission was then operated at monotonically increasing load levels, which ultimately resulted in fracture and partial separation of five of the seeded teeth. The experiment was stopped at this point.

In the first stage of the transmission, the input shaft drives the 19-tooth spiral bevel pinion gear at 6060 rpm, which in turn meshes with a 71-tooth bevel gear. During the tests, vibration data were recorded at several accelerometer locations on the transmission housing, one of which was selected for analysis based on its proximity and radial orientation to the pinion gear. During each run, the raw vibration signals and a once-per-revolution tachometer pulse were recorded. These records were separated by approximately 2-minute intervals. For each record, vibration signals were sampled at a rate of 125 kHz and passed through an anti-aliasing filter of 50 kHz. Likewise for this set, the data were digitized and averaged. The digitized data were then linearly interpolated to produce a 1024-point vector for each revolution.

Fault Detection Method

There are a large number of rotating components in a helicopter transmission, all of which contribute to the vibration signal. The signal is an estimate of the vibration which is harmonically related to the selected shaft. Typically, this will be a vibration at the shaft rotational frequency and at multiples of the shaft rotational frequency. The detection method presented herein does not require a priori knowledge of the frequency characteristics of the fault. The method monitors the summation of spectral energies at selected frequencies of the shaft of interest.

The basic premise of the method is that the monitored gear is initially in a healthy normal state. The normal tooth load fluctuations of the healthy gear are assumed to be known. Those portions of the gear vibration which emerge at frequencies that are multiples of the shaft rotational frequency are termed tooth load fluctuations. Normal tooth load fluctuations arise for perfectly acceptable reasons, totally unconnected with any fault or faults present (ref. 2).

Some of the normal tooth load fluctuations show up at frequencies corresponding to the sidebands of the gear mesh frequency. Gears generate a mesh frequency equal to the number of teeth on the gear multiplied by the rotational speed of the shaft driving it. Sidebands of the mesh frequency are caused by a modulating rotational motion. Gears generate a large number of possible sidebands about the mesh frequency. Sidebands are typically due to such causes as eccentric gears or nonparallel shafts, which allow one gear to "modulate" the speed of the other gear (ref. 3).

The basic theory behind the current method is that a few damaged teeth will cause transient tooth load fluctuations unlike the normal tooth load fluctuations. It is assumed that the transient load fluctuations at low frequencies are significant. This is based on the following heuristic argument.

If the pinion gear on a drive shaft suddenly lost every-other tooth, the normal tooth load fluctuation frequencies would be halved. Of course, this assumes the pinion gear originally had an even number of teeth. So if a gear loses a few teeth or has a few teeth damaged, it will act for a portion of the cycle (when the missing or damaged teeth should have been engaged) like a gear with half the number of original teeth. The gear mesh frequency would be halved. Detection of an increase in energy at frequencies lower than the normal tooth load frequencies would be an indication that this traumatic modulation of the speed of the driven gear occurred.

Amplitude modulation in a signal is most often due to transient variations in the loading (ref. 4). If the frequencies associated with the normal tooth load fluctuations are regarded as the carrier frequencies, then the side frequencies created by modulation will occur at frequencies both lower and higher in value than the corresponding carrier frequencies.

In order to detect anomalous modulation in the signal, a cutoff frequency is selected to exclude the gear mesh frequency and significant normal tooth load fluctuations. Spectral energy is monitored in the interval from the lowest nonzero resolvable frequency up to the cutoff frequency. Some of the lower side frequencies can be detected in the frequency interval selected. No attempt is made to detect the upper side frequencies since they probably will be masked by the significant normal tooth load fluctuations. This technique can provide some information about the signal without having to demodulate it. The sum of the monitored energy provides an estimate of the anomalous amplitude modulation in the signal. For definiteness, a particular normal tooth load fluctuation is regarded as significant herein if it exceeds ten percent of the energy at the gear mesh frequency.

[1] *Seeded* faults are intended to propagate during the experiment and are to be distinguished from *planted* faults, which are based on the installation of predamaged components.

In other words, a few damaged teeth will cause the normal distribution of spectral energy of the gear to change. The method monitors the transfer of energy toward the low frequency end of the spectrum.

The suggested set of rules outlined above to detect gear tooth failure summarizes empirical observations that were made of the Lewis data. A case in point is shown in figures 1(a)–1(d), which show the tooth load fluctuations for the face gear test run #1 reported in reference 1. The test lasted about 18 hours. It was reported that during the last 7 hours of the test all the teeth on the face gear experienced heavy wear damage. One tooth broke off at about 18 minutes before the end of the test, and the test was terminated when a second tooth broke off.

Figure 1(a) shows the normal tooth load fluctuations for this gear at the beginning of the test. The gear mesh frequency is about 8.9 kHz and a significant normal tooth load fluctuation occurs at about 7.5 kHz. Hence the frequency interval of interest in this figure would range from 0 to 7 kHz. Figures 1(b) and 1(c) show the tooth load fluctuations at the time when heavy wear damage was first reported. Figures 1(b) and 1(c) taken together clearly demonstrate the sudden transfer of low frequency energy over a period of 3 minutes. Figure 1(d) shows the tooth load fluctuations at the completion of the run.

Another key element to consider is the level of the energy in the monitored interval. This is related to the everyday experience of stopping a car when it makes a loud noise. The question "Loud compared to what?" has to be answered. Loud usually means it is far noisier than the nominal value. In the detection method proposed, the nominal value of energy is taken to be the level of energy in the monitored interval at the beginning of the run.

Face Gear Results

Results of applying the method to runs #1, #2, #3, and #4 of the Lewis face gear fatigue tests are illustrated in figures 2(a), 2(b), 2(c), and 2(d), respectively. The cutoff frequency for run #1 was 7 kHz as it was for all other runs which had similar spectra.

It can be concluded that the method reacted significantly to the tooth fractures. The results shown correlate with the observations reported in reference 1. For the multiple tooth fracture damage experienced in runs #1 and #2, the method reacted significantly. The method reacted to the gradual pitting damage experienced during the last 3 hours of run #3 and the single tooth fracture experienced in this run. The method reacted to the tooth damage fracture experienced in run #4.

In view of the experimental results presented in reference 1, it can be concluded that the current method detects tooth damage failure when the sum of the monitored energy exceeds twice the initial sum.

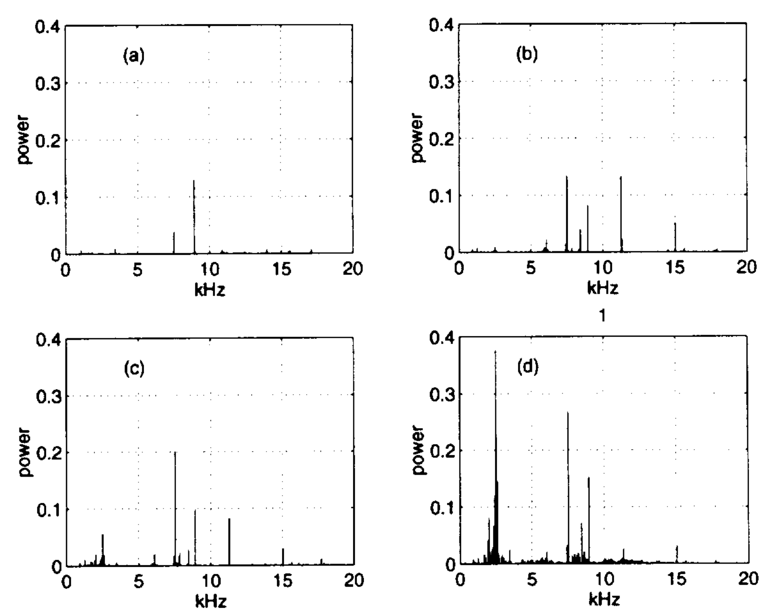

Figure 1. LeRC face gear test results for run #1, power versus frequency; (a) at hour 1.0, (b) at hour 15.50, (c) at hour 15.55, (d) at hour 17.8.

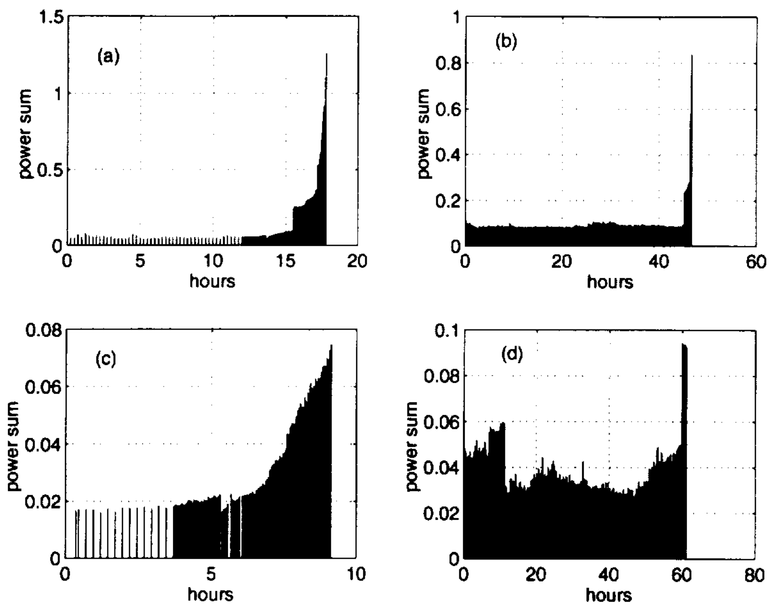

Figure 2. LeRC face gear test results, power-sum versus time; (a) run #1, (b) run #2, (c) run #3, (d) run #4.

OH-58A Results

The current method was developed based on observations of the face gear test results. Now that all the elements of the method are in place, the method can be applied to other cases to detect tooth damage failure. Hence the method will be applied to the OH-58A test results.

Figure 3 shows the normal tooth load fluctuations for the OH-58A test at hour 1. As can be seen from this figure, the normal tooth load fluctuation consists of a significant vibration at 1.9 kHz, the gear mesh frequency. For this run, a cutoff frequency of 1.5 kHz was selected.

The result of applying the method to this case is shown in figure 4. It can be concluded that the method reacted significantly to the tooth damage. For this run, torque data were available and these data are also shown in figure 4. It can be seen from this figure that the method reacted to the changes in the torque.

Significance of Frequency Interval

The selection of the frequency interval is a key element of the method. The significance of this selection is illustrated by the following observations that were made while analyzing the OH-58A data.

Compare figure 3, which shows the spectral energy distribution for the input shaft at hour 1, with figure 5, which shows the distribution at hour 8 after the gear teeth had sustained damage. Figure 5 clearly demonstrates the spawning of energies below the selected cutoff frequency, 1.5 kHz.

As mentioned previously, for this test the input torque was available. Figure 6(a) shows the summation of low frequency spectral energy using 2 kHz as a cutoff. This frequency interval includes the gear mesh frequency. The torque is also shown. When this frequency interval is used, there is no apparent trend as to the effect of torque on vibration. This result is similar to the result reported in reference 5. Figure 6(b) shows the summation using 1.5 kHz as a cutoff, thereby excluding the energy at the gear mesh frequency. Observe that the summation of energy displayed for this frequency interval reacts to the input torque. Evidently, the energy in this frequency interval is an important indicator of the modulation occurring in the transmission.

In light of the interpretation of what the ordinate in figures 6(a) and 6(b) represents, the relation of detecting response to torque changes and detecting gear tooth damage is clear. The ordinate is the sum of the monitored spectral energies. This sum provides an estimate of the amplitude modulation present in the signal.

An analogy to ordinary AM radio broadcasting is helpful here. Consider several radio stations broadcasting with overlapping bandwidths. The case of detecting response to the torque changes (fig. 6(b)) corresponds to an increase in power of a broadcasting station over a period of time. The case of masking the signal (fig. 6(a)) corresponds to a more powerful station broadcasting at the

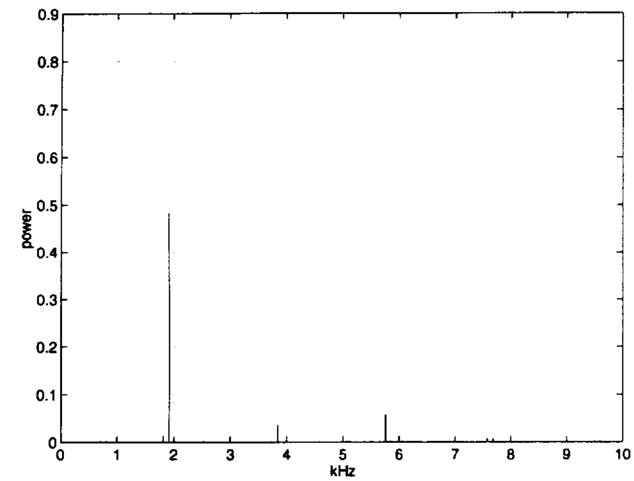

Figure 3. OH-58A test results at hour 1, power versus frequency.

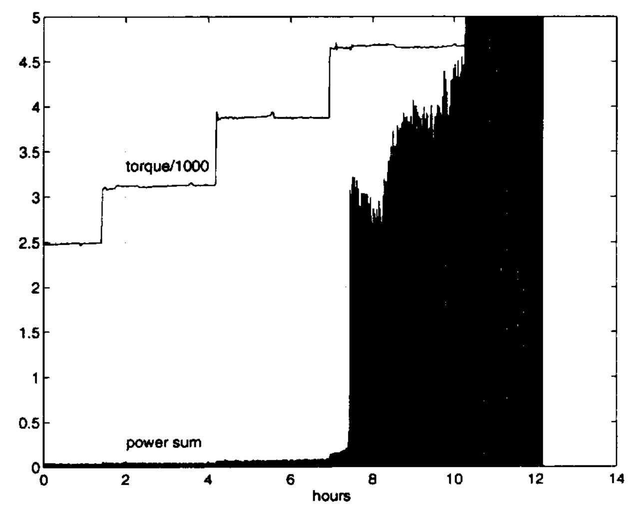

Figure 4. OH-58A test results, power-sum versus time.

same time as the original station. The case of detecting gear tooth damage corresponds to yet more powerful stations broadcasting at later times.

The analogy can be carried one step further if it is recalled that the current method does not attempt to demodulate the signal. Hence the interference shown in figure 6(a) is inevitable since no filtering or tuning takes place. This points out the key role played by the cutoff frequency.

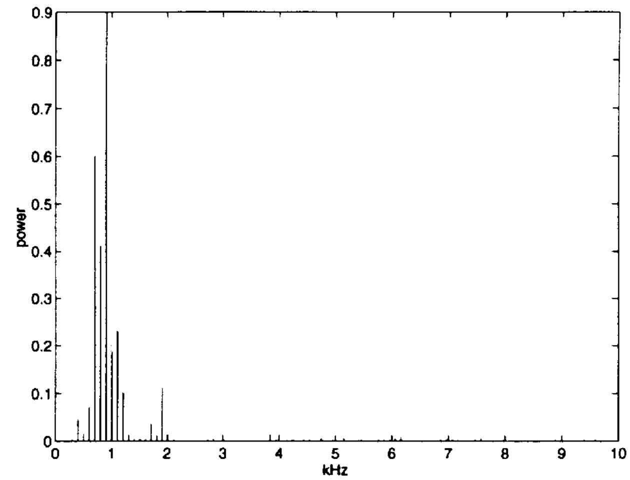

Figure 5. OH-58A test results at hour 8, power versus frequency.

In terms of the analogy, the interference of the radio stations can be eliminated by employing a low pass filter. In the detection method, the masking can be eliminated by restricting measurements to the selected low frequency interval.

The selection of the frequency interval also affects the results for the face gear runs. Recall that the face gear results were obtained using a cutoff frequency of 7 kHz. This choice excludes the gear mesh frequency at 8.9 kHz and a significant tooth load fluctuation at 7.5 kHz. If the normal tooth load fluctuations were not known at the beginning of the run, the only criterion for selecting a cutoff frequency would be the knowledge of the gear mesh frequency. Figure 7 shows the results of applying the method to runs #1 through #4 of the Lewis face gear fatigue tests. For these runs, a cutoff frequency of 8.5 kHz was used. This selection excludes the gear mesh frequency, but it includes the significant tooth load fluctuation at 7.5 kHz. For these tests, the method reacted as before for runs #1, #2, and #3. However, for run #4 the results are different. Inclusion of the significant tooth load fluctuation at 7.5 kHz masks the results obtained earlier for run #4. In this case when only the gear mesh frequency is presumed known, the method is less sensitive than when the knowledge regarding the normal tooth load fluctuations is utilized.

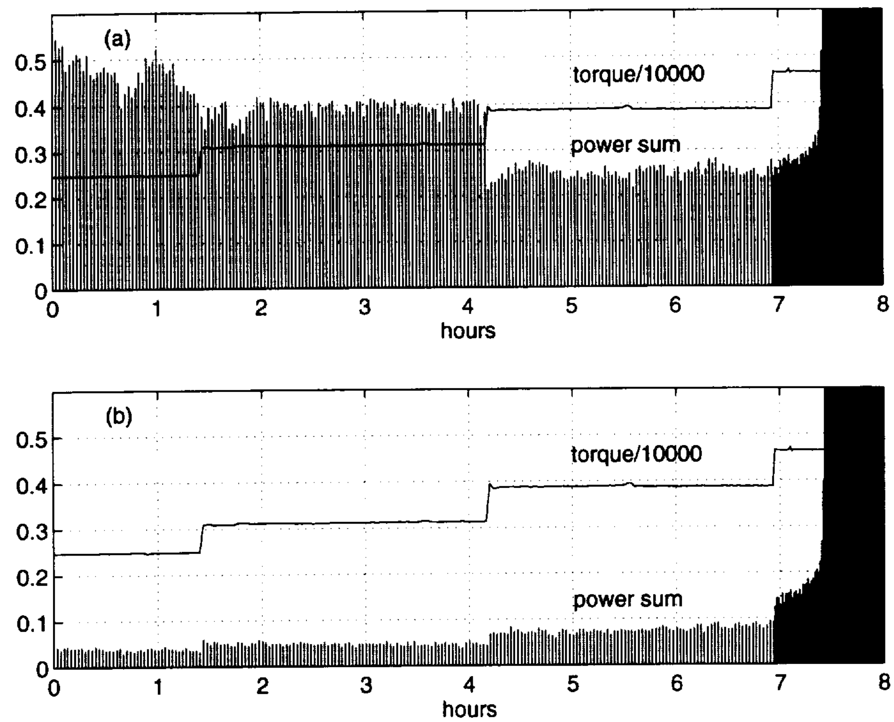

Figure 6. OH-58A test results, power-sum versus time; (a) 2.0 kHz cutoff, (b) 1.5 kHz cutoff.

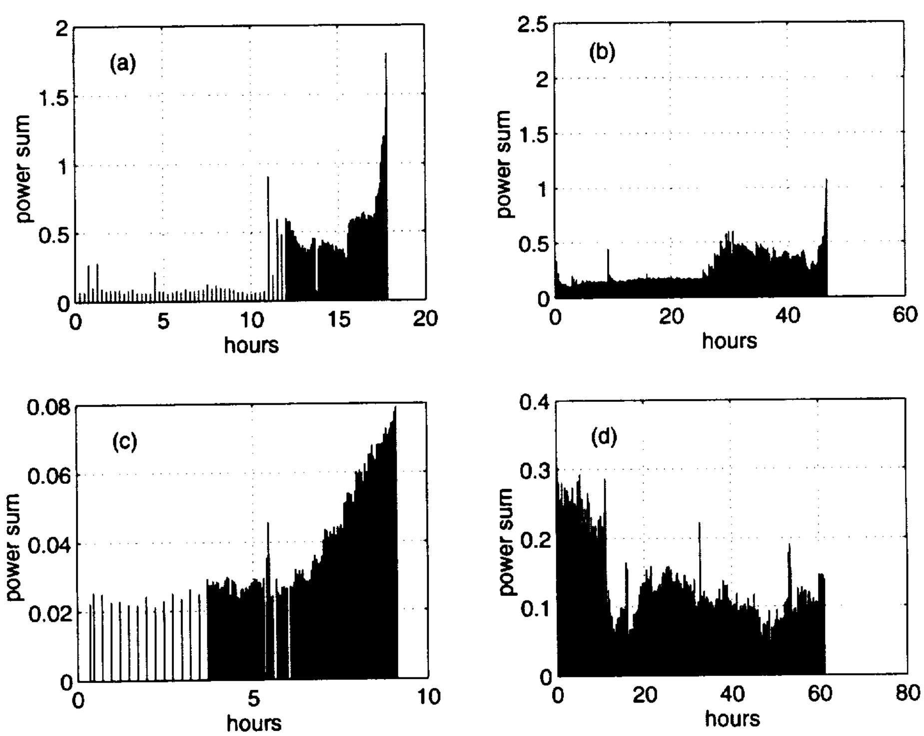

Figure 7. LeRC face gear test results, power-sum versus time; (a) run #1, (b) run #2, (c) run #3, (d) run #4.

Conclusions

A method was developed to detect gear tooth damage that does not require a priori knowledge of the frequency characteristic of the fault. The method monitors the energy in a frequency interval which excludes the normal tooth load fluctuations. The basic idea behind the method is that a few damaged teeth will cause transient load fluctuations unlike the normal tooth load fluctuations, and that the significant transient load fluctuations will be observed at a lower frequency than the frequency of the normal tooth load fluctuations. The sum of the monitored energy provides an estimate of the anomalous amplitude modulation in the signal caused by the transient load fluctuations. The method reacted significantly to the tooth fracture damage results documented in the Lewis data sets which were obtained from tests of high contact ratio face gears and tests of the OH-58A transmission. For all four of the face gear runs, the method reacted significantly as opposed to other reported methods which only reacted significantly to three out of four of the runs.

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13. ABSTRACT *(Maximum 200 words)*

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