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Transmission Diagnostic Research at NASA Lewis Research Center

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TRANSMISSION DIAGNOSTIC RESEARCH AT NASA LEWIS RESEARCH CENTER

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SYNOPSIS: The NASA Lewis Research Center and the U.S. Army Research Laboratory are involved in a joint research program to advance the technology of aerospace transmissions. Within the last six years, a transmission diagnostics research team was formed to address current and future technology barriers in transmission diagnostics. The diagnostics team conducted a survey to determine critical needs of the diagnostics community. Survey results indicated that experimental verification of gear and bearing fault detection methods and damage magnitude assessment were considered the two most critical research areas of a highly reliable health and usage monitoring system. A plan was implemented by the diagnostics team to address these key research areas, by in-house research and university grants. A variety of transmission fault detection methods were applied to experimentally obtained fatigue data. Failure modes of the fatigue tests include a variety of gear pitting failures, tooth wear, tooth fracture, and bearing spalling failures. Accomplishments to date include verification of several specific gear diagnostic methods, verification of a new pattern recognition method to determine failure, and development of a new method to model gear tooth damage. This paper presents the results of these accomplishments in transmission diagnostics research at NASA Lewis Research Center.

1 INTRODUCTION

Transmission diagnostics is becoming an increasingly important area of research within the rotorcraft community as transmission fault related accidents and fleet groundings continue to plague helicopters at an increasing rate. An investigation of serious rotorcraft accidents that were a result of fatigue failures showed that 32 percent were due to engine and transmission components (Astridge, 1989). In addition, government aviation authorities are demanding that the safety record of civil helicopters must match that of conventional fixed-wing turbojet aircraft in the near future. Practically, this can only be accomplished with the aid of a highly reliable, on-line Health and Usage Monitoring (HUM) system. Although a variety of organizations are working in this area, only a few are working on the development and experimental verification of the basic elements of a HUM system. As a result, a HUM research team was formed to address current and future technology barriers in transmission diagnostics by utilizing the unique experimental facilities at NASA Lewis Research Center.

In 1990, the HUM research team conducted a survey to determine the critical needs of the diagnostics community. Participants of the survey included key personnel in U.S. industry and government agencies who work in or have direct influence on transmission diagnostics. In the survey the participants were asked to rate the need of a number of proposed research areas. Each of the research areas were rated individually as either critically needed, moderately needed, or not needed in the overall effort of developing a highly reliable HUM system. Results of the survey are presented in table 1. As seen in the table, verification of current, state-of-the-art, gear and bearing diagnostic methods, along with damage level assessment were deemed critical to the development of a highly reliable HUM system by a large majority of participants. To address these key areas, the HUM team initiated a number of research efforts that use the gear fatigue test rigs at NASA Lewis for experimental verification.

One research effort involved applying a number of state-of-the-art and newly developed gear fault detection techniques to vibration data from spur gear, spiral bevel gear, and face gear fatigue tests to verify and compare the techniques. A number of fault detection methods were investigated, including methods FM4, NA4*, and NB4*. FM4, an isolated fault detection parameter, is a widely referenced time domain discriminant method for gear fault detection (Stewart, 1977). NA4* and NB4* are methods developed at NASA Lewis to provide early detection of gear tooth damage and to continue to react to the damage as it spreads and grows in severity (Zakrajsek, 1993, 1994; Decker, 1994).

A second research effort resulted in the development and verification of a general fault detection technique (Chin, 1993). This new pattern classification technique was applied to experimental data from NASA's 500 Hp helicopter transmission test rig in which a variety of gear and bearing failures were recorded. This method is similar to a neural network. However, unlike a neural network, it requires only a minimum amount of training.

A third research effort involved the development of an analytical procedure to predict the vibration of gear systems with gear tooth wear or fatigue damage present (Choy, 1994). Analytical predictions from this model were compared to experimental results from the spiral bevel gear fatigue tests.

This paper reviews the work performed at NASA Lewis Research Center in the research efforts described above. Sample experimental results along with recent accomplishments in the various areas are presented.

2 TEST APPARATUS AND SAMPLE RESULTS

The experimental data used to verify the various fault detection methods was obtained using a number of test rigs at NASA Lewis Research Center. These rigs are: the spur gear fatigue rig, the spiral bevel / face gear fatigue rigs, and the 500 Hp transmission test rig. The primary purpose of these rigs is not for diagnostic studies. However, due to the nature of the tests being conducted on them, these rigs have become a valuable source of data for transmission diagnostics research. A short description of each rig, along with an example of the resulting experimental data obtained on each rig is given in the following paragraphs.

There are a total of four spur gear fatigue test rigs that have been operational since 1972. The primary purpose of these rigs is to study the effects of gear materials, gear surface treatments, and lubrication types on the surface fatigue strength of aircraft quality gears. The test gears are run offset to maximize contact stress while maintaining an acceptable bending stress. Vibration data from an accelerometer mounted on a bearing end plate was captured on a personal computer with an analog to digital conversion board. The test gears are standard spur gears having 28 teeth and a pitch diameter of 88.9 mm (3.50 in.). The gears were loaded to 74.6 Nm (660 in-lb) at an operating speed of 10 000 rpm. Figure 1a shows a sample of the heavy pitting damage found on a gear tooth surface at the end of a test on the spur gear rig. A total of five tests on this rig were monitored and recorded for gear diagnostics research. The primary mode of failure on all five tests was surface pitting, ranging from light and moderate pitting on a single tooth to heavy pitting and spalling over a majority of the gear tooth surface on a number of teeth.

A spiral bevel gear rig has been dedicated to fatigue testing over the last three years. The primary purpose of this rig is to study the effects of gear tooth design, gear materials, and lubrication types on the fatigue strength of aircraft quality spiral bevel gears. The use of this fatigue rig for diagnostic studies is extremely relevant, since spiral bevel gears are used extensively in helicopter transmissions to transfer power between intersecting shafts. Vibration data from an accelerometer mounted on the pinion shaft bearing housing was captured using a personal computer with an analog to digital conversion board. The 12-tooth test pinion, and 36-tooth gear have a 25.4 mm (1 inch) face width, and a 90 degree shaft angle. The pinion transmits 537 kW (720 Hp), at a nominal speed of 14 400 rpm. Two complete fatigue tests were recorded and documented on this rig. Figure 1b illustrates the damage on the pinion at three distinct times during the first fatigue test. As seen in figure 1b-i, a small pit was first seen on the pinion when the rig was shut down at 5.5 hours. The damage spread to cover more than 75% of the tooth at 12 hours, as seen in figure 1b-ii. At the end of the test, 17.79 hours into the run, the damage covered the majority of three adjacent teeth, with one tooth experiencing a partial tooth fracture, as seen in figure 1b-iii. The second fatigue test exhibited a similar failure pattern, with damage starting with a small pit on one tooth, growing to extensive pitting damage over five consecutive teeth on the pinion.

A spiral bevel rig, similar to the one described above, was also used to run face gear fatigue tests. The application of face gears to aircraft transmissions is part of an advanced rotorcraft transmission technology program. Face gears had never been tested at high speeds and high loads. The primary objectives of the face gear fatigue tests were to determine the load capacity and the primary failure mechanism for this type of gear. A standard 28 tooth spur gear drives the 107 tooth face gear at 19 107 rpm with 67.8 Nm (600 in-lb) of torque. 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. Again, vibration data from an accelerometer mounted on the pinion shaft bearing housing was captured using a personal computer. A total of four face gear fatigue tests were monitored and recorded for gear diagnostics research. Tooth fracture and gear tooth surface pitting were the primary failure modes for all four tests. The damage ranged from pitting with partial tooth breakage on one test to severe pitting with complete tooth fracture of several teeth, as illustrated in figure 1c.

NASA Lewis has two full scale helicopter transmission test stands, one of which is the 500 Hp transmission test facility. The primary purpose of this rig is to perform basic research on a complete helicopter transmission system. The five tests performed on this rig, listed in table 2, were part of a joint NASA/Army/Navy advanced lubricants research program (Lewicki, 1992). The main objective of this program was to determine the relative effects of various transmission lubricants on the failure of critical components. An OH-58 helicopter main rotor transmission gearbox was used in this test. Vibration signals from a number of accelerometers along with oil samples were obtained throughout each test. As seen in table 2, damage in the tests ranged from micro-pitting on bearings to gear tooth spalls and heavy wear, and housing cover cracks.

3 GEAR FAULT DETECTION METHODS RESEARCH

A number of previously published and newly developed methods to specifically detect damage on gear teeth were applied to vibration data from the spur gear, spiral bevel gear, and face gear fatigue tests. The primary purpose was to verify the various methods with naturally occurring faults and to determine their relative performance. Of the various techniques investigated, only methods FM4, NA4*, and NB4* responded to gear damage on a relatively consistent basis over the various gear types and failure modes (Zakrajsek, 1994, 1993). Some basic theory behind these three methods along with an overview of the results obtained using each of these methods are given below.

Method FM4 was developed to detect changes in the vibration pattern resulting from damage on a limited number of teeth (Stewart, 1977). 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 original signal. FM4 is obtained by calculating the fourth normalized statistical moment (normalized kurtosis) of this difference signal. For a gear in good condition, the difference signal would be primarily Gaussian noise, resulting in a FM4 value of 3 (nondimensional). 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. FM4 will react by increasing to a value above the nominal value of three. Example results of method FM4 are given in figure 2. As seen in this figure, FM4 responded to the pitting damage in spur gear test #2 (figure 2a), and the pitting and multiple tooth fracture damage in face gear test #5 (figure 2c). FM4 gave relatively consistent results by detecting the damage in a majority of the spur gear and face gear fatigue tests. FM4 did not react to light pitting damage on a spur gear test nor to a partial tooth fracture on a face gear test. FM4 also did not give a consistent response to the start and progression of pitting damage in the first spiral bevel fatigue test, as seen in figure 2b. The inconsistencies could be due to unexpected speed and load changes experienced during the first spiral bevel test. FM4 did respond to the pitting damage on the second spiral bevel fatigue test.

NA4* is a method recently developed at NASA Lewis to not only detect the onset of damage, but also to continue to react to the damage as it increases (Zakrajsek 1994, 1993; Decker, 1994). A residual signal is first constructed by removing regular meshing components from the signal (shaft frequency and harmonics, primary meshing frequency and harmonics). The fourth statistical moment of the residual signal is then divided by the square of the average variance of the residual signal. The average variance is the mean value of the variance of all previous data records in the run ensemble. In addition, the average variance is "locked" when the instantaneous variance exceeds predetermined statistical limits. With this method, the changes in the residual signal are constantly being compared to a weighted baseline of the specific system under nominal, or "no fault" conditions. NA4* is dimensionless, and as with FM4, gives a value of 3 under nominal conditions. Typical results of method NA4* are shown in figure 3. As seen in this figure, NA4* reacted to and increased with the growing pitting damage found in both spur gear test #2 (figure 3a) and in the first spiral bevel gear fatigue test (figure 3b). NA4* also reacted to the heavy wear in face gear test #5, and had a dramatic response to the fractured teeth at the end of the test (figure 3c). Overall, NA4* detected damage on a majority of the spur gear tests and on all of the face gear and spiral bevel gear tests. NA4* gave a delayed reaction to moderate pitting damage in one spur gear test. NA4* reacts to a variety of gear damage modes ranging from minor gear damage on a single tooth, to major damage over a number of teeth. NA4* also exhibits the ability to increase with progressing gear damage, as seen in figure 3. NA4* is, however, sensitive to speed and load changes, as illustrated by the speed and load induced spikes experienced during the first spiral bevel fatigue test, figure 3b.

NB4* is a method developed at NASA Lewis to give a more robust indication of gear tooth damage (Zakrajsek, 1994). NB4* uses the envelope of the signal bandpassed about the dominant meshing frequency. A complex time signal is created in which the real part is the band-passed 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 transient variations in the loading. The basic 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 in the signal. Similar to the development of NA4*, NB4* is found by calculating the fourth statistical moment of the envelope, and then dividing it by the average variance of the envelope, raised to the second power. With NB4*, the changes in the envelope are constantly being compared to a weighted baseline of the specific system under nominal, or “no fault” conditions. NB4* is dimensionless with a value of 3 under nominal conditions. Typical results of method NB4* are shown in figure 4. Overall, NB4* gave strong reactions to the detected damage on a majority of the tests. This is especially illustrated in figure 4c, where NB4* increases from a nominal value of 3 to a value of 320 when two teeth broke off in face gear test #5. NB4* does, in some instances, fail to maintain a warning level, even as the damage is present and in some cases increasing. This can be observed in NB4*'s decrease to nominal conditions after detecting damage in spur gear run #2 (figure 4a), and in the first spiral bevel gear fatigue test (figure 4b).

4 GENERAL FAULT DETECTION METHOD RESEARCH

A new pattern classification method was developed as an alternative to single-parameter based diagnosis (Chin, 1993). This method is not specific to one element in a transmission, as with the gear fault detection methods. The new technique uses an array of post processed parameters to detect and identify a failure. It is similar to an artificial neural net, in that it also uses non-parametric pattern classification in its model. Thus it is independent of the probabalistic structure of the system. Unlike a neural net, however, this new method does not require an extensive amount of training to minimize false alarms and undetected faults. The new method uses a vector of processed measurements that are converted to binary numbers through a flagging operation. The flagging operation is used to detect the existence of a fault. When a fault is detected the vector of binary measurements, or flagged vector, is analyzed through a diagnostic model that produces a resulting fault vector. This fault vector is a ranking of the possible faults according to their probability of occurrence. The diagnostic model utilizes a multi-valued influence matrix (MVIM), which represents a variety of fault conditions, for comparison with the flagged vector in order to determine fault probabilities.

The new pattern classification method was applied to experimental data from the five tests conducted on the 500 Hp transmission test rig, as listed in table 2. As seen in the table, damage in the test ranged from micro-pitting on bearings to gear tooth spalls and heavy wear, and housing cover cracks. A standard neural network was also applied to the same data for comparison. The vibration data was digitized and processed using a commercial system to produce the input data for the pattern classifier and neural network. A total of eighteen test cases, representing different combinations of the five experimental tests were used for training data sets. The new pattern classification method outperformed the neural net in a majority of the test cases, with fewer undetected faults and false alarms. As shown in table 3, on average the new pattern classification method produces less false alarms, and only half as much undetected faults as a standard neural net.

5 GEAR TOOTH DAMAGE MODELING RESEARCH

An analytical modeling procedure was developed to address a key concern in diagnostics research. Verification of fault detection, diagnosis, and prognosis techniques require a substantial database covering a wide range of failure modes and damage levels. Unfortunately, only a limited amount of this type of data is currently available. In order to populate a comprehensive database of different damage types and magnitudes, an analytical procedure was developed to predict vibrations in a gear transmission system with gear tooth wear and fatigue damage present (Choy, 1994).

The analytical procedure couples a gear tooth damage model with a previously developed global dynamic model (Choy, 1993). To numerically simulate extensive pitting damage, a combination of phase shift and amplitude changes are introduced into the gear mesh stiffness model. Additional friction effects are also added to the model to simulate the roughness of the tooth surface due to pitting. The effects of these localized changes in the gear mesh are incorporated into each gear-rotor model for the dynamic simulation. The dynamics of each gear-rotor system are coupled with each other through the gear mesh interacting forces, and the bearing support forces provide the coupling between each rotor and the housing structure. The global vibrations of the system are evaluated by solving the transient dynamics of each rotor system simultaneously with the vibration of the housing. In order to minimize the computational effort, the number of degrees of freedom of the system are reduced by using a modal synthesis procedure.

Initial verification of the model was made by attempting to simulate the vibration resulting from the pinion damage in the first spiral bevel fatigue test. Figure 5 represents the actual vibration signature from the test at 12 hours into the test (figure 5a), where pitting damage is limited to one tooth (ref. figure 1b-ii), and at the end of the test (figure 5b), where pitting damage covers three teeth, one with a partial fracture (ref, figure 1b-iii). The vibration signature in figure 5 is represented in the time domain and frequency domain, and also in the joint time-frequency domain, using the Wigner-Ville Distribution method (Shin, 1993). The joint time-frequency domain gives a comprehensive representation of the vibration signal, and provides an interactive relationship between time and frequency within the signal, allowing for phase and other changes in the signal to be highlighted.

The analytical modeling procedure developed was used to simulate the vibration at the housing for the pinion damage at 12 hours, and at the end of the test. The heavily pitted tooth was simulated by a loss of stiffness at the first 20% of the tooth contacting period, coupled with an increase in sliding friction. The fractured tooth at the end of the test was modeled by a 50% loss in mesh stiffness through the contact period of that tooth. Results of the simulated vibration for the single tooth damage at 12 hours, and the multiple tooth damage at the end of the test are given in figure 6a and 6b, respectively. A good correlation between simulated and actual vibration can be seen by comparing the results in figure 6 to those in figure 5. The single tooth damage is clearly seen in both figures 5a and 6a, and the tooth breakage at the end of the test is displayed by the large cross pattern in both the simulated and actual vibration signals (figures 5b and 6b).

6 CONCLUDING REMARKS

This paper reviewed recent activities in transmission diagnostics research at NASA Lewis Research Center that were performed in-house, and through NASA and U.S. Army sponsored grants. Accomplishments of these activities are summarized below.

Out of the gear fault detection techniques investigated, the methods FM4, NA4*, and NB4* were found to give the most reliable indications of gear tooth damage present for a number of different gear types and a variety of gear failure modes. In addition, the method NA4* responds better to damage progression than the other two parameters.

The new pattern classification method (multi-valued influence matrix) exhibited better results in detecting general transmission faults than a standard neural network algorithm, even when using simple post processing parameters as input.

An analytical method was developed to predict the dynamics of a gear transmission system with simulated gear tooth damage present. A preliminary study showed predicted results to be in good agreement with experimental results.

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TABLE 1.—1990 DIAGNOSTICS SURVEY RESULTS

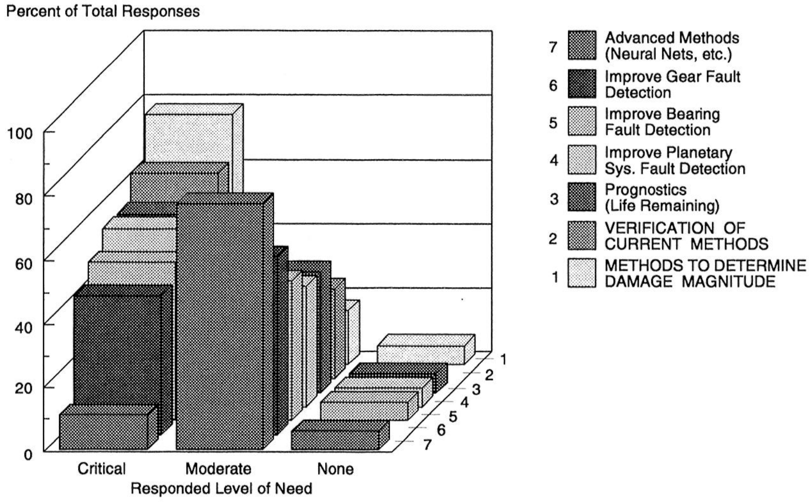

TABLE 2.—SUMMARY OF COMPONENT FAILURES FOR FIVE TESTS CONDUCTED ON 500 HP TRANSMISSION TEST RIG

Test	Failure
1	Sun gear tooth spall. Spiral bevel pinion scoring/heavy wear.
2	None
3	Planet bearing inner race spall. Top cover housing crack. Planet bearing inner race spall. Micropitting on mast bearing.
4	Planet bearing inner race spall. Sun gear tooth pit.
5	Sun gear teeth spalls. Planet gear tooth spall. Top housing cover crack.

TABLE 3.—COMPARISON OF AVERAGE RESULTS OF MULTI-VALUED INFLUENCE MATRIX METHOD (MVIM) TO A NEURAL NETWORK

Diagnostic method	Undetected faults	False alarms	Total average test errors
Neural net	1.8	0.9	2.7
MVIM	0.9	0.7	1.6

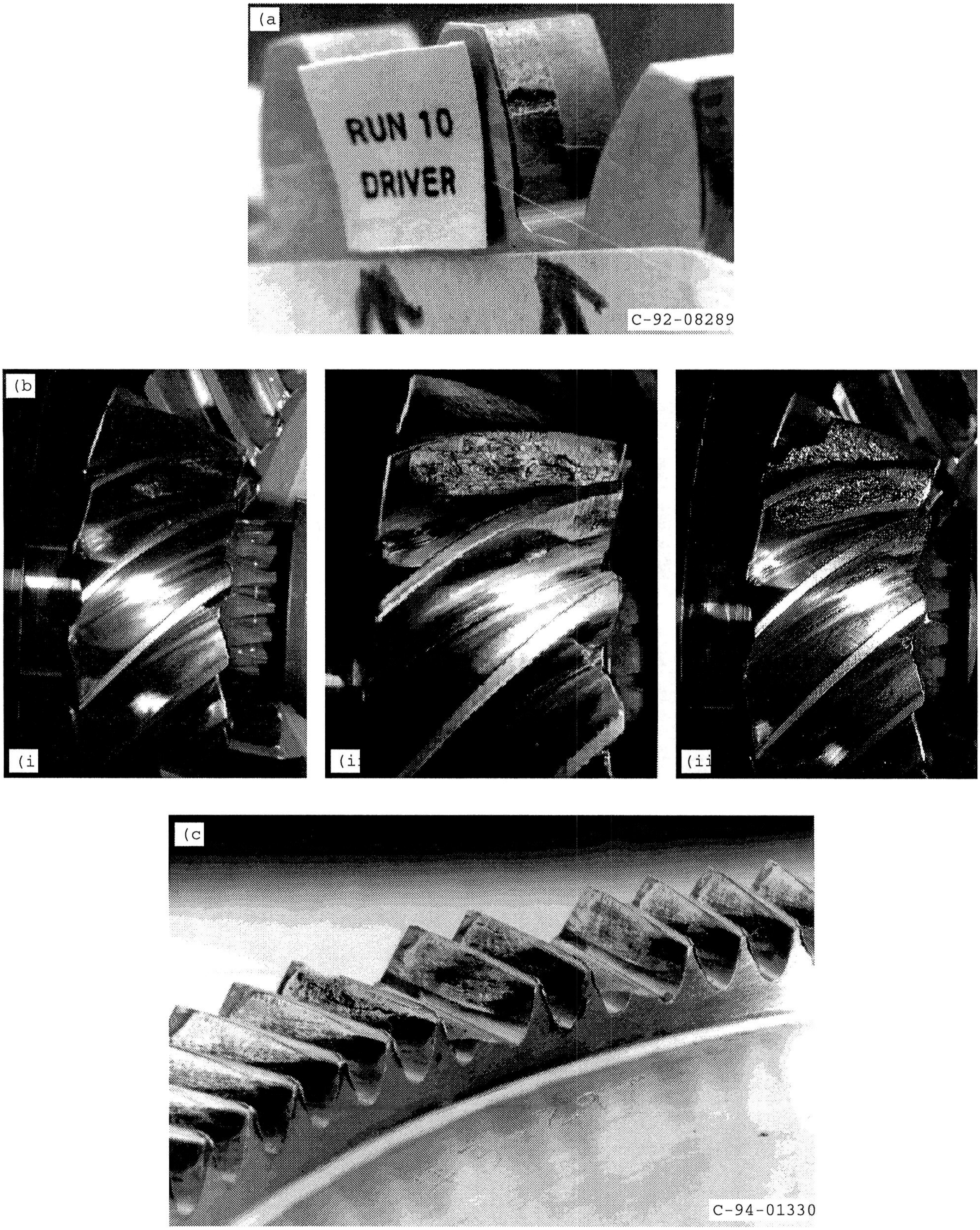

Figure 1.—(a) Sample of pitting damage on spur gears (spur gear test #2). (b) Spiral pinion damage during spiral bevel fatigue test #1. (i) At t = 5.5 hr. (ii) At t = 12.0 hr. (iii) At t = 17.79 tooth fracture damage on face gears (face gear test #5).

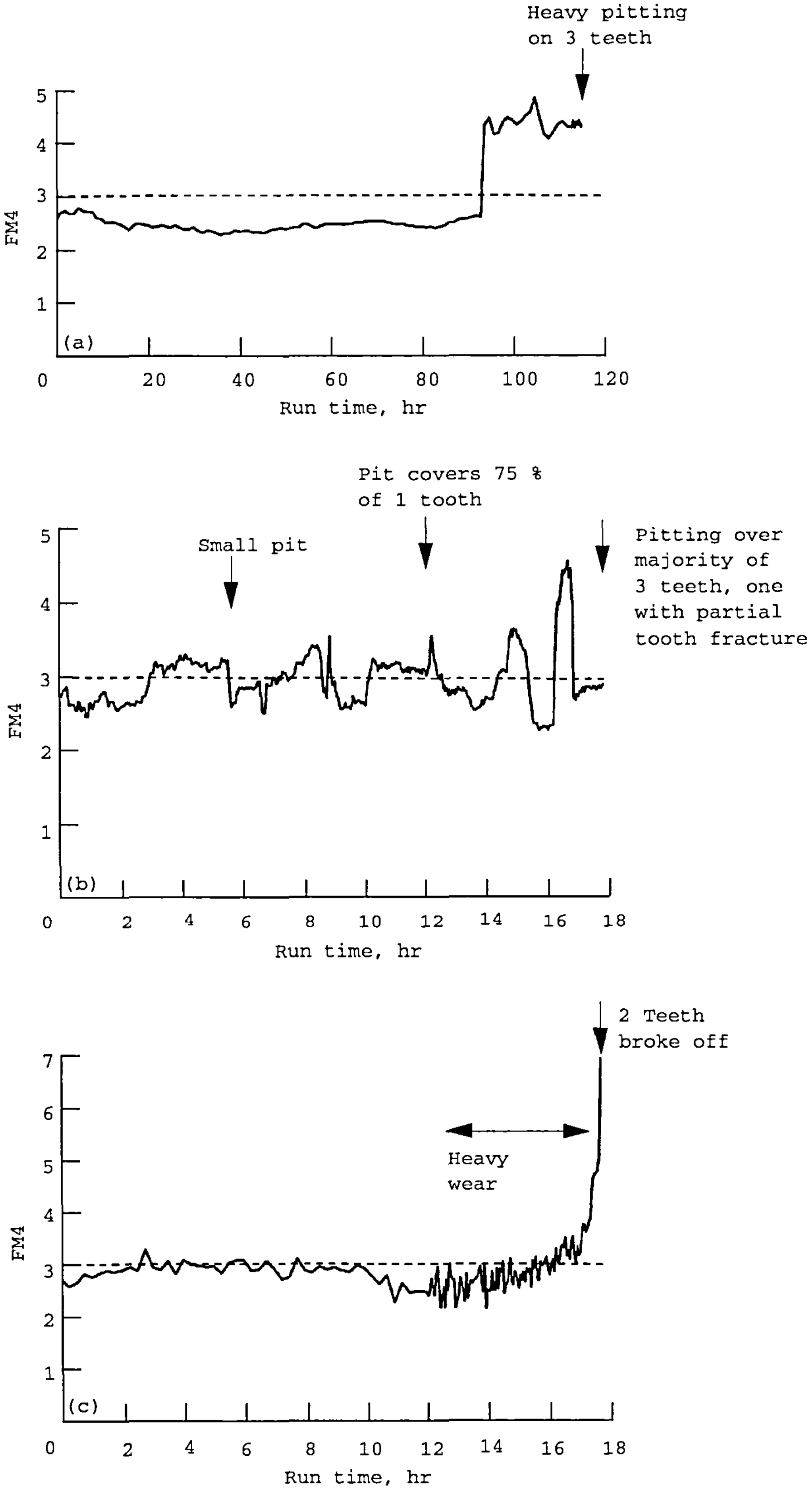

Figure 2.–Example results of method FM4. (a) Spur gear test #2. (b) Spiral bevel gear test #1. (c) Face gear test #5.

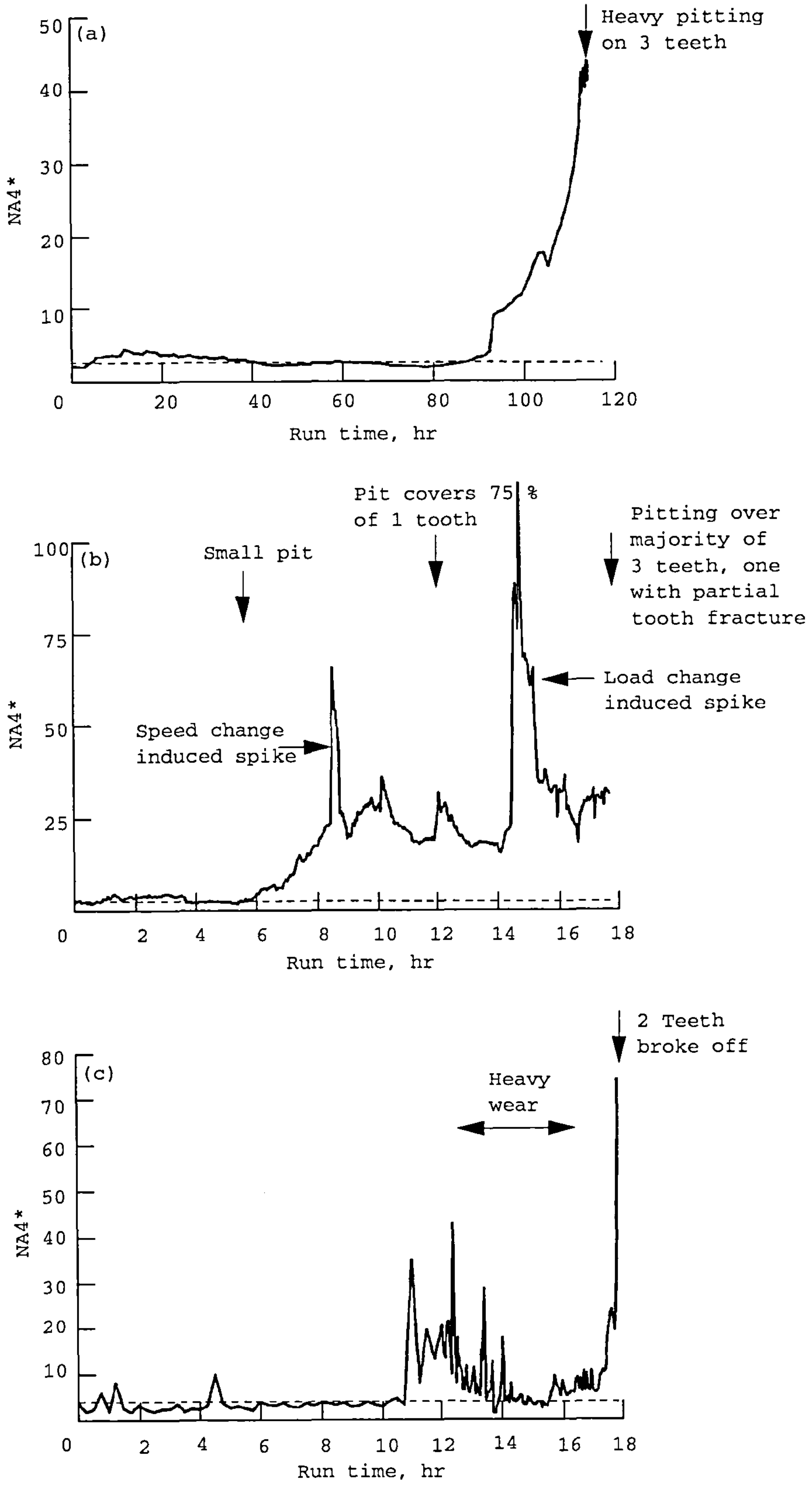

Figure 3.—Example results of method NA4*. (a) Spur gear test #2. (b) Spiral bevel gear test #1. (c) Face gear test #5.

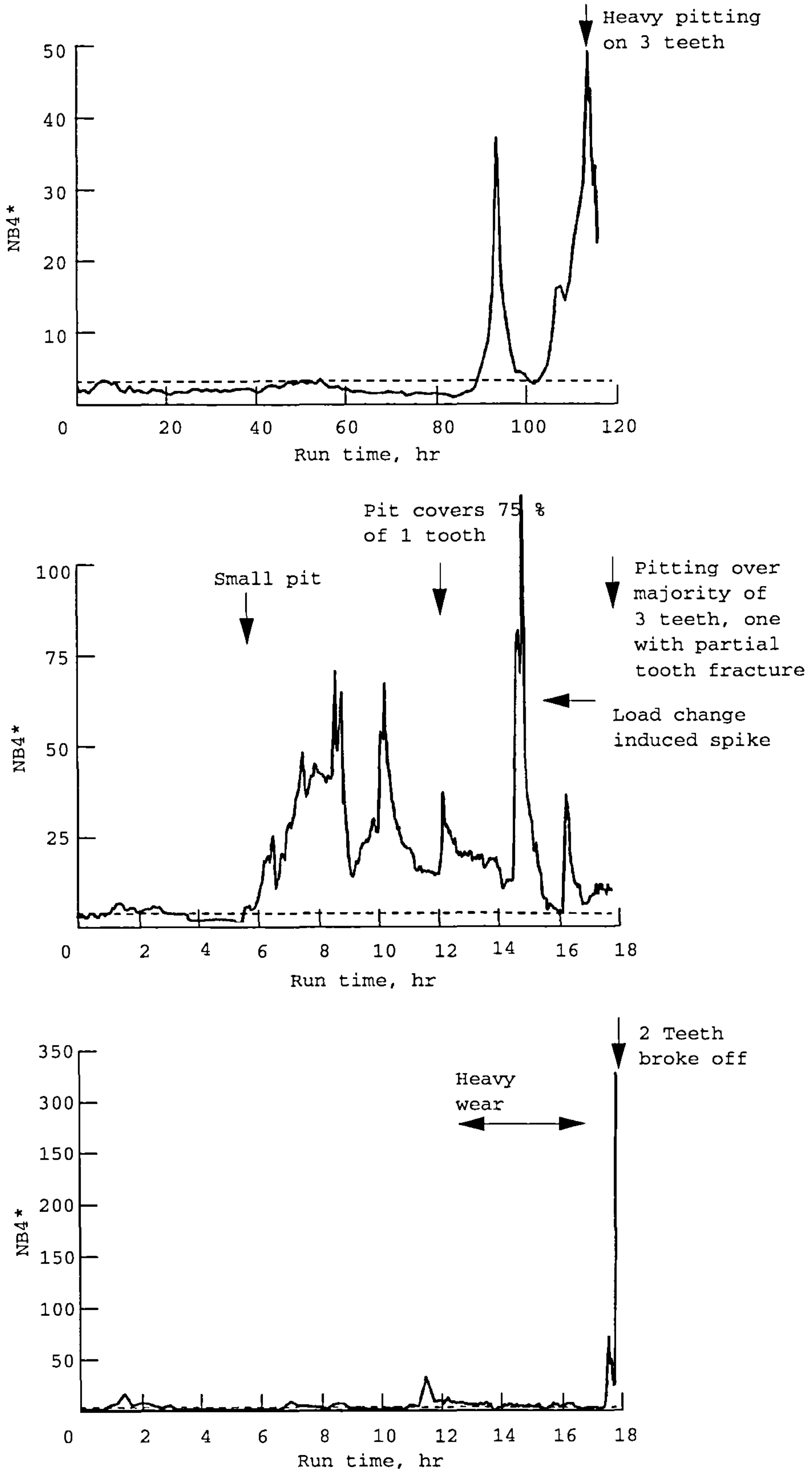

Figure 4.–Example results of method NB4*. (a) Spur gear test #2. (b) Spiral bevel gear test. #1. (c) Face gear test #5.

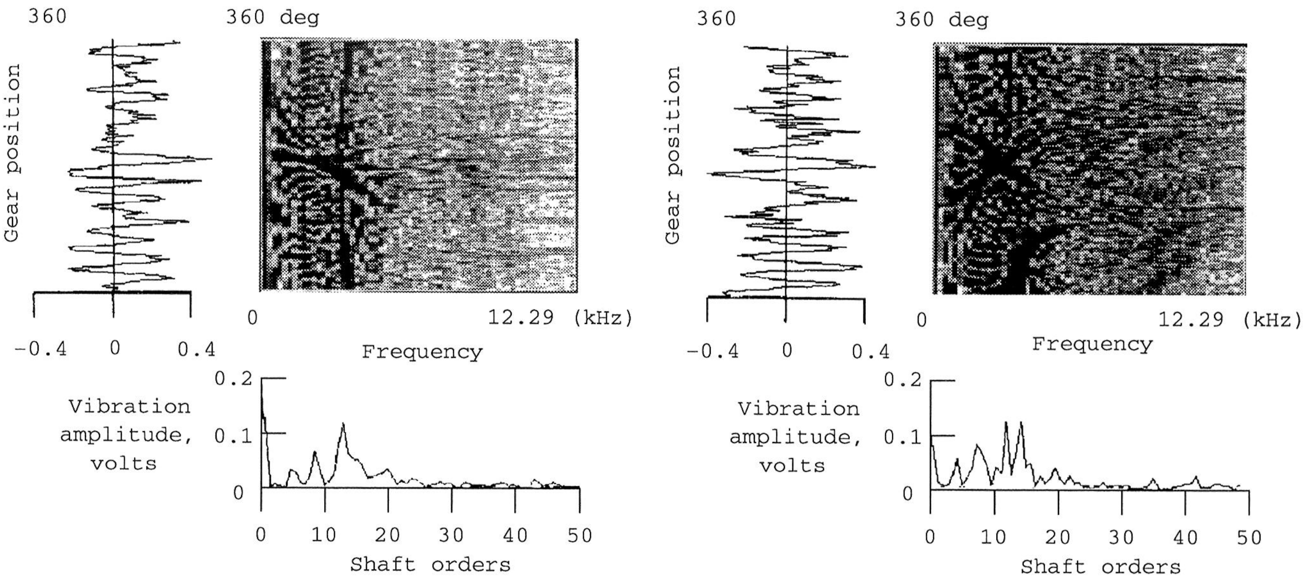

Figure 5.—Experimentally obtained pinion vibration signature due to tooth wear and pitting damage (fatigue test #1). (a) Single tooth, (12 hr). (b) Three teeth (17.79 hr).

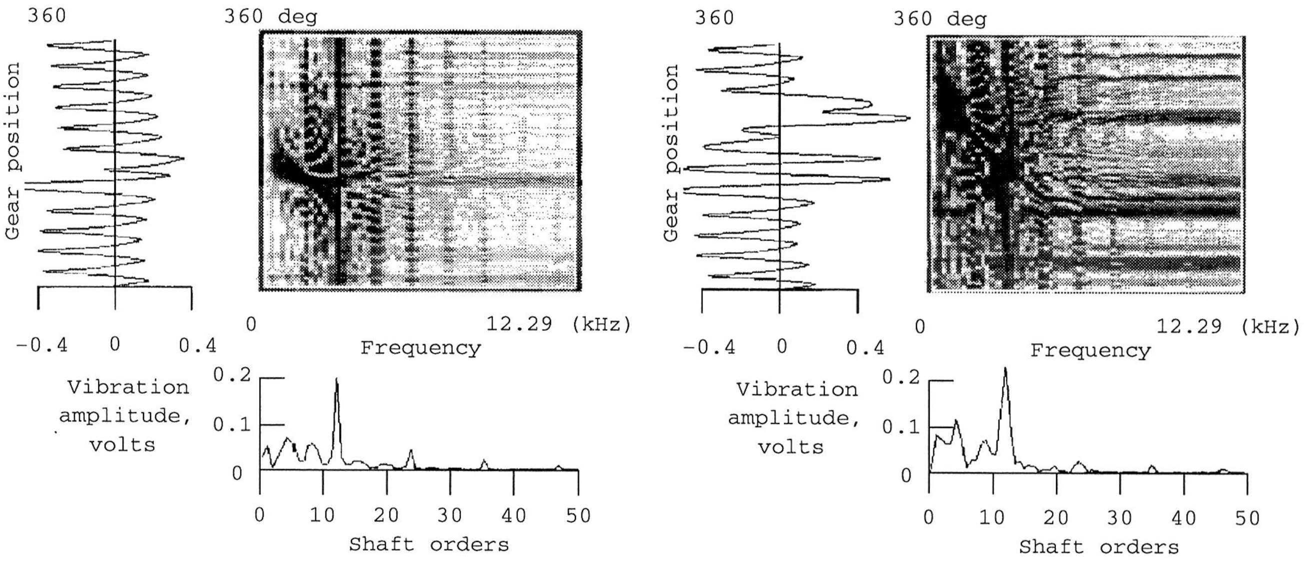

Figure 6.—Numerically simulated pinion vibration signature due to tooth wear and pitting damage. ((b) Three teeth.

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13. ABSTRACT ***(Maximum 200 words)***

The NASA Lewis Research Center and the U.S. Army Research Laboratory are involved in a joint research program to advance the technology of aerospace trans-missions. Within the last six years, a transmission diagnostics research team was formed to address current and future technology barriers in transmission diagnostics. The diagnostics team conducted a survey to determine critical needs of the diagnostics community. Survey results indicated that experimental verification of gear and bearing fault detection methods and damage magnitude assessment were considered the two most critical research areas of a highly reliable health and usage monitoring system. A plan was implemented by the diagnostics team to address these key research areas, by in-house research and university grants. A variety of transmission fault detection methods were applied to experimentally obtained fatigue data. Failure modes of the fatigue tests include a variety of gear pitting failures, tooth wear, tooth fracture, and bearing spalling failures. Accomplishments to date include verification of several specific gear diagnostic methods, verification of a new pattern recognition method to determine failure, and development of a new method to model gear tooth damage. This paper presents the results of these accomplishments in transmission diagnostics research at NASA Lewis Research Center.

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