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TURBOMACHINERY INCIPIENT FAILURE DETECTION INDICATORS AND ANALYSIS

Prepared for:

National Aeronautice
& Space Administration
George C. Marshall
Space Flight Center

August 1985

SHAKER RESEARCH CORPORATION
968 Albany Shaker Road
Latham, New York 12110

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Tape recorded signals from case-mounted accelerometers are examined to determine the feasibility of detecting spalls on bearing balls in the liquid oxygen (LOX) pump in the Space Shuttle Main Engine (SSME). The nonperiodic nature of the spall impact on inner and outer bearing races caused traditional techniques to be unsuccessful. A technique involving statistical techniques and spectra ratios was used to review available pump test tapes.

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LIST OF FIGURES

1.0 INTRODUCTION

The purpose of the work described in this report was to review several NASA supplied data tapes using a previously developed Incipient Failure Detection (IFD) technique. The developed (IFD) technique was described thoroughly in a previous Shaker report (1), but a brief description is included herein for completeness. The (IFD) procedure was intended for use on the space shuttle liquid oxygen (LOX) turbine-pump bearings, and for general use on high-speed turbomachinery. The tape recorded data used during the study was originally taken from a series of LOX pump tests performed on a rocket engine by NASA-MSFC engineers. The tape library used in the present study consisted of fourteen tapes each with 300 seconds of recorded information. Each tape had fourteen channels of information taken from a variety of test sensors.

Machinery component degradation and ultimate failures have been explored in the past for a characterization of the failure onset mechanisms and their detection. Analysis schemes which have provided meaningful failure prevention signals on some occasions may not have proven effective on another. Success of an Incipient Failure Detection (IFD) technique in a given application can depend upon many factors. The technique itself may be viable but the environment to which it is applied may not be suited to the selected scheme of detection. In addition, a known environment may not lend itself simply to any previously applied detection schemes, and new concepts may have to be applied in order to provide adequate system protection.

A potential method for extracting asynchronous vibratory failure information was identified by Shaker Research in a previous contract with NASA. Traditional methods of signal extraction had not been effective since most of these schemes rely upon the long term presence of repetitive signals. The character of the intermittent ball defect signal was more like noise than it was like a stationary failure signal, and consequently was averaged out of the data by tradition approaches. A statistical technique was developed during the previous project that made use of the ratio of two typical methods of data analysis. The identified method of ratioing showed promise of being able to detect incipient degradation of rolling element bearing components.

This report presents the efforts involved in surveying a set of available (LOX) pump tape data with the new failure detection concept. Results are presented for sensor locations near the failed bearing, as well as, on the outer housing of the turbine-pump structure.

2.0 BACKGROUND

Because of the reusability concept of the space shuttle program, monitoring and diagnosis of impending mechanical failure are important aspects to NASA. The project reported herein investigated diagnostic techniques that would allow the identification of impending failure of the space shuttle main engine (SSME) liquid oxygen (LOX) pump turbine-end bearing.

Available data in a previous Shaker contract included vibration, acceleration, pressures and temperatures measured and recorded during rocket engine tests. Three data recordings of the Challenger's SSME test series were made available to SRC. The first tape, ID #901-339, was recorded early in the test series and was thought to contain data representative of "good" bearing operation. Tape ID #901-340 was recorded mid series and was thought to contain data of "broken in" components, while the last tape of the series, ID #901-352, was thought to have been recorded with a spalled ball in the turbine-end bearing.

The recorded data included accelerometers which were mounted on the outer casing flange of the pump as depicted in Figure 1. Ideally, sensors should be located as close to the bearing as possible. In this case, however, the structural path between bearing and sensor was indirect and distant. The content of the recorded acceleration data was all low-frequency, less than 10 KHz. Traditionally, successful rolling element bearing analysis techniques have been made on data at 20 KHz and above. In addition the data contained high level pump and turbine blade pass frequencies which dominated the frequency spectrum and fell within the frequency range of the calculated rolling element defect frequencies. This provided a very low signal-to-noise ratio for the bearing related frequencies of interest. Because of these problems, it was questionable whether or not the tapes contained defect information and, if so, how was it to be unmasked from normal operating signals present.

Traditional vibration analysis techniques were ineffective due to the nonperiodic nature of the defect signal (spalled balls). These techniques could not sufficiently enhance the defect amplitudes in the presence of such signals as the blade passing signal.

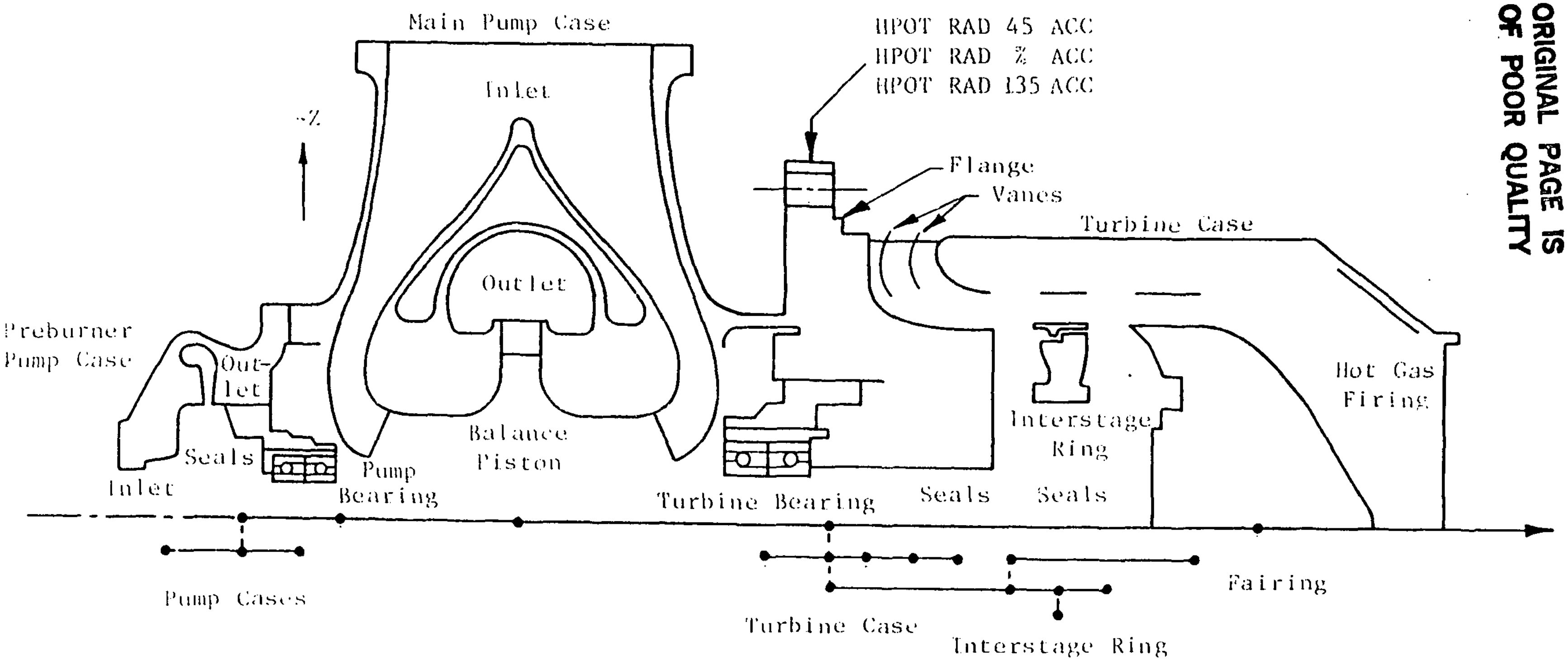

Fig. 1 Location of Accelerometers Sensing Turbine Bearing

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Section 3.0 of this report discusses in detail the application of a ratioing technique which showed some enhancement of the defect frequencies under such conditions. The technique used is statistically based and may have promise of application to high-speed turbomachinery in general.

3.0 DISCUSSION OF RESULTS

NASA provided several data tapes that were reviewed during the present study. Each tape contained approximately 300 seconds of data on each of fourteen channels provided for storage. Recorded signals were derived from internally mounted sensors, as well as, outer case mounted devices. Both strain gage and accelerometer type devices were used in generating the recorded vibrational information. Several reviews of the available data were made in order to establish the detectability of (or lack of) incipient failure signals. Signals were reviewed with the standard Nicolet spectrum analyzer, as well as, with the HP 5451C Fourier Analyzer System (shown in Figure 2). The details of the data tape review and the procedures developed for the detection of rolling element bearing component failure are contained in this section of the report.

3.1 Rolling Element Bearing Failures

Bearing failure detection can be represented schematically as a function of time by a plot similar to those shown in Figure 3. Although no single failure might follow the curve(s) shown it is known that bearings generally follow the trends displayed by the plot. Region one of Figure 3, portrays the tendency for new bearings to become "quieter" after a short period of break-in. This is normally attributed to the irregularities of construction being smoothed-out after a short period of running.

The second region of failure signal detection is schematically represented by the middle portion of the diagram. This represents the typical quiet period for the majority of a normal bearing's operating life. In practice this diagnositic signal is well below the typical failure warning level provided by conventional failure detection devices.

The third time block depicted in Figure 3, is the period of incipient failure found in most rolling element bearings. During this period the typical diagnostic signal increases steadily in strength until the bearing fails catastrophically. However, signals similar to that depicted by the dotted trace are occassionally observed. For example, the dotted trace shown could represent the effects of small chunks of metal being released from within the bearing.

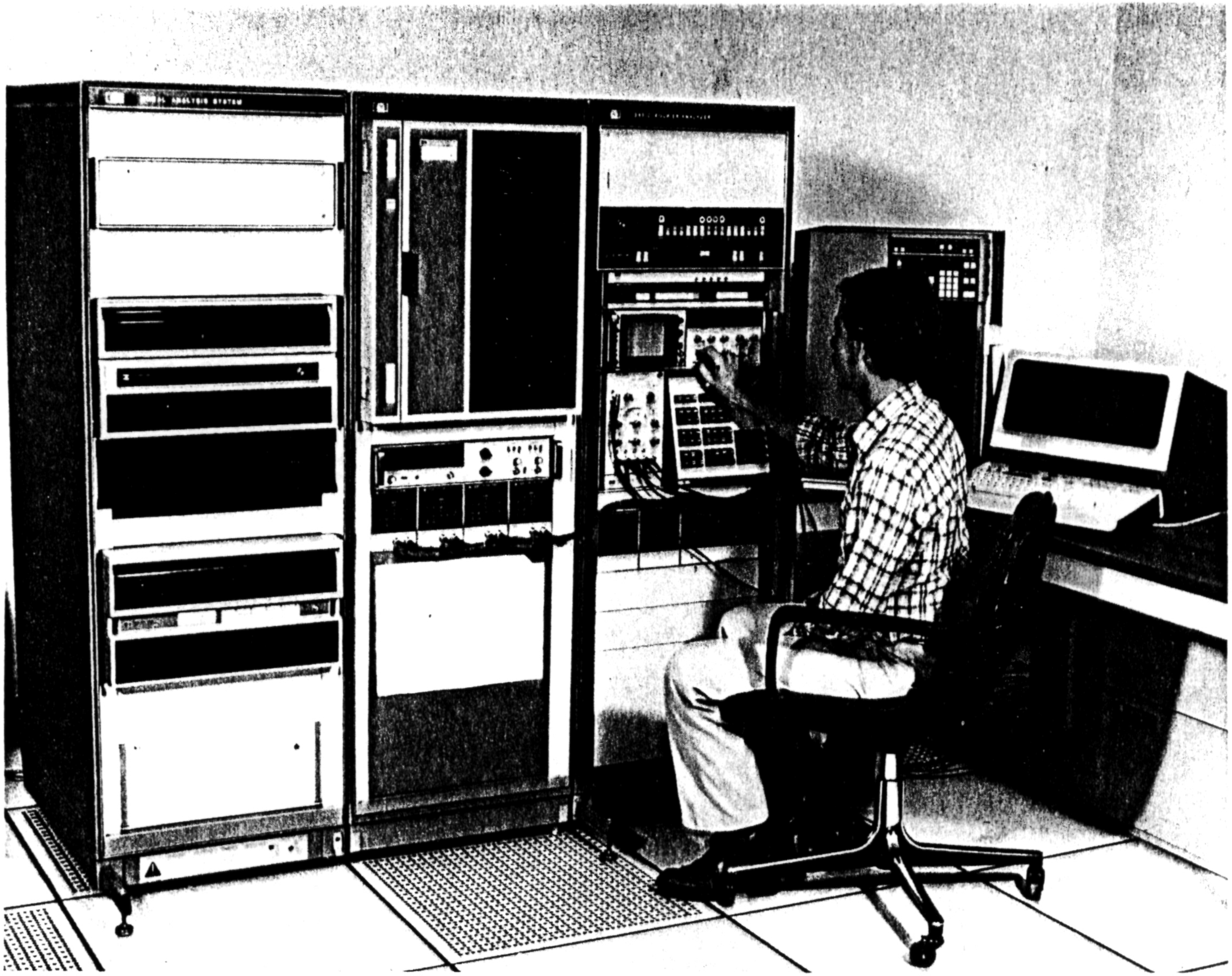

FIGURE 2 - SRC's HP 5451C Data Processing System

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FAILURE DETECTION SIGNALS FROM TYPICAL ROLLING ELEMENT BEARINGS

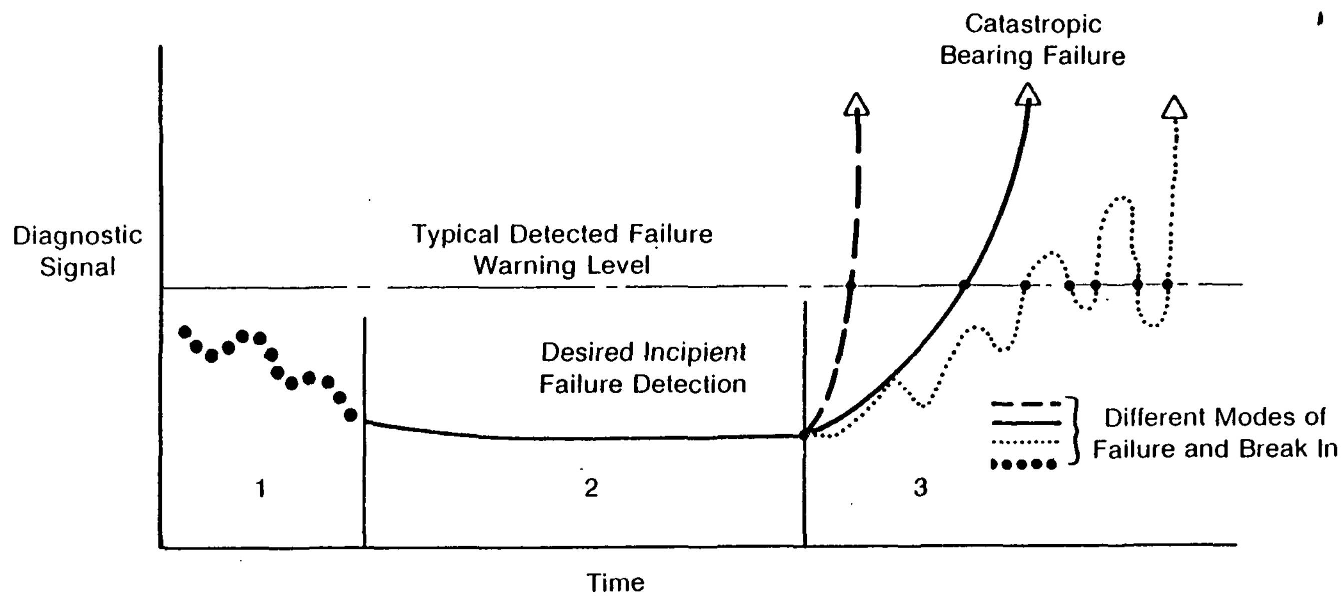

FIGURE 3 - Failure Detection Signals from Typical Rolling Element Bearings

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Initially, this release might result in a rise in the failure detection signal. The signals could quickly subside however, as the particles become worn or spread throughout the bearing (or thrown off to the side of it).

The goal of any successful incipient failure detection method is to determine the instant at which the bearing system has entered the third (see Figure 3) or final stage of its operating life. The sooner it is known that a bearing has entered its final stages of operability the sooner action can be taken to prevent catastrophic failure. Incipient failure signals might also be used for initiating system maintenance actions. Advance notice and change-out of critical component substructures could then insure future safe operation.

3.2 Review of Supplied Data Tapes

Appendix B contains a list of the data tapes supplied to Shaker for review with the developed analytical techniques. Both the conventional real time spectrum analyzer and the computerized HP 5451C Fourier analyzer were used in reviewing the tapes. The tapes reviewed contained signals which were mounted inside, as well as, outside the pump and turbine test fixture.

A typical analog spectra of the test data is shown in Figure 4. This is a multipass average of the available spectral information and contains an image of the engergy available in the 0-5000Hz band. A limited amount of information is available above the band shown.

Traditional failure analysis techniques would anticipate increases in the displayed spectrum amplitudes at the identified bearing component frequencies as these components began to fail. Normal bearing operation will usually result in slight variations of the spectral peaks even in steady-state operation. This time variation of peaks is depicted schematically in Figure 5, for a spectral peak which is shown passing from normal operation into abnormal operation. The selected spectral peak distribution has gone from a relatively low average to a higher value. This is indicative of the increased energy present at the frequency shown.

REAL TIME SPECTRUM SUM AVERAGE FROM THREE COMPLETE PASSES OVER TEST TAPE

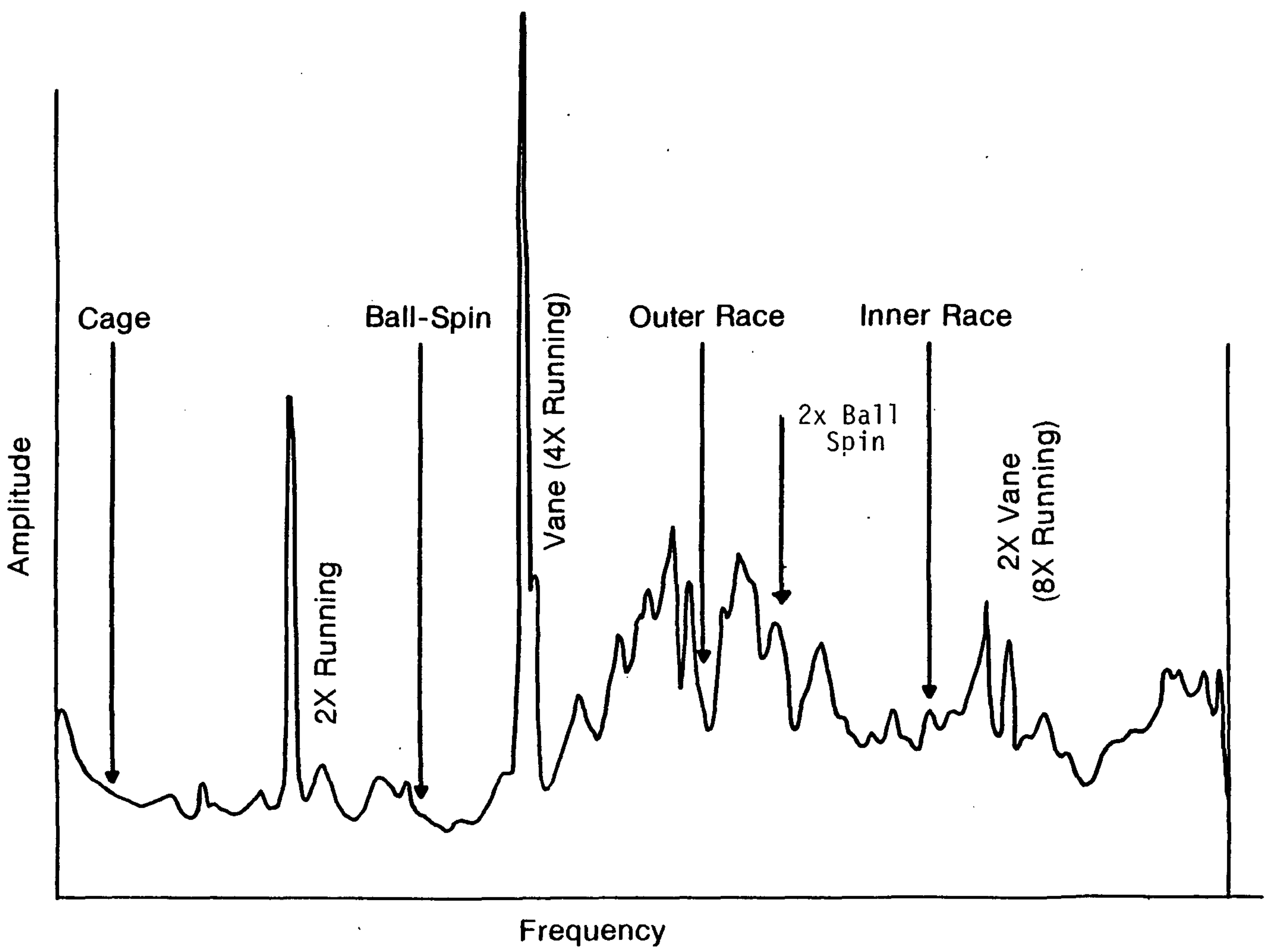

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FIGURE 4 - Real Time Spectrum Sum Average from Three Complete Passes Over Test Tape

PEAK AMPLITUDE RESPONSE

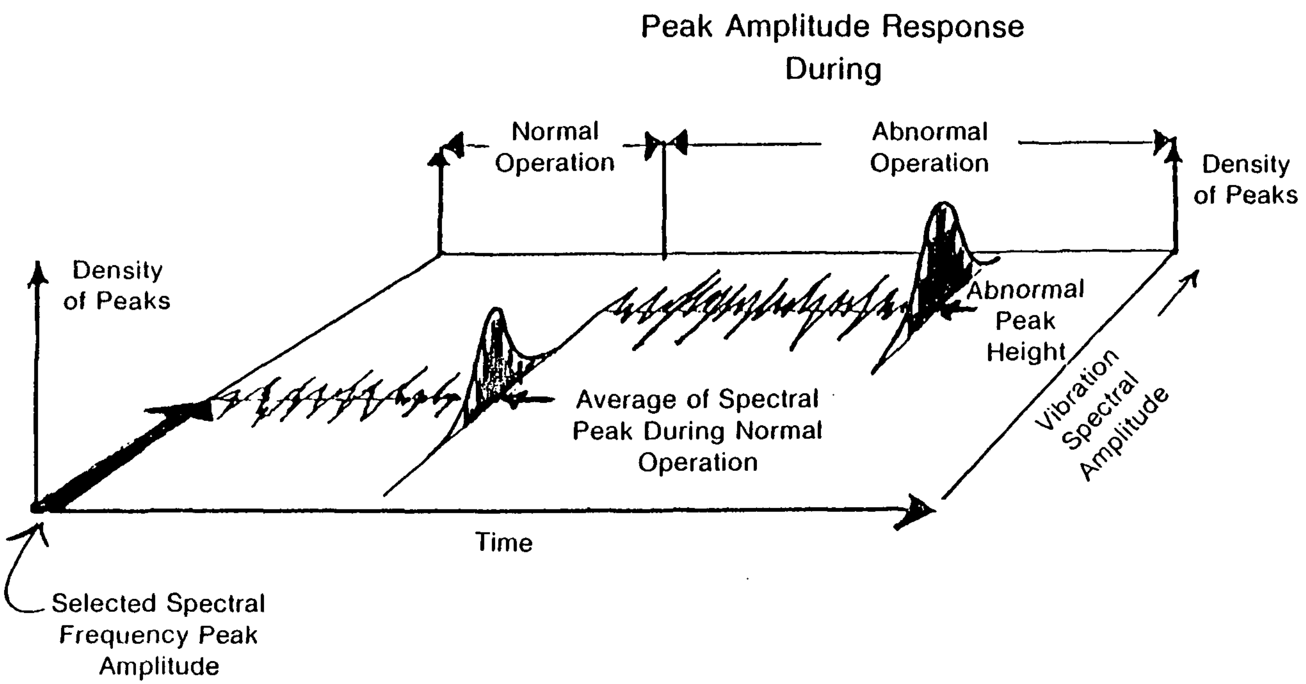

FIGURE 5 - Peak Amplitude Response During Normal, as well as, Abnormal Operation

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To be sure that signals of bearing components which were undergoing periods of stress could be observed in this manner one of the supplied tapes were reviewed from beginning to end for specific amplitude changes. The results displayed in Figure 6, represent the full amplitude changes of four specific bearing related frequencies over the extent of the test tape. From this review it was established when the cage failure occurred on the tape. In addition, it can be seen that high amplitude spikes at the ball and outer race defect frequencies did occur prior to the ultimate cage related failure. Point "c" in the ball defect signal is the first indicator of an abnormal signal amplitude. This signal is roughly two times the height of the nominal distribution established by the bearing sensor up to that point in time.

The total time span shown is approximately 250 seconds or 125,000 revolutions of the test bearing. The 4x running signal amplitude shown was reduced by a factor of four for presentation purposes.

3.3 Computer Analysis of Supplied Data Tapes

3.3.1 Computer Programs for Reviewing Data

Appendix A contains a set of program listings for the type of analysis used in the present study. The programs listed operate from a main selection menu shown in Figure 7. Spectral analysis resulting in plotted outputs representing sums, differences, dispersions (variances), peak hold, ratios, and histograms can be performed with the programs included. In addition, combinations of these routines can be accomplished by saving intermediate computations onto disks for later recall and manipulation.

3.3.1.1 Loading Tape Data to Computer.

The 5451C Fourier Analyzer System can perform analysis of time and frequency data containing frequencies from D.C. to 50KHz. The system can be used to analyze time-series data from mechanical vibrations and acoustic phenomena. These analyses can be used to detect hidden signals in noise, or locate critical functions in complex systems. Programmed steps can be used to perform a partic-

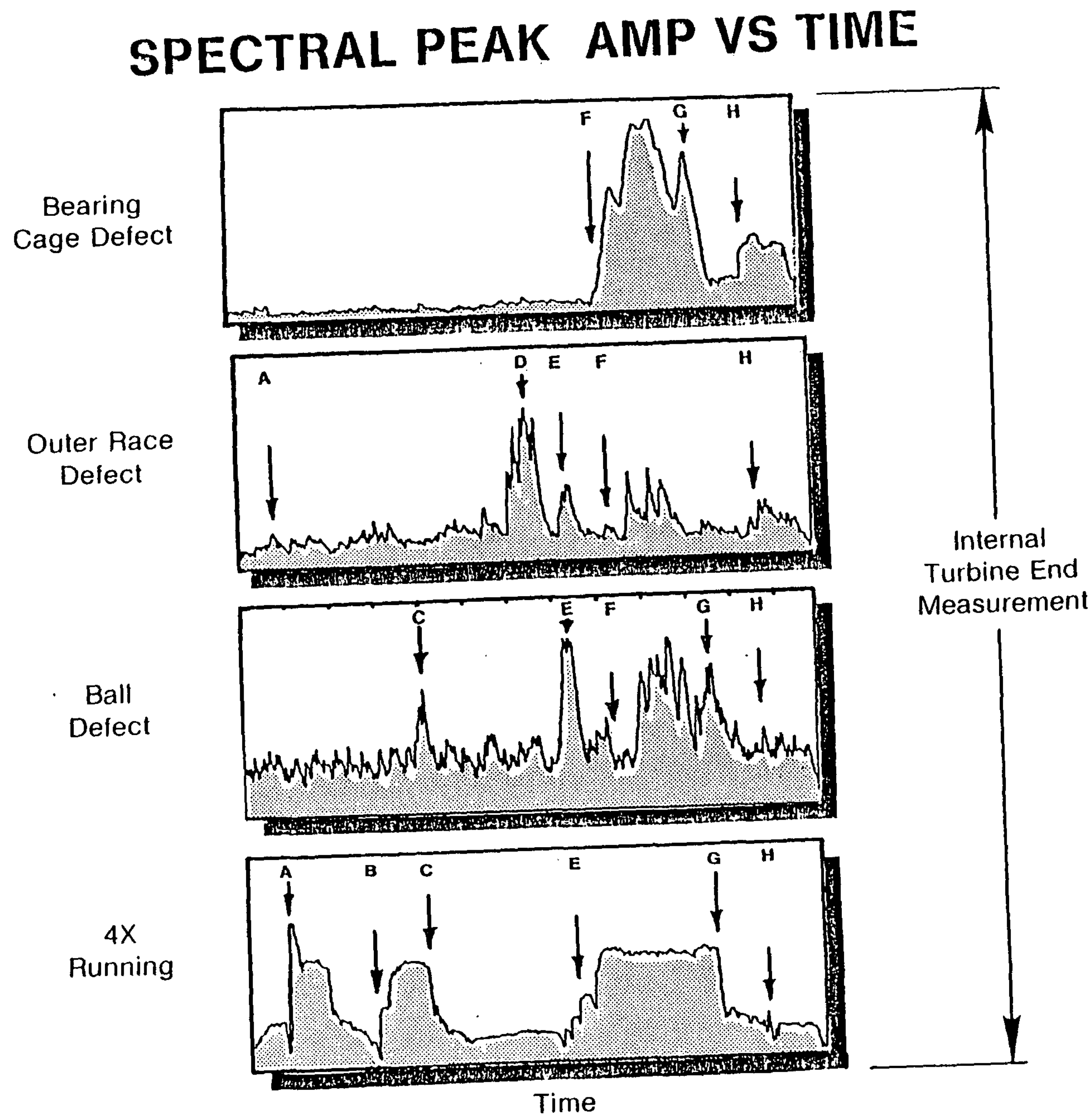

FIGURE 6 - Spectral Peak Amplitude versus Time for Four Bearing Component Frequencies

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PROGRAM MENU

[ ] 1 — STORES DATA TO DISK FROM ACD IN FORM OF SPECTRA
[*] 2 — RANKS DISK SPECTRA AMPLITUDES FROM CHANNEL YOU SELECT
[*] 3 — PLOT SPECTRUM FROM A SELECTED DISK FILE
[*] 4 — PLOT PEAKS OF ALL SPECTRA FROM A SELECTED CHANNEL
[*] 5 — GRAPH MAXIMUM PEAK HEIGHTS OF A GROUP OF SPECTRA
[*] 6 — GRAPH MINIMUM PEAK HEIGHTS OF A GROUP OF SPECTRA
[*] 7 — PLOT THE DIFFERENCE BETWEEN TWO SPECTRA
[*] 8 — PLOT THE RELATIVE (%) DIFFERENCE BETWEEN TWO SPECTRA
[*] 9 — PLOT RATIOS OF AVERAGES OF TWO GROUPS OF SPECTRA
[*] 10 — PLOT ENSEMBLE SUM AVERAGE OF A GROUP OF SPECTRA
[*] 11 — PLOT DISPERSION (VARIANCE) OF A GROUP OF SPECTRA
[*] 12 — PLOT HISTOGRAM OF ALL SPECTRA FROM A SELECTED CHANNEL

[ ] — MUST BE PERFORMED MANUALLY FROM PROGRAM STACK
[*] — AUTOMATIC UPON SELECTION

FIGURE 7 - Main Menu for Access to Programs used in the Present Study

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ular set of operations. Programs, as well as, analyzed data can be stored on hard disks for re-entry and review with the Fourier Analyzer.

Data input and loading is controlled from keyboard programs such as the ones listed in Appendix A (Stacks "5" and Stacks "12" & "18"). Data is entered through the Analog-to-Digital Converter in digital form onto the hard storage disk 7900. Results of all data operation are displayed on the oscilloscope contained in the 5451C system. Results can be printed or plotted on the CRT or hardcopy printer.

Externally triggered sampling of data is often required to get the sprectral information on an "order" basis. This procedure may be required when the taped data is from a system which is varying in speed during the recorded period of interest.

3.3.1.2 Data Manipulation and Analysis Procedures.

All the programs listed in Appendix A operate in general as follows:

1. Load from Stack "0" the Menu program
2. Use the 5451C keyboard to jump to Label "0". (Wait for plot to be completed and the full menu to appear)
3. Select desired Menu control by entering the number of the menu item to be run
4. Either enter second requested entry when questions appears, or wait for plot to appear on CRT (if no second entry is required)
5. After reviewing plot enter any numeric key for return to main menu
6. If desired make intermediate copies on printer from CRT.

3.3.2 Computer Review of Tape Data

Several sets time based data were loaded to the computer disk storage files. In the final analysis of the tape data this provided for the manipulation and review of individual, as well as, combinations of stored spectra. Spectra stored in the computer are usually loaded in a contiguous fashion on the basis of time from the original data tapes. See program for loading data from tape to computer in Appendix A.

3.3.2.1 Spectral Maps (Waterfall Plots).

Plots similar to those displayed in Figure 8, are spectra maps of contiguous time blocks taken from recorded tape data. A single peak frequency element of these contiguous blocks of data can be charted over the time represented by stored data. The side view of the spectral map displays how the amplitude of a single frequency band will vary over time. It can be seen in Figure 8, that a single peak amplitude varies to some extent as the recording proceeds. The extent to which a peak varies with time is partially dependent on the condition of the bearing system which generates the signals, as will be shown in a later section.

3.3.2.2 Sum Averaging.

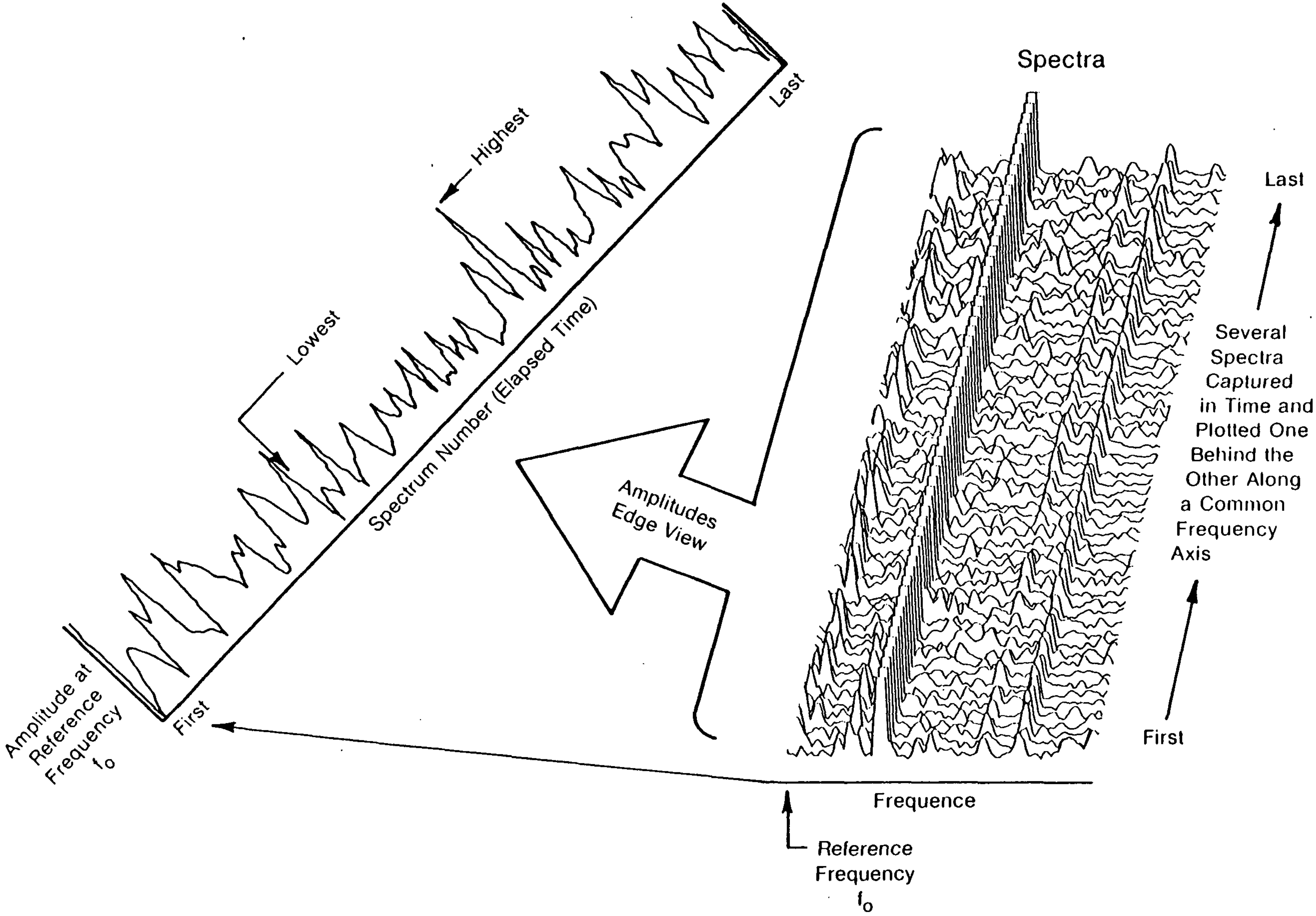
Ensemble sum averaging as displayed previously (Figure 4), was used to establish the mean values of the spectral peaks. These sums were used in two ways; 1) for establishing the expected amplitudes present in the system spectral energy output and 2) for relative normalization of subsequent spectra by ratioing.

3.3.2.3 Dispersions (Variance) of Spectral Amplitudes with Time and Ratio.

One character of the distribution created by spectral peak amplitudes is the dispersion (or variance). The dispersion is a measure of the distribution width; where the width in this case is a measure of how much a given peak varies in time.

FIGURE 8 -

SCHEMATIC OF SPECTRA REVIEW TECHNIQUE



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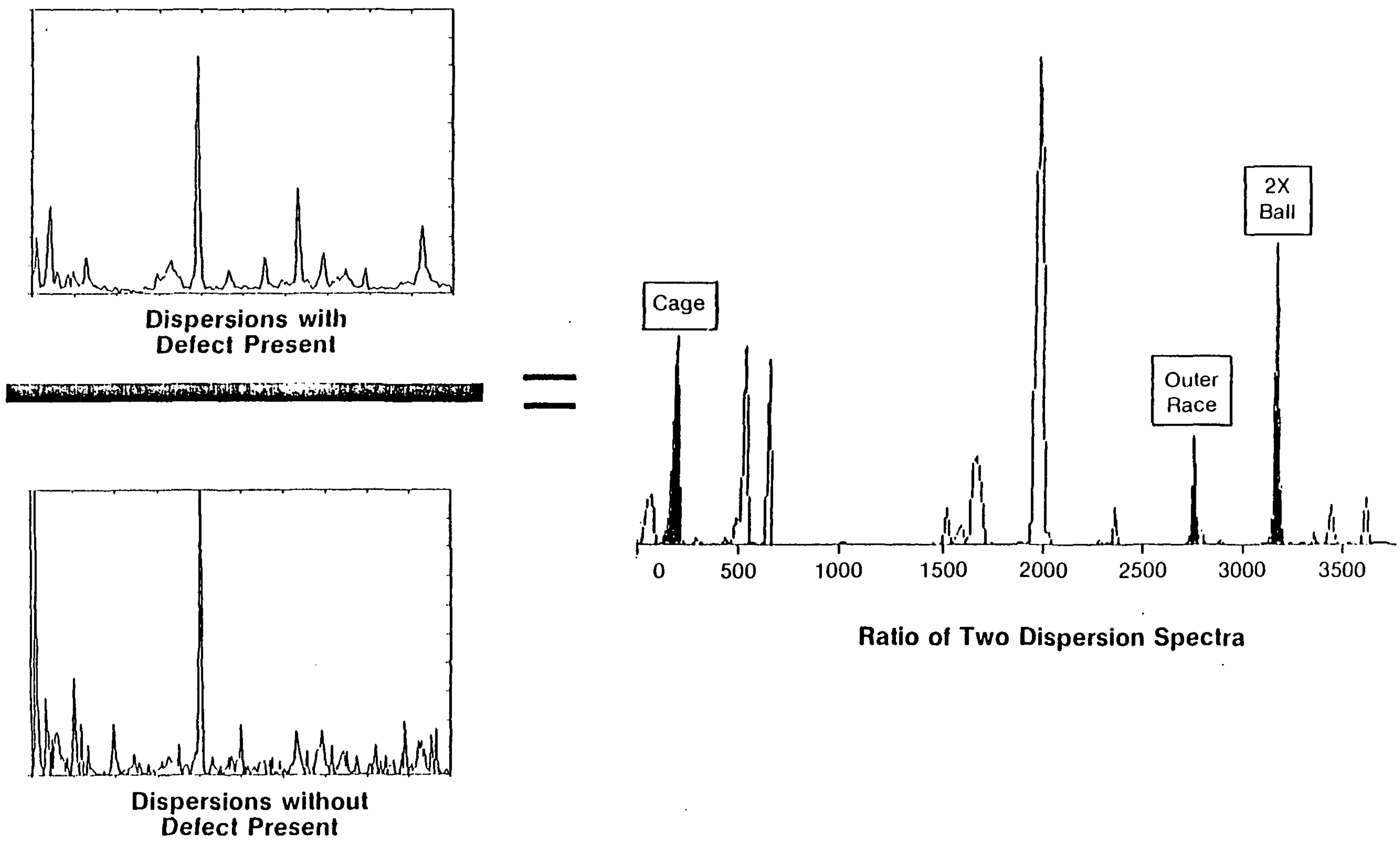

FIGURE 9 - Ratio Enhancement of Defect Signals from Several Bearing Components

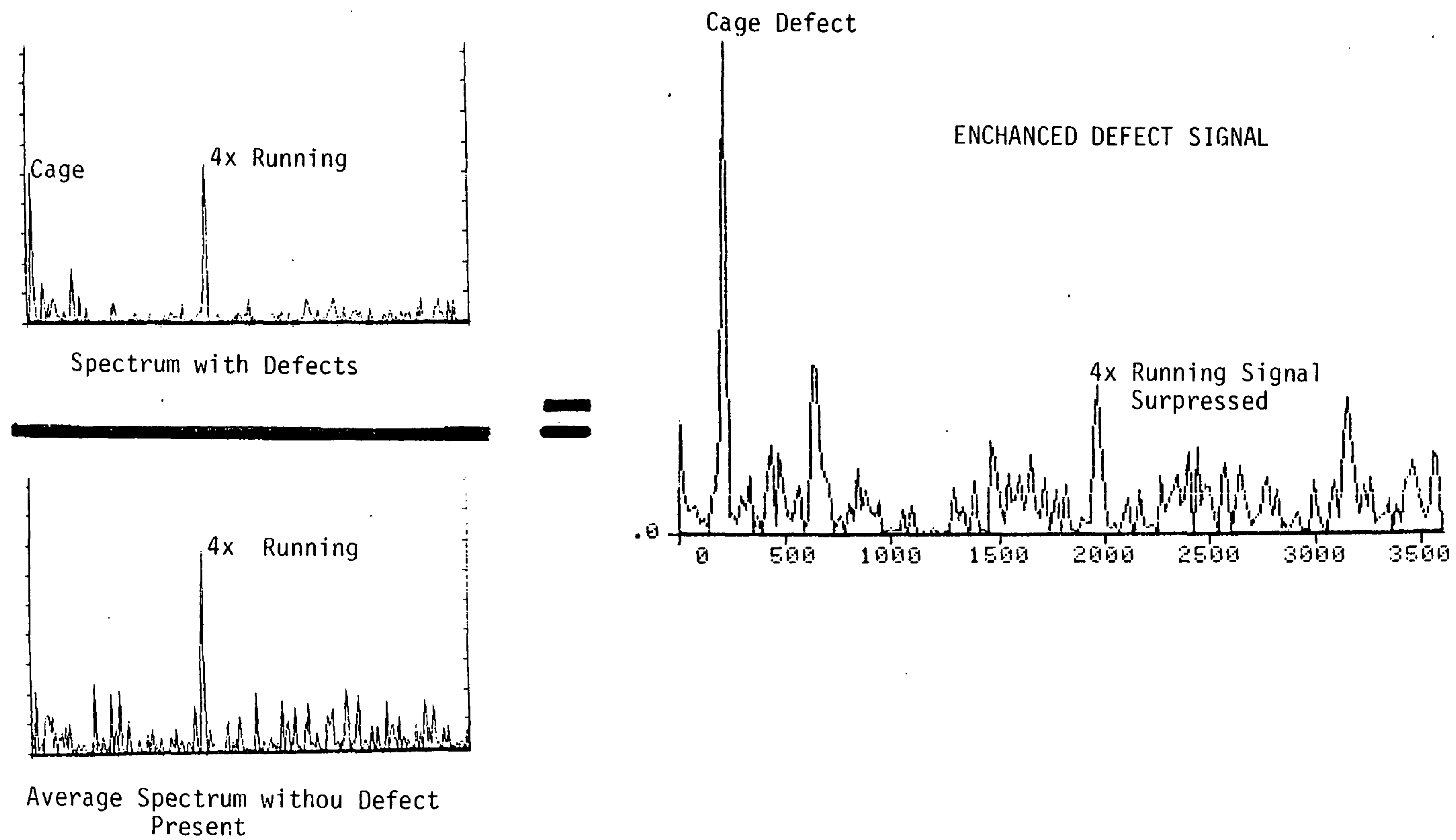

FIGURE 10 - Ratio Enhancement of "Cage Only" Defect Signals

The dispersion of bearing component frequencies is apparently dependent upon their amplitudes. This is graphically shown in Figure 9. Shown are two (the smaller spectra on the left) dispersion spectra (peak variance at every frequency) when there was a bearing defect present (upper) and when there was no defect present (lower).

Ratioing these two spectra provides an increase in amplitude or enhancement of the bearing component frequencies which were operating under conditions of near failure. The reason for the presence of a few other peaks (non-component frequencies) in the ratio plot was not established. However, the two peaks near the 500 cycle running frequency comes about because of their very low amplitude components (almost zero) in the dispersion plot without defect present. The 4x times running spike may be extra large because of variations in vane passing energy under the two separate conditions of running.

Ratioing spectra from two other portions of the data also shows that the "cage only" defect signal can be enhanced to be greater than the dominate 4x times blade passing signal. This is shown in Figure 10.

3.3.3 Comparisons of Signals from Four Separate Data Tapes

Discussion to this point has centered on the development of diagnostic methods which can provide failure onset detection. The methods of ratioing two average spectra; one which has definite failure content to one which is representative of the systems long term non-defective nature has been shown to be effective. Up to this point the major discussion has centered around signals which are gathered from internal rig mounted sensors. The discussion which follows compares data not taken from internally mounted sensors; but from external sensors. Signals from these sensors have had to travel from the source (bearing) through several mechanical interfaces and typically have a different power distribution than the internally mounted sensors.

3.3.3.1 Approach to Diagnostic Comparison of Tapes.

Previous work (see Reference 1) established that enhancement of bearing component frequency peaks could be attained through ratioing. The impetus for these methods was derived from the fact that component frequency spikes could occasionally be enhanced when a moving average of 4-8 spectra (window average) was compared (ratioed) to the sum average of the whole tape.

When a failure onset signal on internally mounted sensors is present from a rolling element bearing two changes in component frequency peak amplitude occur. First the component frequency amplitude increases, and secondly there may be a broadening of the frequency distribution at the new (higher) amplitude. Both of these characteristics are depicted schematically in Figure 11.

Shown also in Figure 11, is a residual low-amplitude portion of the distribution which portrays the possibility of a mixed operating character of the bearing.

When a bearing is operating during the onset of a failure mode it is possible for the high amplitudes to be pulsed in nature. The sporadic nature of this type of operation would provide some low amplitude signals, as well as, high amplitudes and was displayed from the data tapes in Figure 8, shown in a previous section.

In view of this preliminary conclusion involving failure component signals four different tapes were reviewed:

1. No-Known Defects (TAPE 211 #1)

2. Cage Onset Defect (TAPE 212 #1)

3. Possible Spall Defect (TAPE 352 #3)

4. No-Known Defects (TAPE 339 #1)

The externally mounted 90° radial accelerometer on the high pressure turbine end of the test rig was used in the following review. It was known that diagnostic success could be attained from internally mounted sensors and it was conjectured that externally mounted sensors might prove amenable to a similar analysis. Some resulting plots taken from the four tapes reviewed are displayed in Figure 12.

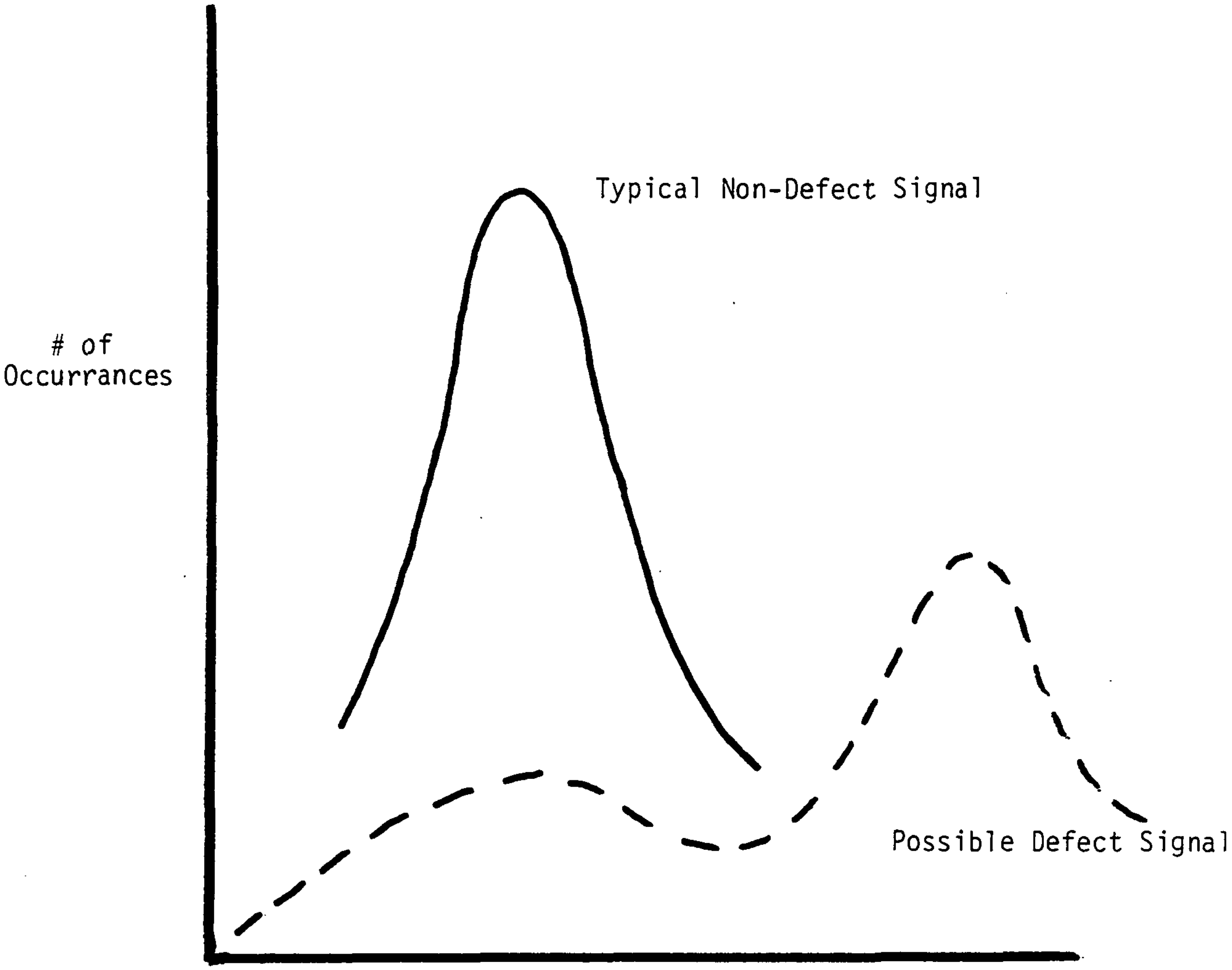

FIGURE 11 - Frequency Distribution (Histogram)

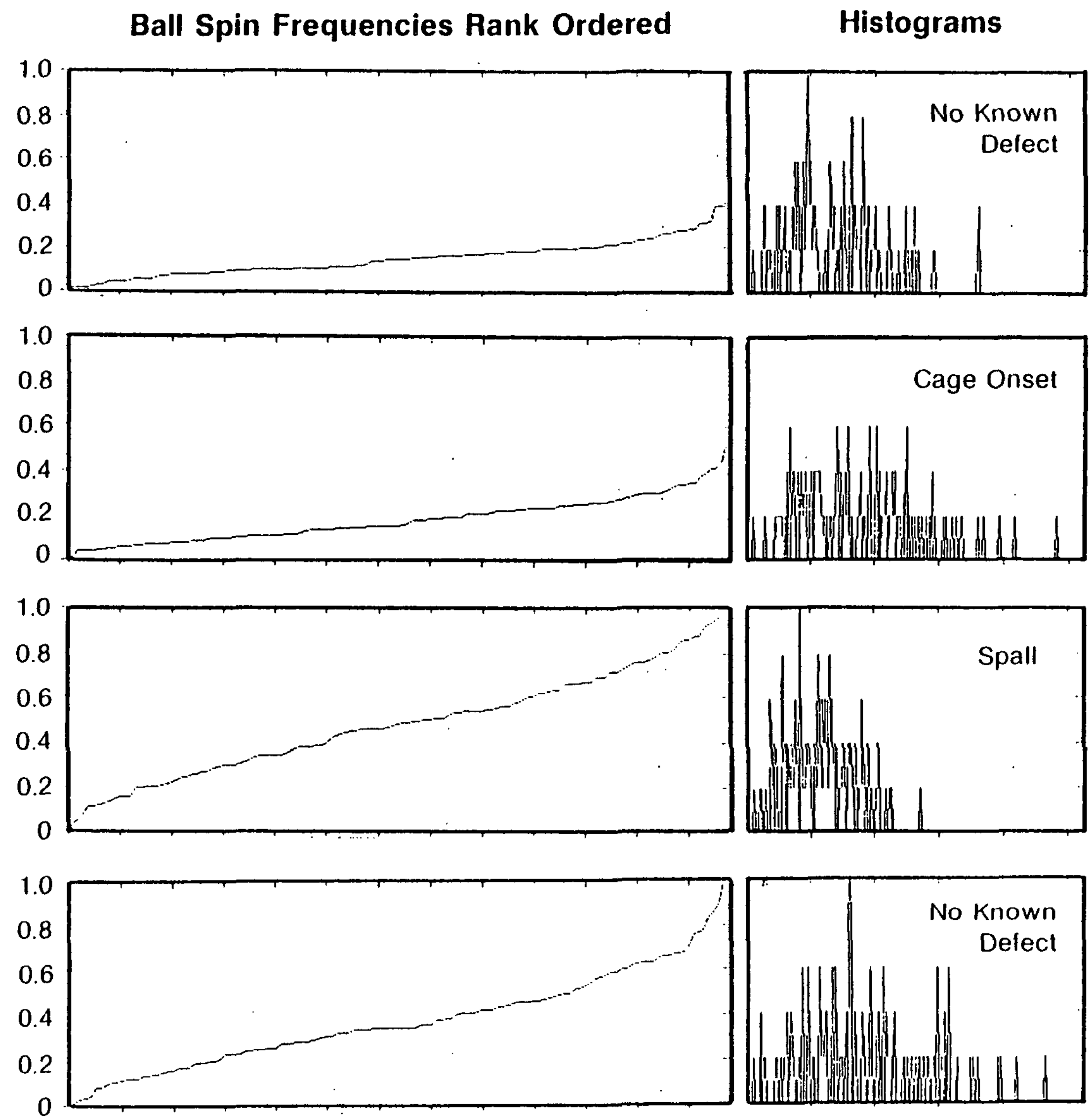

FIGURE 12 - Comparison of Four Different Taped Signals

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It is not clear that the frequency distributions taken from 128 spectra from each tape reveal the appropriate diagnostic results. Although the tape contin-ing the "cage onset" defect signals does display a skewed distribution (counts on the right side of the histogram shown), so does the last tape reviewed which does not have any known defects present during the recording. In other words, the results from a distributive view appear inconclusvie when signals from externally mounted sensors are considered.

4.0 DISCUSSION OF RESULTS

This project involved scanning several NASA-provided data tapes each containing approximately 6 internally mounted , as well as, externally case-mounted accelerometer signals from LOX pump testing. The analysis performed made use of the conventional spectra analyzer, as well as, the HP 5451C. Programs for storing and analyzing data on the HP 5451C Fourier Analyzer were transferred to NASA.

Although the developed procedures for enhancement of bearing failure signals could be demonstrated on signals obtained from internally mounted strain gages, the results were less encouraging when externally mounted accelerometers were the source for sensing vibrations.

Taped data from internally mounted sensors appeared amenable to programmable analysis which enhanced the defect signal relative to the noise present in the signal. Techniques which involved ratioing two sets of spectral information provided the following conclusions:

1. Non-repetitive pulses from defective bearing components can be enhanced by comparing the pulsed portions of the taped signal to the sum average of the signals time history

2. Spectral peaks corresponding to bearing components defect tend to:

   a. Increase in amplitude as the defect becomes more pronounced, and

   b. become more dispersive (have larger variances) in their resulting distribution.

Taped data from externally mounted sensors when viewed with algorithms which enhance failure on-set signals from internally mounted sensors did not yield conclusive diagnostic results. Either the failure component signals were too small to be detected or the captured spectra reviewed (typically 128 per tape) were not from the appropriate sections of tape which corresponded to the component failure output signal.

5.0 RECOMMENDATIONS

1. The techniques used during the present study could be more fully examined if computer storage were available for processing a larger number of spectra. It is possible that the analysis of the signals obtained from the externally mounted sensors was not broad enough; a 128 spectra was the maximum available per review attempt in the present HP 5451C system. These signals may require 20 to 50 times the available spectra in order to resolve the small amplitude pulsed signal which may be present in the taped information.

2. Moving based spectral averaging windows compared to long term history of the system average spectra when processed and scanned over the full extent of the tape may improve the chances of capturing significant "defect" signals.

3. All comparison of spectral signals should be done on an orders basis (if possible) so that slight variations in speed do not "average out" the small signal at a given frequency which might be present.

4. Use of High frequency (0-40,000Hz) sensors and recording instrumentation may be used along with resonant demodulation technology in order to discriminate the small energy pulses which eminent from the onset of bearing defects.

5. Test runs could be made on the statistical distribution character of a large number of spectra from a test rig which could be set up with "known" bearing defects in order to review failure detection methods under controlled conditions.

APPENDIX A

PROGRAM MENU SELECTIONS

and

PROGRAM LISTINGS

Contained in Appendix A are listings of the HP 5451C programs which are relevant to the work described here. When the program of stack "0" is accessed the menu selections of Figure A-1 are available for operation. A wide variety of plotted outputs ranging from the dispersions of a group of spectra to the rank ordered display of a selected channel of all 128 stored spectra are provided. A description of how each of the 12 selections can be used to process stored spectral information follows. (Refer to Figure A-1).

<u>Menu Selection ( ) 1</u> - Stores data to disk from ADC in form of Spectra.

Previously taped data loaded through the analyzer with a program such as that shown in the listings under stack "5" can be converted with the programs listed under the stack "12" and "18" headings. This particular function is the only part of the program included in the present work which will not operate automatically and must be accessed manually from the 5451C keyboard. This prevents the accidential selection of this menu item which could result in an improper over writing of the stored spectral data.

<u>Menu Selection (*) 2</u> - Ranks Disk Spectra Amplitude from Channel you Select.

The amplitudes of a selected channel of all spectra are re-order into a ranked file of the smallest to largest amplitude. The progress of the reordering process can be viewed on the oscilloscope of the 5451C. Total ranking time for this selection is about 30 sec. to one minute. The spectrum with the biggest amb. amplitude, second biggest, etc., can be located by checking the ranked file number list of the stored spectra.

<u>Menu Selection (*) 3</u> - Plot Spectrum from a Selected Disk File.

This routine allows one to review any of the available spectra though plotting them on the CRT or printer.

<u>Menu Selection (*) 4</u> - Plot Peaks of All Spectra from a Selected Channel.

A provision for obtaining a "side view" of the spectral map of all the spectra is the basis of this calling routine. The location of the side view is provided for in the channel number selection. There are 256 channels in the displayed spectra of these routines which represents the zero to full scale frequency of the stored spectra.

Menu Selection (*) 5 - Graph Maximum Peak Heights of a Group of Spectra.

This portion of programming is similar to the "Peak Hold" operation of the standard commercial spectrum analyzer. The largest peak of all spectra in every channel (frequency) of the selected group of spectra are sought-out and displayed by the routine.

Menu Selection (*) 6 - Graph Minimum Peak Height of a Group of Spectra.

Similar to the previous menu selection.

Menu Selection (*) 7 - Plot the Difference Between Two Spectra.

Any two stored spectra may be recalled for this computation.

Menu Selection (*) 8 - Plot the Relative (%) Difference Between Two Spectra.

Any two stored spectra can be recalled and operated upon in this manner. The values computed for each channel follow the form:

$$\frac{(A - B) * 100}{B}$$

where A and B represent the numeric amplitudes of each channel of each spectra.

Menu Selection (*) 9 - Plot Ratios of Average of Two Groups of Spectra.

The computation called for by this selection involves three steps. First the two stored groups of spectra are identified as two contiguous sets of stored spectra through input selection. Then ensembled averages are computed automatically for the two identified sets. Finally, a ratio of these averages is computed channel by channel (frequency-by-frequency) over the whole range of frequencies.

Menu Selection (*) 10 - Plot Ensemble Sums Average of a Group of (N) Spectra.

The following form is used to compute:

$$\left(\sum_{i=1}^{N} X_i\right) /N$$

the sum average for each channel (frequency) is computed over the group of spectra selected.

Menu Selection (*) 11 - Plot Dispersion (Variance) of a Group of Spectra.

This computation invloves the evaluation of the formula:

$$\frac{N \sum (A)^2 - (\ \ A)^2}{N\ (N - 1)}$$

for each channel (frequency) over the group of spectra selected. Where A is the amplitude of selected channel.

Menu Selection (*) 12 - Plot Histogram of all Spectra from a Selected Channel.

An amplitude distribution of a selected channel from all stored spectra can be plotted.

PROGRAM MENU

[ ] 1 — STORES DATA TO DISK FROM ACD IN FORM OF SPECTRA
[*] 2 — RANKS DISK SPECTRA AMPLITUDES FROM CHANNEL YOU SELECT
[*] 3 — PLOT SPECTRUM FROM A SELECTED DISK FILE
[*] 4 — PLOT PEAKS OF ALL SPECTRA FROM A SELECTED CHANNEL
[*] 5 — GRAPH MAXIMUM PEAK HEIGHTS OF A GROUP OF SPECTRA
[*] 6 — GRAPH MINIMUM PEAK HEIGHTS OF A GROUP OF SPECTRA
[*] 7 — PLOT THE DIFFERENCE BETWEEN TWO SPECTRA
[*] 8 — PLOT THE RELATIVE (%) DIFFERENCE BETWEEN TWO SPECTRA
[*] 9 — PLOT RATIOS OF AVERAGES OF TWO GROUPS OF SPECTRA
[*] 10 — PLOT ENSEMBLE SUM AVERAGE OF A GROUP OF SPECTRA
[*] 11 — PLOT DISPERSION (VARIANCE) OF A GROUP OF SPECTRA
[*] 12 — PLOT HISTOGRAM OF ALL SPECTRA FROM A SELECTED CHANNEL

[ ] — MUST BE PERFORMED MANUALLY FROM PROGRAM STACK
[*] — AUTOMATIC UPON SELECTION

FIGURE A-1 - Computer Program for 5451C Menu Selection

852894

```
//////////////////////////////////////////////////////////
////////////  MENU SELECTION PROGRAM  /////////////
//////////////////////////////////////////////////////////
  1 L       0
  5 Y    5821      6
 10 Y K
 14 CL      0
 18 L       1
 22 BS    512
 26 Y    5814
 30 Y    5838      1
 35 Y    5819      1
 40 Y R       0
 45 Y *       0      0D      10
 52 J      0D
 56 L      10
 60 J       1
 64 L      20
 68 J       1      9
 73 J       1
 77 L      30
 81 J       1     11
 86 J       1
 90 L      40
 94 J       1      1
 99 J       1
103 L      50
107 J       1      3
112 J       1
116 L      60
120 J       1      2
125 J       1
129 L      70
133 J       1      8
138 J       1
142 L      80
146 J       1      6
151 J       1
155 L      90
159 J       1      4
164 J       1
168 L     100
172 J       1      7
177 J       1
181 L     110
185 J       1     13
190 J       1
194 L     120
198 J       1     10
203 J       1
207 L     130
211 J       1
215 L     140
219 J       1
223 .
```


MEMORY STACK '0'

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OF POOR QUALITY

```
///////////////////////////////////////////////////////////////
////////////        MEMORY STACK   '1'     /////////////
///////////////////////////////////////////////////////////////

  1 L       -1
  5 L        1
  9 Y     5814
 13 BS     512
 17 CL       0
 21 Y     5838          2
 26 Y     5819          1
 31 Y R          2
 36 Y _          1         0
 42 MS      31          0
 47 L        3
 51 MS      11          1
 56 Y X<    3013          1         2D
 63 Y X>    3013          0         1D
 70 Y A+         1        1D          1
 77 Y IF         1      127         1         1
 85 J        3
 89 BS     128
 93 Y     5814
 97 Y K
101 Y R          0
106 J        1          0
111 .
```

PLOT PEAKS OF ALL SPECTRA FROM A SELECTED CHANNEL

```
/////////////////////////////////////////////////////////////
/////////////      MEMORY STACK  '2'      //////////////
/////////////////////////////////////////////////////////////

   1 L        -2
   5 L         1
   9 BS      512
  13 CL        0
  17 Y      5814
  21 Y      5838       3
  26 Y      5819       1
  31 Y R          0
  36 Y R          1
  41 Y A+         1       1D        1
  48 Y A-         3       1D        0D
  55 MS       31       0D
  60 MS       11
  64 MS       31       0D
  69 L         2
  73 MS       11       1
  78 Y _          2       0
  84 L         3
  88 Y X<     2000        0        2D
  95 Y X<     2001        1        2D
 102 Y IF     2000    2001D        1        -2
 110 Y X>     2001        0        2D
 117 Y A+         2       2D        1
 124 #         3     255       0
 130 #         2      3D        0
 136 Y      5821       6
 141 TP
 144 Y K
 148 Y R          0
 153 J         1       0
 158 .
```

GRAPH MINIMUM PEAK HEIGHTS OF A GROUP OF SPECTRA

```
//////////////////////////////////////////////////////
////////////       MEMORY STACK  '3'     /////////////
//////////////////////////////////////////////////////
```

1	L		-3				
5	L		1				
9	BS		512				
13	CL		0				
17	Y		5814				
21	Y		5838		3		
26	Y		5819		1		
31	Y	R		0			
36	Y	R		1			
41	Y	A+		1	1D	1	
48	Y	A-		3	1D	0D	
55	MS		31		0D		
60	MS		11				
64	MS		31		0D		
69	L		2				
73	MS		11		1		
78	Y	_		2	0		
84	L		3				
88	Y	X<	2000		0	2D	
95	Y	X<	2001		1	2D	
102	Y	IF	2000		2001D	1	2
110	Y	X>	2001		0	2D	
117	Y	A+		2	2D	1	
124	#		3		255	0	
130	#		2		3D	0	
136	Y		5821		6		
141	TP						
144	Y	K					
148	Y	R		0			
153	J		1		0		
158	.						

GRAPH MAXIMUM PEAK HEIGHTS OF A GROUP OF SPECTRA

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```
//////////////////////////////////////////////////////////////
////////////      MEMORY STACK   '4'     //////////////
//////////////////////////////////////////////////////////////

   1  L       -4
   5  L        1
   9  CL       0
  13  CL       1
  17  Y     5814
  21  Y     5839        3
  26  Y     5819        1
  31  Y  R       0
  36  Y  R       1
  41  Y     5838        3
  46  Y     5819        1
  51  Y  R      10
  56  Y  R      11
  61  Y  A      13       11D        10D
  68  Y  A+      1        1D         1
  75  Y  A-      3        1D         0D
  82  MS      31      0D
  87  L        2
  91  MS      11       1
  96  A+       1
 100  #        2      3D        0
 106  :        0      3D
 111  X        2
 115  CL       0
 119  CL       1
 123  MS      31     10D
 128  L       20
 132  MS      11       1
 137  A+       1
 141  #       20     13D        0
 147  :        0     13D
 152  :        2
 156  TR
 159  Y  K
 163  Y  R       0
 168  J        1       0
 173  .
```

PLOT RATIOS OF AVERAGES OF TWO GROUPS OF SPECTRA

```
///////////////////////////////////////////////////////////
////////////       MEMORY STACK   '5'     /////////////
///////////////////////////////////////////////////////////
```

```
 Y        100     5000         -4          1

             INSERT IF FILTERS REQUIRED
```

```
 1 L         1   <--
 5 MS       32
 9 MS       22         1       128
15 MS       31
19 MS       32
23 MS       72
27 .
```

GATHERS AND TRANSCRIBES DATA FROM TAPE RECORDER INPUT

```
///////////////////////////////////////////////////////////
////////////       MEMORY STACK   '6'     /////////////
///////////////////////////////////////////////////////////
```

```
 1 L         -6
 5 L          1
 9 Y       5814
13 Y       5838        3
18 Y       5819        1
23 Y R          0
28 Y R          1
33 MS        31        0D
38 MS        11
42 MS        31        1D
47 MS        11        1
52 X>         2
56 TR         0
60 TR         1
64 TR         2
68 A-         1
72 *          0      100
77 :          2
81 Y K
85 Y R          0
90 J          1        0
95 .
```

PLOT THE RELATIVE (%) DIFFERENCE BETWEEN TWO SPECTRA

```
////////////////////////////////////////////////////
////////////      MEMORY STACK   '7'     /////////////
////////////////////////////////////////////////////
```



```
  1 L        -7
  5 L         1
  9 CL        0
 13 CL        1
 17 Y      5814
 21 Y      5838       3
 26 Y      5819       1
 31 Y R          0
 36 Y R          1
 41 Y A+         1      1D       1
 48 Y A-         3      1D       0D
 55 MS       31       0D
 60 L         2
 64 MS       11       1
 69 A+        1
 73 #         2       3D      0
 79 :         0       3D
 84 TP
 87 Y K
 91 Y R          0
 96 J         1       0
101 .
```

PLOT ENSEMBLE SUM AVERAGE OF A GROUP OF SPECTRA

```
////////////////////////////////////////////////////
////////////      MEMORY STACK   '8'     /////////////
////////////////////////////////////////////////////
```

```
  1 L        -8
  5 L         1
  9 Y      5814
 13 Y      5838       3
 18 Y      5819       1
 23 Y R          0
 28 Y R          1
 33 MS       31       0D
 38 MS       11
 42 MS       31       1D
 47 MS       11       1
 52 X>        2
 56 TR        0
 60 TR        1
 64 TR        2
 68 A-        1
 72 Y K
 76 Y R          0
 81 J         1       0
 86
```

PLOT THE DIFFERENCE BETWEEN TWO SPECTRA

```
//////////////////////////////////////////////////////////
////////////     MEMORY STACK  '9'     /////////////
//////////////////////////////////////////////////////////
```

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```
  1 L        -9
  5 L         1
  9 Y      5814
 13 BS      512
 17 CL        0
 21 CL        1
 25 CL        2
 29 Y      5838     2
 34 Y      5819     1
 39 Y R         3
 44 Y _        10      3D
 50 Y      5838     5
 55 Y      5819     1
 60 Y _         2     128
 66 Y _         1     128
 72 L         2
 76 Y X>        1       1       2D
 83 Y A+        1      1D       -1
 90 Y A+        2      2D       -1
 97 #         2    128       0
103 MS       31     0
108 Y _         1       1
114 L         3
118 MS       11     3
123 Y X<     3000       3       3D
130 Y X>     3000       0       1D
137 Y A+        1      1D        1
144 #         3    128       0
150 BS      128
154 X         1
158 X         4
162 X         1
166 Y _         6     128
172 Y _         3       1
178 Y _         4       1
184 Y _      2000       1
190 Y :      2000   2000D       2
197 Y A+        0      6D        1
204 Y X>        0       2       3D
211 J        15    20 <  . . REQUIRES STACK  '20'
216 L        10
220 Y A+     2001     10D    2000D
227 Y X>     2001       1        0
234 MS       31    201
239 MS       21      1
244 MS       31    200
249 MS       21
253 Y K
257 Y R         0
262 J         1      0
267 .
```

RANKS DISK SPECTRA AMPLITUDES FROM CHANNEL YOU SELECT

ORIGINAL PAGE IS
OF POOR QUALITY

```
///////////////////////////////////////////////////////
////////////       MEMORY STACK  '10'    /////////////
///////////////////////////////////////////////////////

  1 L       -10
  5 L         1
  9 Y      5814
 13 BS      512
 17 CL        0
 21 Y      5838         2
 26 Y      5819         1
 31 Y R         2
 34 Y _         1         0
 42 MS       31         0
 47 L         3
 51 MS       11         1
 56 Y A+       10         1D       128
 63 Y A+       11         1D       256
 70 Y A+       12         1D       384
 77 Y X<    3013          1         2D
 84 Y X>    3013          0         1D
 91 Y X>    3013          0        10D
 98 Y X>    3013          0        11D
105 Y X>    3013          0        12D
112 Y A+        1         1D         1
119 Y IF        1      127          1          1
127 J         3
131 Y      5814
135 CL        1
139 RM        1
143 X<        1
147 *         0    8192
152 Y K
156 Y R         0
161 J         1         0
166 .
```

PLOTS HISTOGRAM OF ALL SPECTRA AMPLITUDES
FROM A SELECTED CHANNEL (FREQUENCY).

```
//////////////////////////////////////////////////////////
////////////      MEMORY STACK  '11'    /////////////
//////////////////////////////////////////////////////////

    1 L       -11
    5 L         1
    9 BS      512
   13 CL        0
   17 Y      5814
   21 Y      5838        4
   26 Y      5819        1
   31 Y R        0
   36 Y      5814
   40 MS       31       CD
   45 MS       11
   49 Y K
   53 Y R        0
   58 J          1       0
   63 .
```

PLOT SPECTRUM FROM A SELECTED DISK FILE

```
//////////////////////////////////////////////////////////
////////////      MEMORY STACK  '12'    /////////////
//////////////////////////////////////////////////////////
    1 L          1
    5 BS       512
    9 MS        31        1
   14 Y _          1          1
   20 L          2
   24 MS        31       1D
   29 MS        11        1
   34 H1         1
   38 F          1
   42 TP         1
   46 MS        31       1D
   51 MS        21        1
   56 Y A+        1         1D        1
   63 Y IF       1D        129        1        1
   71 J          2
   75 .
```

STORES DATA TO DISK FROM ADC IN FORM OF SPECTRA

(SEE STACK '18' FOR STARTING @ FILE '0')

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OF POOR QUALITY

```
/////////////////////////////////////////////////////////////
////////////       MEMORY STACK   '13'    /////////////
/////////////////////////////////////////////////////////////

  1 L       -13
  5 L         1
  9 BS      512
 13 CL        0
 17 CL        1
 21 CL        2
 25 Y      5814
 29 Y      5839         3
 34 Y      5819         1
 39 Y R          0
 44 Y R          1
 49 Y A+         1        1D        1
 56 Y A-         3        1D        0D
 63 MS       31         0D
 68 MS       11
 72 MS       31         0D
 77 L         2
 81 MS       11
 85 TR
 88 X>        1
 92 *         1
 96 A+        2
100 X>        0
104 #         2         3D        0
110 CL        0
114 MS       31         0D
119 L         3
123 MS       11         1
128 TR
131 A+        1
135 #         3         3D        0
141 X>        1
145 *         1
149 *         2         3D
154 X>        1
158 A-        2
162 :         0         3D
167 Y A-         2        3D        1
174 :         0         2D
179 TP
182 Y K
186 Y R          0
191 J         1         0
196 .
```

PLOT DISPERSION (VARIANCE) OF A GROUP OF SPECTRA

```
////////////////////////////////////////////////////
////////////     MEMORY STACK  '14'    /////////////
////////////////////////////////////////////////////
```

NOT USED

```
////////////////////////////////////////////////////
////////////     MEMORY STACK  '15'    /////////////
////////////////////////////////////////////////////
```

NOT USED

```
////////////////////////////////////////////////////
////////////     MEMORY STACK  '16'    /////////////
////////////////////////////////////////////////////
```

NOT USED

//
///////////   MEMORY STACK '17'   /////////////
//

```
 1 L          1
 5 BS       512
 9 CL         0
13 Y _           1        0
19 L          2
23 Y /L          1        1
29 MS        31       1D
34 MS        11
38 TR
41 H1
44 F
47 TP
50 MS        31       1D
55 MS        21
59 Y A+          1        1D       1
66 #          2    128       1
72 J          2
76
```

SIMILAR TO STACK '12'
ALTERNATE FORM USING 'RECT' OPERATION

//
///////////   MEMORY STACK '18'   /////////////
//

```
 1 L          1
 5 BS       512
 9 MS        31       1
14 Y _           1        Q
20 L          2
24 MS        31       1D
29 MS        11       1
34 H1         1
38 F          1
42 TP         1
46 MS        31       1D
51 MS        21       1
56 Y A+          1        1D       1
63 Y IF          1D       128      1        1
71 J          2
75 .
```

STORES DATA TO DISK FROM ADC IN FORM OF SPECTRA

```
////////////////////////////////////////////////////
////////////      MEMORY STACK  '19'    /////////////
////////////////////////////////////////////////////
```

NOT USED

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```
////////////////////////////////////////////////////
////////////      MEMORY STACK  '20'    /////////////
////////////////////////////////////////////////////
```

```
  1 L      -20
  5 L        1
  9 L       13
 13 Y X<   3000        0        8D
 20 Y X<   3001        0        9D
 27 Y X>   3001        0        8D
 34 Y X>   3000        0        9D
 41 Y X<   2900        1        8D
 48 Y X<   2901        1        9D
 55 Y X>   2901        1        8D
 62 Y X>   2900        1        9D
 69 D         0      1      127         4
 76 <    15392
 80 L       15
 84 Y X<      2        2        3D
 91 Y A+      1        4D       -1
 98 Y A-      0        2D        4D
105 Y IF      0        3         1        1
113 J       52
117 Y A+      0        1D        2D
124 Y .       5        0D        2
131 L       22
135 Y A+      1        1D        1
142 Y IF      1        2D        2        2
150 Y IF      1        2D        1       -2
158 J       40
162 Y X<   2900        0        1D
169 Y X<   2901        0        5D
176 Y IF   2900    2901D         1        2
184 J       22
188 L       30
192 Y A+      2        2D       -1
199 Y IF      1        2D        2        2
207 Y IF      1        2D        1       -2
215 J       40
219 Y X<   2900        0        2D
226 Y X<   2901        0        5D
233 Y IF   2900    2901D         1       -2
241 J       30
245 Y -       3        1D
```

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251	Y	_	9	2D		
257	J		13			
261	J		22			
265	L		40			
269	Y	IF	1	5D	1	1
277	J		45			
281	Y	A+	1	1D	-1	
288	L		45			
292	Y	IF	2	5D	2	2
300	Y	IF	2	5D	1	-2
308	J		50			
312	Y	_	8	1D		
318	Y	_	9	5D		
324	J		13			
328	L		50			
332	Y	A+	3	3D	1	
339	Y	A+	2001	1D	2000D	
346	Y	X>	2001	2	3D	
353	J		15			
357	L		52			
361	Y	A-	0	2D	4D	
368	Y	IF	0	2	1	1
376	J		60			
380	Y	X<	2900	0	4D	
387	Y	A+	0	4D	1	
394	Y	X<	2901	0	0D	
401	Y	IF	2900	2901D	1	1
409	J		60			
413	Y	_	8	4D		
419	Y	A-	9	4D	1	
426	J		13			
430	L		60			
434	Y	X<	4	2	3D	
441	Y	A+	4	4D	1	
448	Y	A-	3	3D	1	
455	Y	IF	3	0	1	-1
463	J		15			
467	J		10	9		
472	.					

APPENDIX B

LIST OF SUPPLIED DATA TAPES

LIST OF TAPES

#	Code	Number	Tape	Cals	Data	Dated
1	A3	212	1	15	240	12/20/84
2	A3	211	1	15	159	12/20/84
3	A3	231	1	15	15	12/17/84
4	A3	212	4	15	175	12/17/84
5	A3	215	1	15	150	01/14/85
6	A3	214	4	15	156	02/23/85
7	A3	215	4	15	150	12/17/84
8	A3	212	5	15	180	12/17/84
9	A3	215	5	15	150	12/17/84
10	A3	214	1	15	150	01/14/85
11	A3	232	1	15	150	12/17/84
12	A3	227	1	15	150	12/17/84
13	A3	214	5	15	150	12/17/84
14	A3	225	1	15	150	12/17/84

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