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SPACE SHUTTLE MAIN ENGINE VIBRATION DATA BASE

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Science and Engineering Directorate

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16. ABSTRACT

This memorandum describes the Space Shuttle Main Engine Vibration Data Base. It includes a detailed description of the data base components, the data acquisition process, the more sophisticated software routines, and the future data acquisition methods. Several figures and plots are provided to illustrate the various output formats accessible to the user. This document reveals the numerous vibration data recall and analysis capabilities available through automated data base techniques.

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INTRODUCTION

The Space Shuttle Main Engine (SSME) single engine test program has been underway since 1975. Throughout this time, engineers have been responsible for reporting on the dynamic characteristics of the engine and its components. The specific components of primary concern dynamically have been the two low pressure pumps and two high pressure pumps. Increased engine performance requirements, more aggressive testing schedules, and demand for higher resolution analysis have led to the development of the SSME Vibration Data Base. This data base has been operational since 1983 and has decreased data reduction turnaround time by a factor of three, while increasing significantly the diagnostic analysis capability.

The primary objective of the SSME Vibration Data Base is to make available to the dynamicist, in an efficient, systematic and timely manner, data analysis techniques which can be used in the evaluation of the operational integrity of the SSME turbomachinery. The vast majority of the evaluations can be performed with conventional power spectral density (PSD) and root-mean-square (RMS) time history analysis. For those cases where these types of analysis are not adequate or where failures or major incidents occur, the analog magnetic tapes are available for more detailed and elaborate analysis. Analog magnetic recordings of all dynamic measurements are obtained for each test as standard operating procedure. Further, during the history of testing of the Space Shuttle Main Engine (SSME), there has been a need to develop techniques to describe special (peculiar) characteristics of the SSME turbomachinery. As a result, special purpose diagnostic algorithms, which tend to be somewhat heuristic in nature, have been developed in order to define these characteristics and to provide insight into their fundamental mechanisms.

Both the PSD/RMS analysis and the special purpose diagnostic algorithms are discussed in detail. These routines have evolved to the present state over a given period of time. Adjustments are continually being made in the algorithms in order to make them more efficient and accurate. As the need for more algorithms occur, they will be developed and incorporated into the data base. Collectively, these algorithms eliminate the routine drudgery associated with engineering data reduction analysis. This therefore allows the dynamicists more time to spend in assessing the effects of the dynamic characteristics of the components under test.

DATA BASE COMPONENTS

The SSME Vibration Data Base consists of three components: (1) Power Spectral Density (PSD) Isospectral Data Base, (2) Diagnostic Data Base, and (3) Anomalous Frequency Data Base. The Isopectral and Diagnostic Data Base will be described in detail in this memorandum. The Anomalous Frequency Data Base will be presented in a later document. Each data base component is a self-contained software system; however, the Isospectral Data Base has the capability of communicating data to the Diagnostic Data Base.

Each data base contains information acquired from vibration accelerometers located on the High Pressure Fuel Turbopump (HPFTP) and the High Pressure Oxygen Turbopump (HPOTP). The Diagnostic Data Base contains data associated with sixteen measurements per single engine test or STS flight. The Isospectral Data Base can handle up to 75 measurements per test or flight. This extra set of data includes low pressure fuel and oxygen turbopump accelerometers, internal strain guages and accelerometers on the high pressure pumps, and other external measurements of interest. A typical list of measurements is shown in Figure 1.

```
THESE ARE THE MEASUREMENTS AVAILABLE.
 1) MCC OUT DT  FL X
 2) MCC OUT DT FL Y
 3) MCC OUT DT FL Z
 4) LPFT DR DT Y ACC
 5) LPFT DR DT Z ACC
 6) LPFP RAD 150 ACC
 7) LPFP RAD 240 ACC
 8) LPFP RAD 330 ACC
 9) LPFT RAD 180 ACC
10) LPFT RAD 270 ACC
11) LPFT AX 180 ACC
12) LPOP RAD 90 ACC
13) LPOP RAD 270 ACC
14) LPOP RAD 180 ACC
15) HPOT RAD 90 ACC
16) HPOT RAD 135 ACC
17) PBP RAD 225
18) PBP RAD 135-2
19) PBP RAD 45-1
20) PBP RAD 45-3
21) HPFP RAD 0
22) HPFP RAD 186
23) HPFP RAD 174
24) HPFT RAD 90 ACC
25) HPFP RAD 90
26) HPFT RAD 180 ACC
ENTER MEASUREMENT # TO BE INCLUDED
>
```

Figure 1. Typical set of measurements for a single engine test.

PSD ISOSPECTRAL DATA BASE

The Isospectral Data Base is housed on the UNIVAC 1100 series mainframe computer at Slidell Computer Complex, Slidell, Louisiana. This data base requires a large amount of mass storage, hence the need for a large computer system. The basic unit of this data base is the Power Spectral Density (PSD). Contiguous PSD's for the entire test duration are stored for each measurement. The PSD is a frequency domain representation of a time signal. The general frequency composition of a signal is described in terms of the spectral density of its mean squared value [1]. The PSD is defined as:

$$Gxx(f) = \frac{2}{\Delta f} \; |X(f,T)|^2 \qquad (1)$$

where X(f,T) is the discrete fourier transform of the time signal. There are several advantages of storing the data in the frequency domain PSD format rather than the time domain. The PSD format needs one-half the computer mass storage required by time domain. This is critical due to the high digitizing sample rate used. Also important is the fact that the root mean square (RMS) value of any frequency range can be easily computed by simply integrating the PSD over that range. The RMS value can be obtained by

$$Grms = \sqrt{\int_{f_1}^{f_2} Gxx(f)df} \quad .$$

A significant disadvantage of PSD format is that all phase information is lost. However, for routine single engine tests, all of the necessary analysis required for data review reporting can be derived from PSD formatted data. Since the data is in the frequency domain, any discrete frequency can be easily detected and classified in terms of its speed and amplitude. Specifically important is the classification of all discrete frequencies related to the pump rotor rotation speed.

The Isospectral Data Base requires a considerable amount of mass storage per SSME test. The factors affecting this amount are the test duration and the number of measurements processed. For example, a 300 second test with 20 measurements processed would generate 16.4 million floating point numbers. Given a 500 sec test (i.e., typical STS flight duration) with 40 measurements processed, the amount of floating point numbers would increase to 53.2 million. Due to these mass storage demands, only three to five complete tests can be on-line simultaneously. More on-line tests can be made available by limiting the number of measurements on-line per test. An example of this would be to have on-line only those measurements associated with the HPOTP. This would reduce the number of measurements per test from 40 down to 6 to 10. There is a tremendous amount of processing and display capability in the Isospectral Data Base. Each computational task is made more efficient due to the fact that the data is only digitized once. In the pre-data base processing system, the analog data would have to be converted to digital form everytime analysis was done, resulting in repetitious processing. Now, most processes or tasks can be executed in the amount of time required to simply digitize the data. This ability to store a completely digitized measurement is a significant factor in reducing the data reduction turnaround time. The following is a description of the various analysis and display capabilities of the data base software.

PSD Ensemble Averaging

An ensemble averaged PSD can be computed and displayed for any user defined time interval. The user has complete control over the plot bandwidth, the number of decades in the Y-axis, the start time of the averaging computation, and the number of averages to be used. Each PSD plot annotates the six highest peak values listing the frequency and amplitude. Also annotated is the composite RMS value (i.e., the

RMS value computed over the plot bandwidth). The synchronous speed RMS component is noted when applicable. An example PSD plot is given in Figure 2.

RMS Computation

There are two methods used in the data base software to calculate RMS values. The first method simply integrates over a fixed frequency interval to compute what is termed a composite RMS. The second method computes RMS values associated with pump speed discrete frequencies. This method uses a sophisticated speed tracking algorithm to detect synchronous related harmonics and compute the associated RMS components. The speed tracking algorithm will be discussed in detail later. Both methods use the same display routine which allows the user both automatic scaling and manual scaling privileges. The user has the capability of plotting RMS values or pump speed frequency versus time (Figs. 3 and 4) and also RMS values versus pump speed (Fig. 5).

Isospectral Display

Probably the most dramatic plot available in the data base is the Isospectral Plot (ISOPLOT). This routine plots consecutive PSD's on top of each other in a "waterfall" form (Fig. 6). A hidden line algorithm is used to preserve the three-dimensional character of the plot. This particular display is useful in identifying discrete frequencies. In just a couple of pages, the signature of the data can be defined for the entire test. All pump speed related peaks as well as those not related to pump speed can be readily identified. The ISOPLOT display can also be skewed from left to right (Fig. 7) or from right to left (Fig. 8). This tilting of the display allows the user to identify relative changes in amplitude of a given discrete frequency. It also helps to identify closely spaced frequencies.

Peak Identification

This routine analyzes each PSD and documents the six highest peak frequencies and their associated amplitudes. The user has control over the start and stop times of printout, and the minimum and maximum frequency range for the peak search. This particular routine is useful in identifying closely spaced discrete frequency components, particularly those which tend to cross over one another. An example output is given in Figure 9.

Anomalous Frequency Tracking

As mentioned earlier, all pump speed related components can be identified. However, in some SSME tests, discrete frequencies are present which do not qualify as a pump speed integer harmonic. Those frequencies are termed anomalous frequencies. These anomalous frequencies can take the form of unknown "wandering frequencies" in which the frequency and its amplitude changes continuously during the test, or of the form of subharmonics related to subsynchronous whirl characteristics associated with instabilities of the HPOTP and HPFTP. Anomalous frequency tracking can be executed by simply rejecting the previously identified pump speed harmonics and retaining the next highest peak value. This peak value is searched for within a user defined frequency interval. When an anomalous frequency is present (i.e., its amplitude is above the background noise), the tracking routine

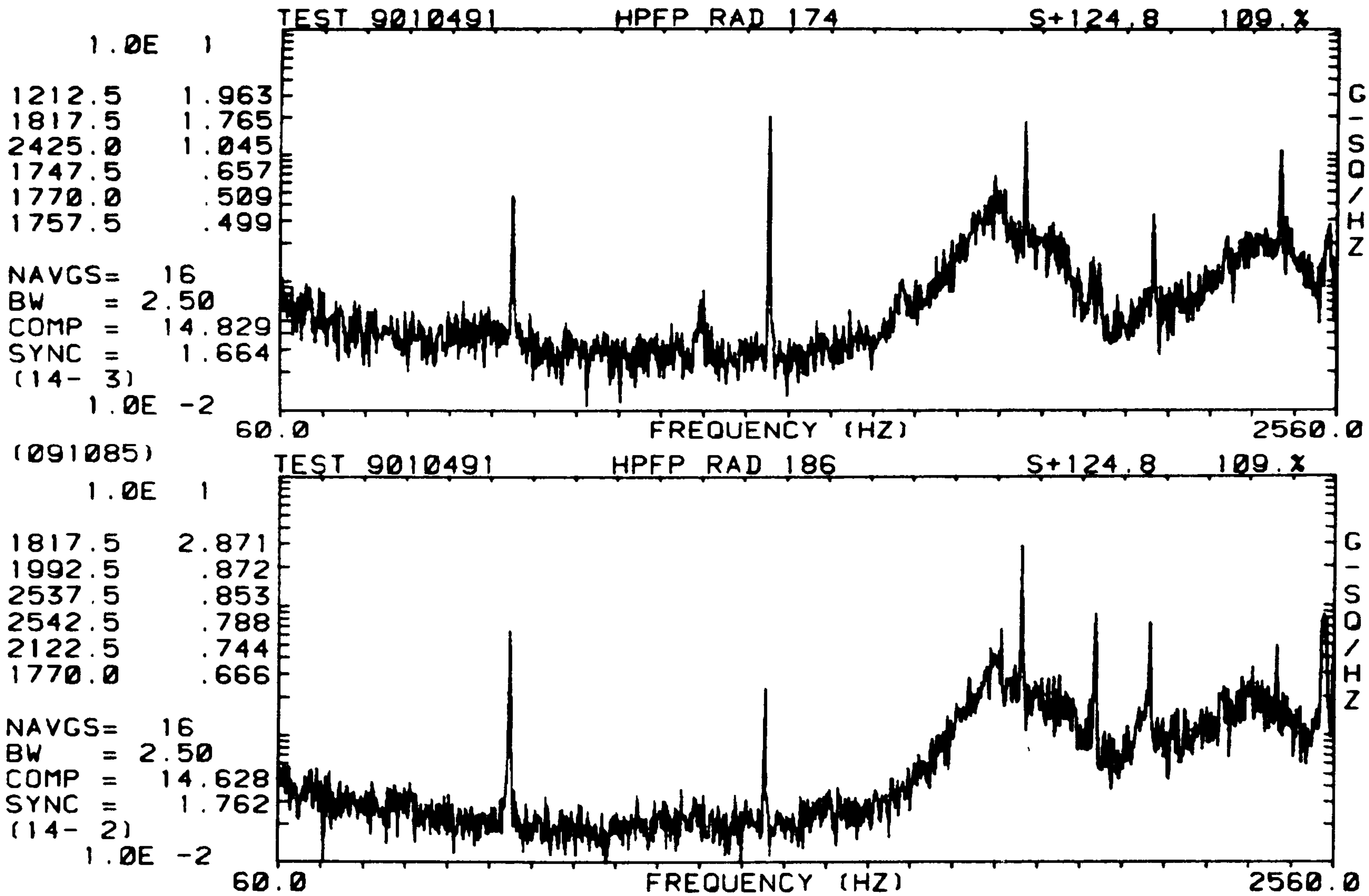

Figure 2. PSD plot.

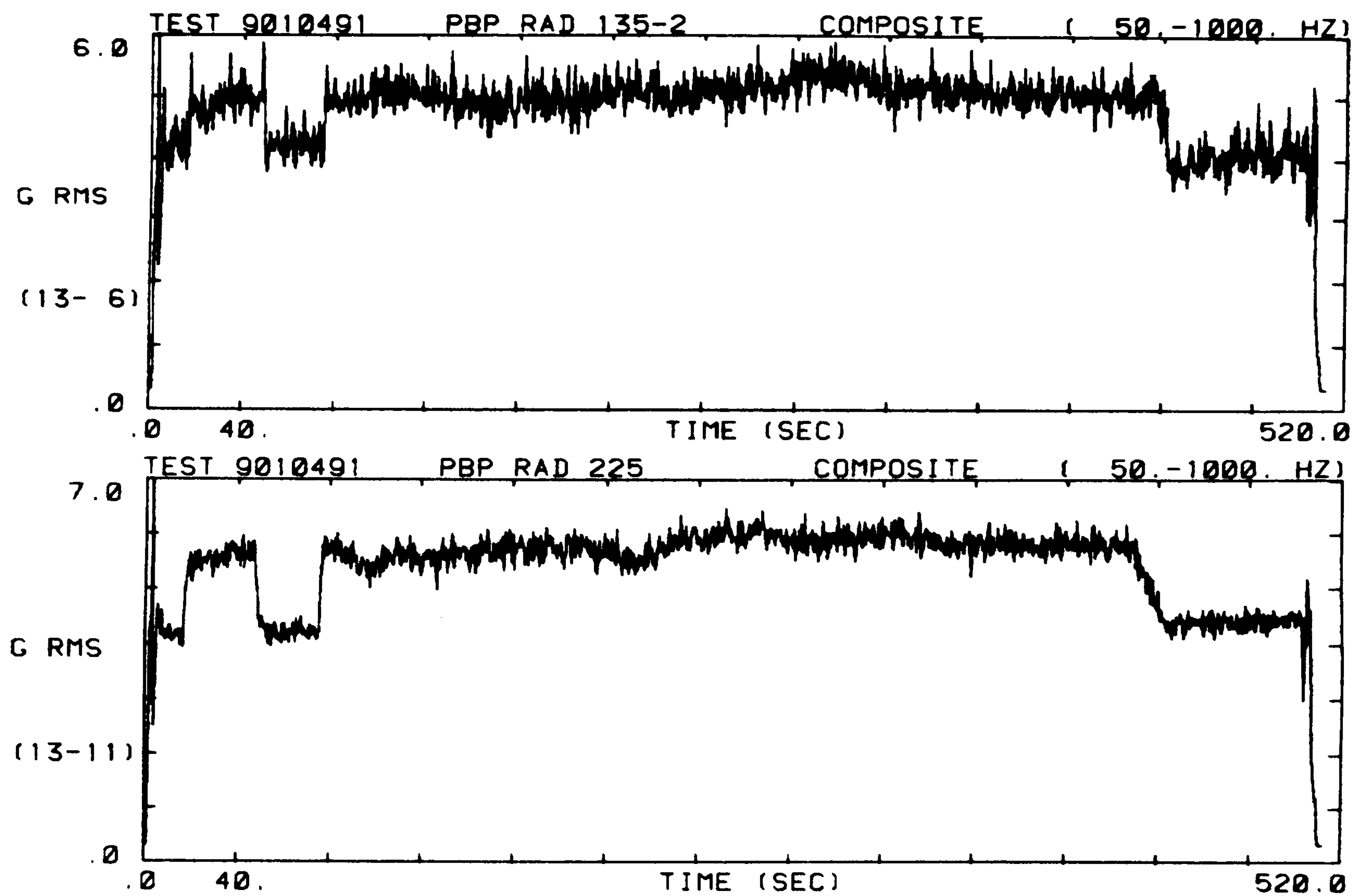

Figure 3. RMS time history.

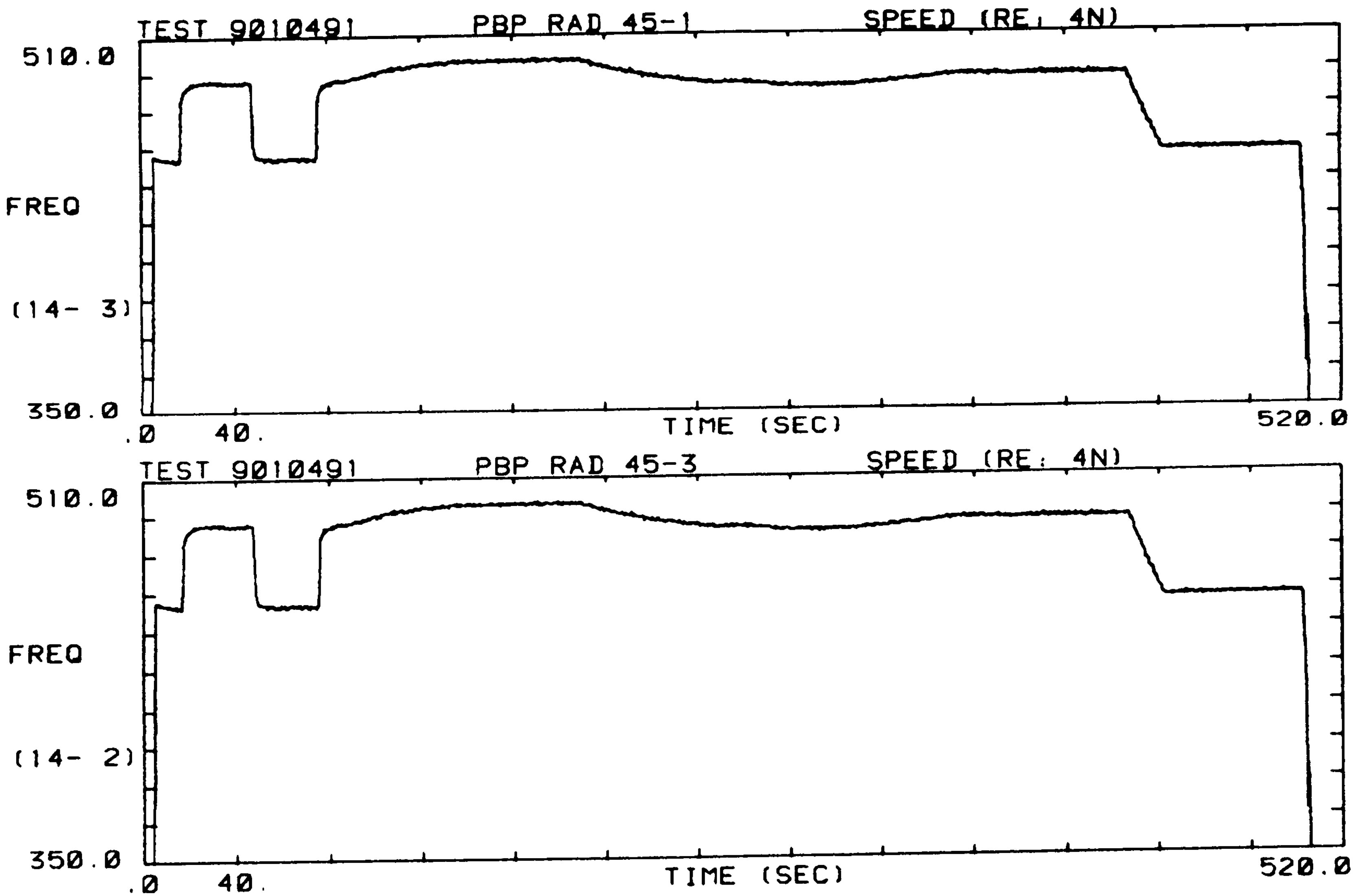

Figure 4. Component speed trace.

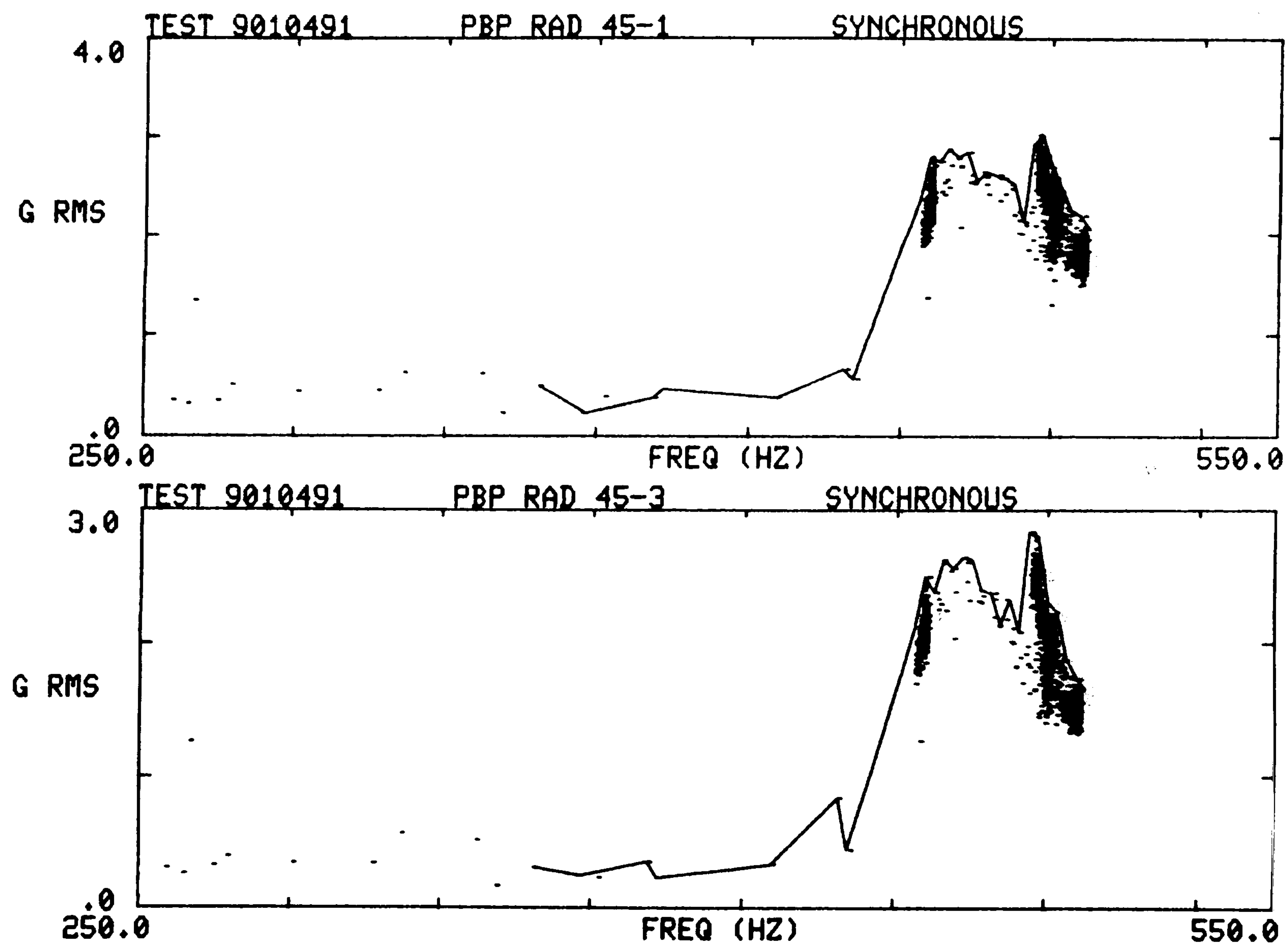

Figure 5. RMS versus speed.

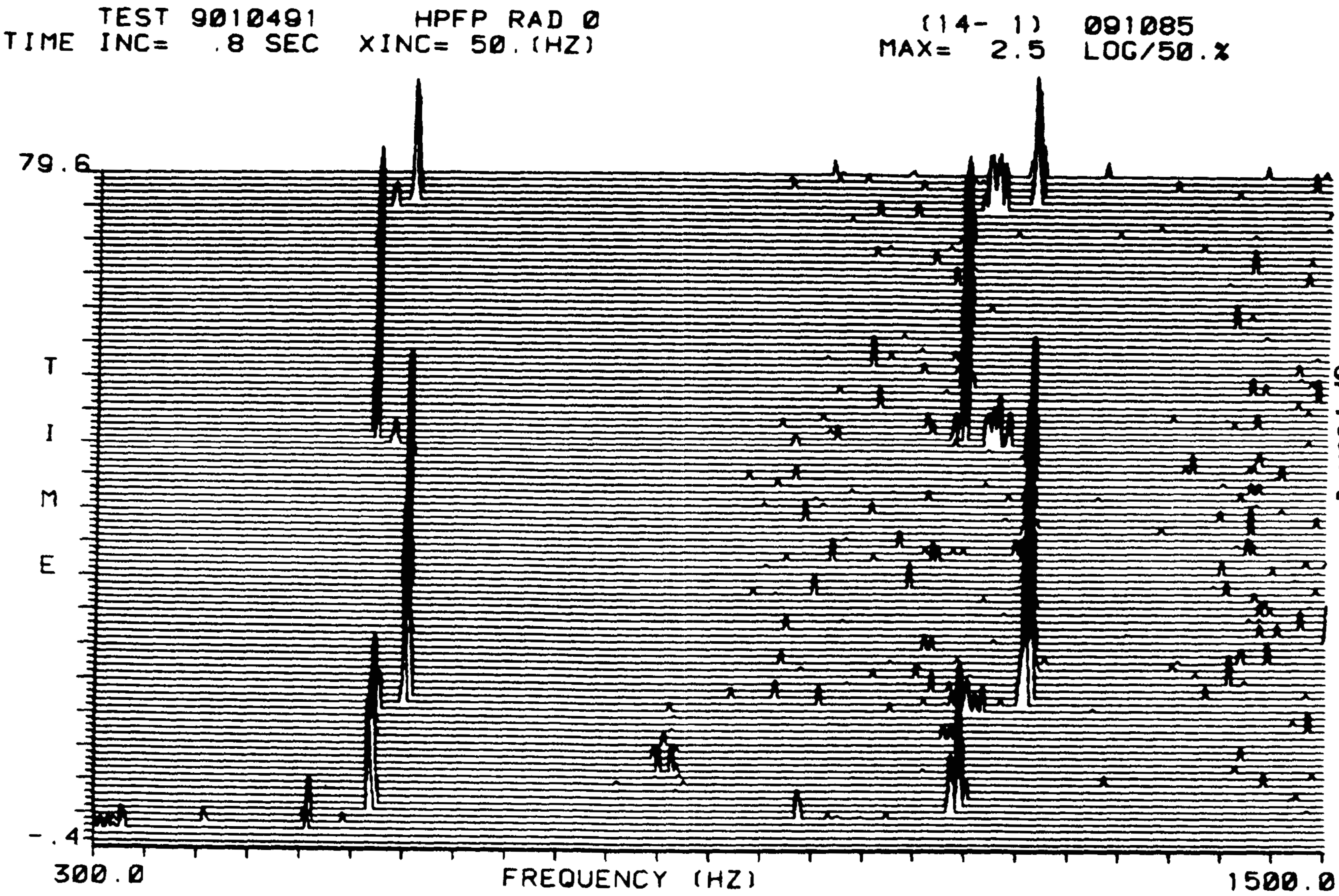

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Figure 6. ISOPLOT (not skewed).

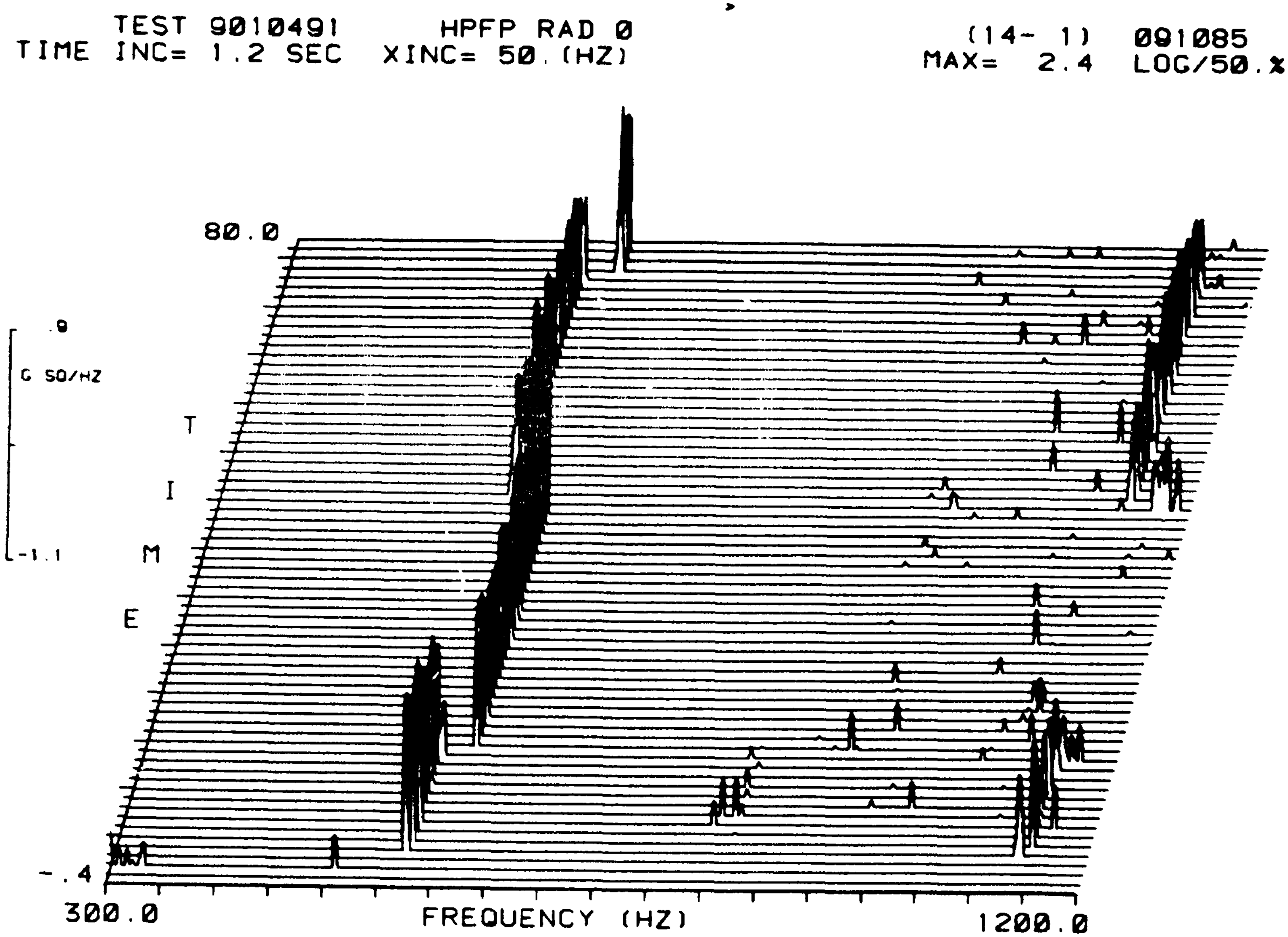

Figure 7. ISOPLOT skewed left to right.

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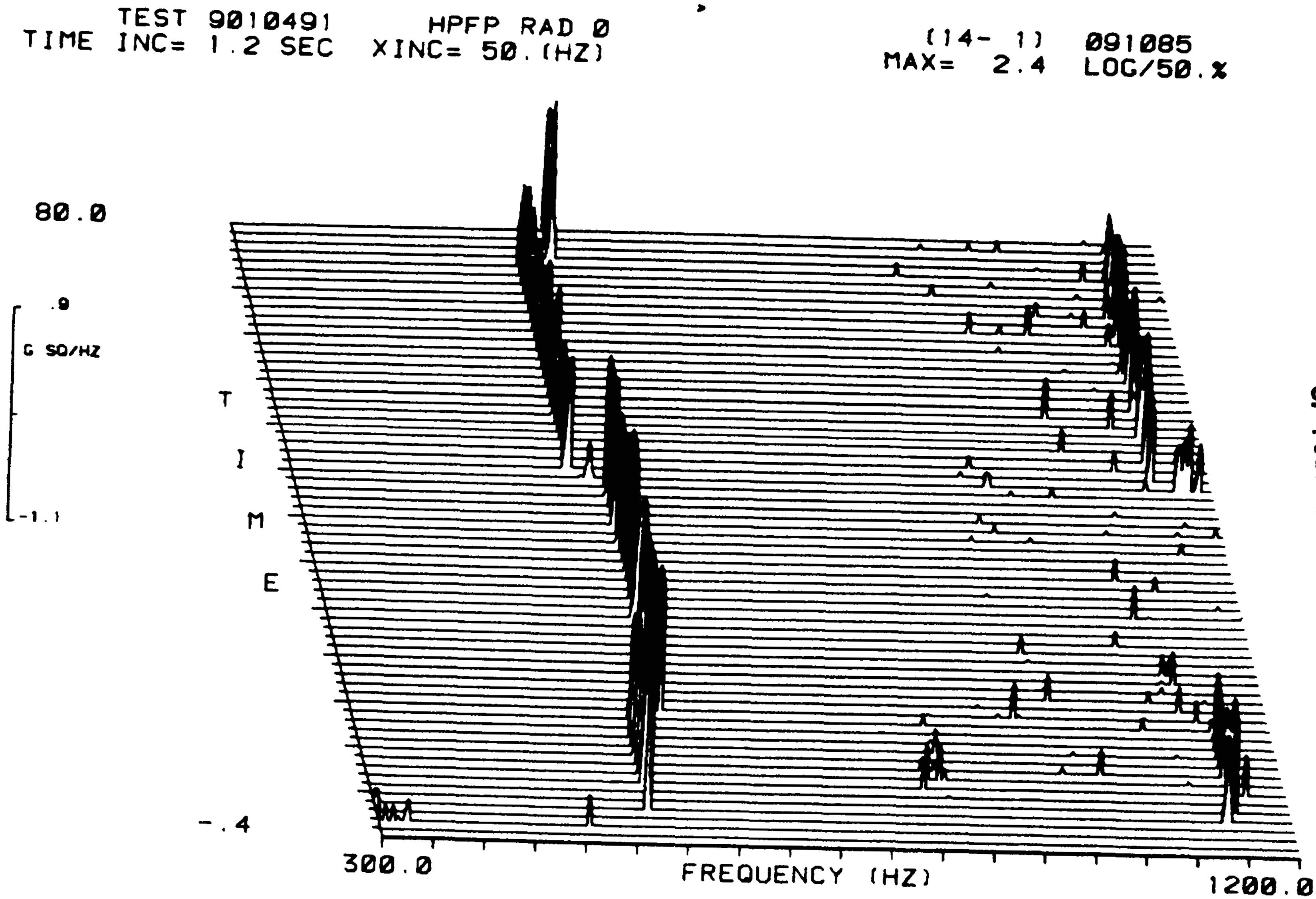

Figure 8. ISOPLOT skewed right to left.

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TEST 9020383 1600.0 TO 1900.0 HZ

1) HPFP RAD 0
2) HPFP RAD 90
3) HPFP RAD 174
4) HPFP RAD 186

TIME	PWRLVL	MEAS #	SYNC	FREQ	AMP	FREQ	AMP	FREQ	AMP	FREQ	AMP	FREQ	AMP
100.0	104.0%	1)	581.4	1705.0	.297	1847.5	.142	1747.5	.267	1682.5	.226	1865.0	.147
		2)		1722.5	.648	1750.0	.712	1745.0	.678	1727.5	.544	1700.0	.452
		3)		1705.0	.471	1847.5	.556	1745.0	.686	1720.0	.261	1710.0	.486
		4)		1745.0	.418	1790.0	.447	1750.0	.379	1767.5	.381	1865.0	.612
100.4	104.0%	1)	581.5	1655.0	.251	1690.0	.107	1745.0	.183	1685.0	.202	1680.0	.198
		2)		1705.0	.492	1740.0	.504	1745.0	2.196	1732.5	.227	1710.0	.383
		3)		1735.0	.532	1762.5	.483	1745.0	.396	1715.0	.399	1820.0	.353
		4)		1847.5	.672	1787.5	.345	1745.0	.611	1760.0	.541	1710.0	.463
100.8	104.0%	1)	581.4	1700.0	.352	1740.0	.212	1730.0	.183	1685.0	.304	1827.5	.209
		2)		1745.0	1.129	1900.0	.365	1762.5	.346	1715.0	.358	1735.0	.349
		3)		1745.0	.935	1737.5	.561	1790.0	.432	1785.0	.341	1827.5	.850
		4)		1820.0	.608	1832.5	.392	1762.5	.599	1780.0	.412	1847.5	.405
101.2	104.0%	1)	581.1	1760.0	.211	1720.0	.198	1670.0	.197	1710.0	.179	1705.0	.176
		2)		1745.0	1.318	1717.5	.597	1732.5	.237	1680.0	.540	1700.0	.404
		3)		1762.5	.406	1720.0	.337	1687.5	.455	1737.5	.306	1742.5	.970
		4)		1827.5	.932	1745.0	.833	1822.5	.492	1817.5	.418	1790.0	.529
101.6	104.0%	1)	581.2	1760.0	.178	1752.5	.189	1650.0	.227	1707.5	.232	1680.0	.463
		2)		1762.5	.528	1742.5	1.353	1735.0	.294	1710.0	.307	1705.0	.417
		3)		1757.5	.301	1752.5	.553	1742.5	.723	1837.5	.373	1867.5	.492
		4)		1760.0	.447	1772.5	.241	1767.5	.443	1742.5	.937	1780.0	.394
102.0	104.0%	1)	581.4	1697.5	.289	1752.5	.269	1745.0	.213	1717.5	.158	1637.5	.236
		2)		1760.0	.330	1752.5	.384	1742.5	1.215	1725.0	.435	1707.5	.304
		3)		1697.5	.293	1752.5	1.185	1740.0	.393	1710.0	.388	1802.5	.384
		4)		1807.5	.458	1752.5	.702	1742.5	.357	1765.0	.538	1827.5	.355
102.4	104.0%	1)	581.5	1712.5	.380	1727.5	.218	1692.5	.209	1707.5	.204	1662.5	.194
		2)		1745.0	1.060	1760.0	.239	1752.5	.633	1732.5	.292	1740.0	.233
		3)		1745.0	1.099	1810.0	.431	1767.5	.321	1722.5	.391	1852.5	.356
		4)		1752.5	1.152	1877.5	.343	1855.0	.345	1847.5	.319	1802.5	.335
102.8	104.0%	1)	581.5	1715.0	.142	1750.0	.238	1737.5	.161	1657.5	.236	1722.5	.292
		2)		1745.0	2.824	1790.0	.527	1737.5	.420	1732.5	.546	1722.5	.571
		3)		1745.0	.493	1750.0	.673	1730.0	.480	1755.0	.319	1722.5	.344
		4)		1745.0	.690	1852.5	.573	1820.0	.395	1787.5	.440	1862.5	.331
103.2	104.0%	1)	581.5	1662.5	.334	1775.0	.313	1677.5	.295	1630.0	.276	1650.0	.185
		2)		1745.0	2.570	1750.0	1.299	1730.0	.560	1737.5	.221	1722.5	.475
		3)		1662.5	.366	1867.5	.376	1677.5	.213	1685.0	.251	1745.0	.537
		4)		1750.0	.812	1772.5	.445	1857.5	.512	1745.0	.543	1730.0	.465
103.6	104.0%	1)	581.1	1707.5	.276	1790.0	.203	1690.0	.152	1700.0	.123	1695.0	.145
		2)		1745.0	1.505	1892.5	.452	1882.5	.313	1755.0	.378	1737.5	.321
		3)		1765.0	.477	1790.0	.387	1895.0	.289	1720.0	.383	1730.0	.272
		4)		1745.0	.467	1802.5	.433	1795.0	.379	1782.5	.226	1765.0	.366

Figure 9. Peak identification.

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locks on to it and computes its frequency, RMS value, and the ratio of its frequency to the current pump frequency. The onset of the anomalous frequency can be easily seen by observing the frequency versus time plot. During the time in which the anomalous frequency is not present, or its amplitude is below the background noise, the plot has a great deal of variation, i.e., the tracker is simply picking up random noise peaks. At onset, however, the tracker locks on and the frequency versus time trace smooths out dramatically. An example anomalous frequency plot is given in Figure 10.

Summarized Data Computation

During each static firing or flight, it is necessary to define a single value (G RMS) to characterize each measurement response at each power level. These response values are used to define the operating environment for an individual pump during a particular test. These values, when taken together, will describe the overall health of each pump subsequent to the following test. Previously, these values were determined manually by the dynamicist during each test evaluation exercise. This manual technique would be to define an average-maximum value sustained during each power level of the test duration from the RMS time history data. Considerable engineering judgement was required to insure that no spurious peaks or other short-lived responses were considered while the maximum sustained responses were identified. These average-maximum values were then inputed into the Diagnostic Data Base by hand for use in statistical analyses or other analysis of the data.

An algorithm was developed to simulate this engineering method by computing 11-point floating averages over each power level duration. It has been observed that a sliding average of this order closely approximates the value that would normally be obtained by a dynamicist evaluating the test. The maximum average computed is preserved for each measurement at all power levels and output in tabular form (Fig. 11). This provides a quick summary of the overall character of the test under evaluation. The exercise of ruling out spurious peaks or other short-lived responses is left to the engineer. A significant feature of this routine is the ability to transfer this summarized data to the MSFC located Diagnostic Data Base. This host-to-host automated transfer saves hours of manual data entry time and eliminates manual data entry error.

Speed Histogram

A recent development in the Isospectral Data Base is a routine which calculates and displays a histogram of the pump rotation speed. This plot shows the cumulative time in seconds that the pump speed was active. This display is useful in defining the amount of time spent at potentially detrimental speeds. The user has total control over all plot scales and the frequency bin width. The user also has the option to include more than one test in the analysis. An example histogram is shown in Figure 12.

DIAGNOSTIC DATA BASE

The Diagnostic Data Base is located in-house at MSFC, ED24, on a Tektronix microcomputer. The data storage medium is a TransEra 40 Mbyte Winchester Disk. This data base contains the summarized RMS values computed in the above mentioned routine. There are currently 599 single engine tests, 4 flight readiness firings, and

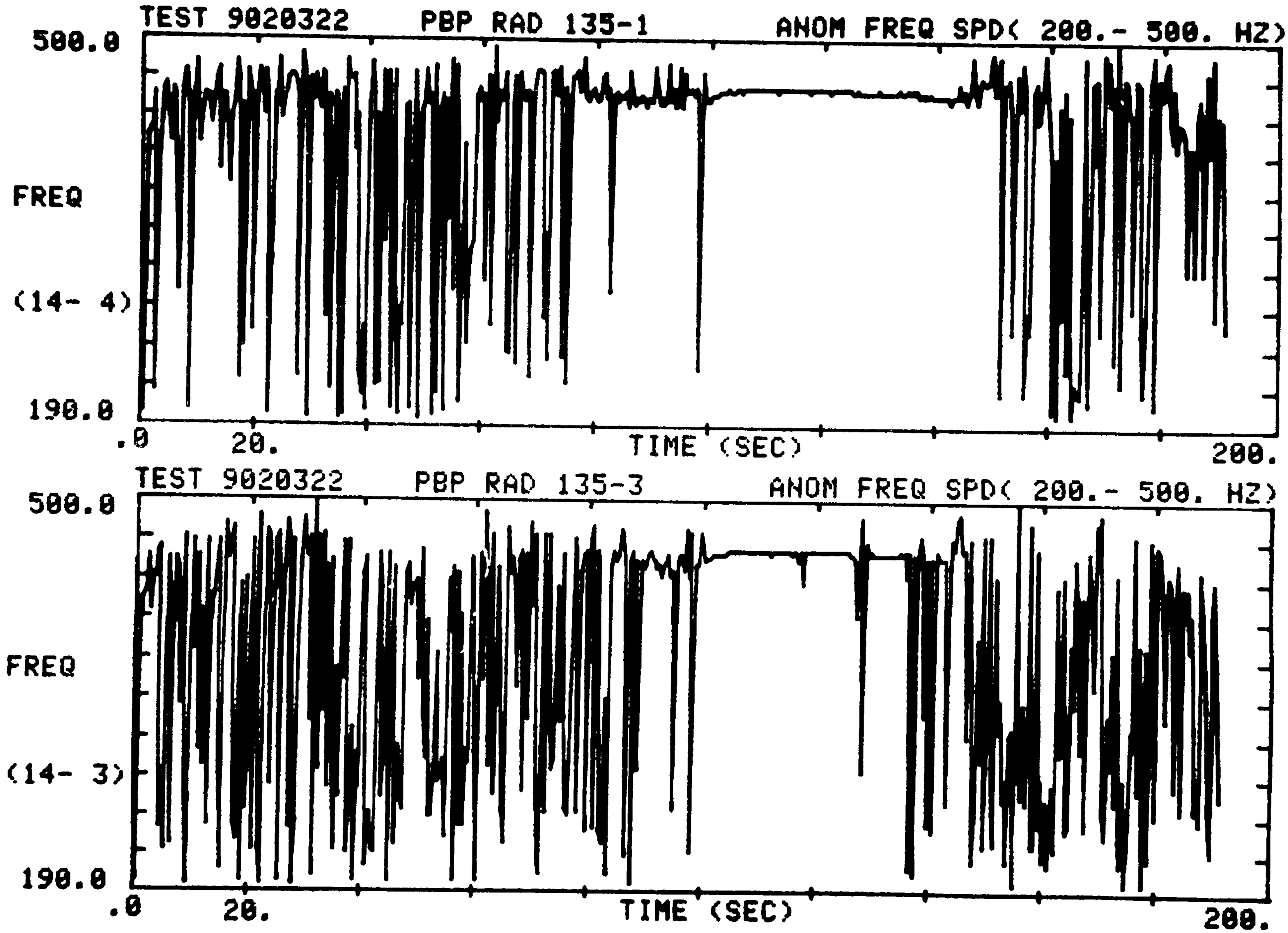

Figure 10. Anomalous frequency plot.

TEST 9020375 (091085)	65.% 453.	100.% 570.	104.% 590.	109.% 605.
HPFP RAD 0				
COMP (50-1K)	1.4	2.2	3.4	4.1
SYNCHRONOUS	.9	.6	2.6	3.4
2*SYNC	.2	.4	.5	.5
3*SYNC	.5	.8	1.4	1.4
4*SYNC	.3	.5	1.3	1.2
HPFP RAD 90				
COMP (50-1K)	1.0	1.4	3.1	2.3
SYNCHRONOUS	.6	.3	2.2	1.7
2*SYNC	.2	.2	.7	.3
3*SYNC	.3	1.0	2.3	5.2
4*SYNC	.8	1.1	1.7	1.4
HPFP RAD 174				
COMP (50-1K)	1.5	2.5	4.6	4.2
SYNCHRONOUS	1.0	.8	3.7	3.1
2*SYNC	.3	.7	1.1	.6
3*SYNC	.2	1.4	2.8	6.0
4*SYNC	1.0	.7	2.0	2.4
HPFP RAD 186				
COMP (50-1K)	1.4	2.9	4.8	5.0
SYNCHRONOUS	.9	1.1	3.6	3.3
2*SYNC	.3	.7	1.4	.5
3*SYNC	.3	1.3	2.6	5.8
4*SYNC	1.1	.8	1.7	2.3
HPFT RAD 90 ACC				
COMP (50-1K)	2.5	6.3	6.6	7.2
SYNCHRONOUS	.8	1.1	2.8	2.1
2*SYNC	.5	1.0	2.5	3.2
3*SYNC	1.9	1.7	2.8	2.4
4*SYNC	2.5	1.9	2.4	1.6

Figure 11. Summarized data tabulation.

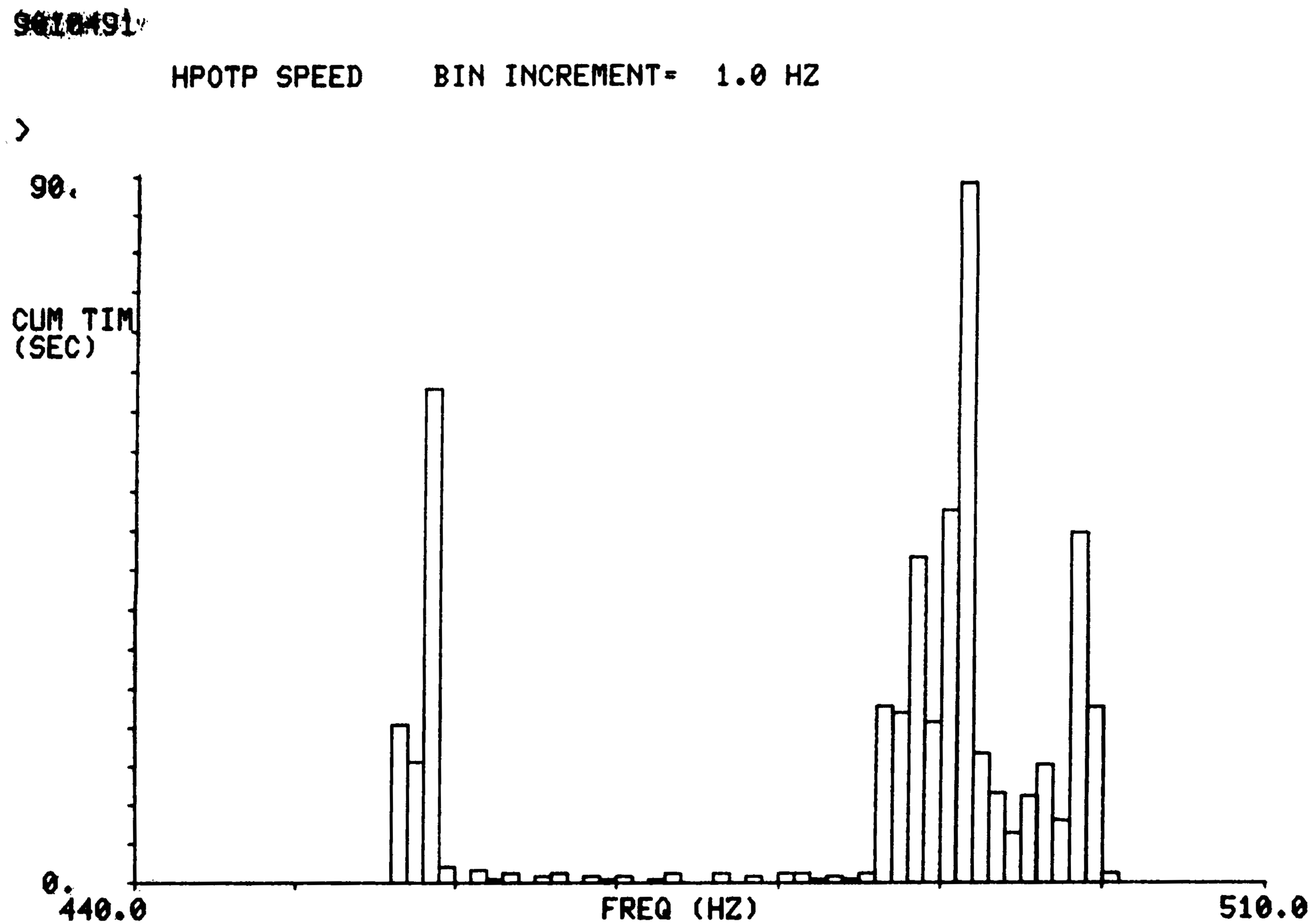

Figure 12. Speed histogram.

25 STS flights available to the user. Sixteen measurements are maintained, eight for the HPFTP and eight for the HPOTP. Other test related parameters are housed, including engine, HFPTP and HPOTP serial numbers, power level profile, and pump speeds at each defined power level. The serial number information is also stored in a separate directory file, giving the user the capability to access test(s) by a particular pump or engine identification. This option allows for direct comparison between different pumps or pump-build configurations. It also saves the user from the time consuming task of typing in all the desired test numbers.

Several processing and display routines are available to the user. The more widely used functions are described below. It is important to note here that all processing can be done for the composite, synchronous, two * synchronous, three * synchronous or 4 * synchronous RMS amplitudes.

Directory

This option not only lists the tests available, but also lists the test date, the engine, HPFTP and HPOTP serial numbers, and the power levels for which data is available (Fig. 13). This on-line per test information printout is a detailed window as to what data are contained in the data base.

Lifetime Power Level Activity List

This function documents the complete lifetime hot firing activity for a user defined engine or pump. This lifetime is broken down and categorized by each individual test and further by each power level active during the test. Using this printout, the user can immediately identify the amount of time (in seconds) a particular pump (including revisions, if desired) has been active for each power level and the total operational time. An example output is given in Figure 14.

Summary Sheet Printout

This option prints out the RMS values for a user defined set of tests in a block chart format. The chart includes the RMS values for all 16 measurements, 8 per page (Figs. 15 and 16). This output provides the user with a tabular listing of the RMS amplitudes over any test range. This document is also used as the standard overhead viewchart for reporting pump vibration performance during engine data reviews and evaluations.

Statistical Analysis

Without a doubt the most powerful computation routine in the Diagnostic Data Base, the statistics option has been used extensively to develop statistical models characterizing normal and abnormal pump behavior and to establish and update engine cutoff redlines. The statistics software computes the mean, standard deviation, and the maximum RMS amplitude for all sixteen measurements. Also computed is the probability density/distribution function using a GRMS bin width of 0.5. The output of this package includes a tabular listing of mean, standard deviation, and maximum RMS amplitude broken down by test stand (Fig. 17), probability distribution (Fig. 18), and probability density plots (Fig. 19). For the distribution and density plots, the user can request an overlay of several classical statistical functions. The application

TEST #	DATE	ENG #	HPFTP #	HPOTP #	90	100	102	104	109
A1-450	7/26/84	0207	0309R1	2308R1		X			X
A1-451	8/9/84	0207	0309R2	2308R1		X			
A1-452	8/21/84	0207	90701R1	2606R2	X	X			X
A1-453	08/31/84	0207	90701R1	2606R2	X	X		X	X
A1-454	09/12/84	0207	90701R1	2606R2	X	X			X
A1-455	09/21/84	0207	90701R2	2606R3		X			X
A1-456	9/25/84	0207	90701R2	2606R3		X			X
A1-457	09/29/84	0207	90701R2	2606R3		X			X
A1-458	10/05/84	0207	90701R2	2606R3		X			X
A1-459	10/26/84	0207	0309R3	2606R3		X			X
A1-460	11/12/84	0207	0309R3	9505		X			X
A1-461	12/28/84	0207	2209	9505R1		X			X
A1-462	01/05/85	0207	2209R1	9505R1		X			X
A1-463	01/14/85	0207	2209R1	9505R1		X			X
A1-464	1/17/85	0207	2209R1	9505R1		X			X
A1-465	1/19/85	0207	2209R1	9505R1		X			X
A1-466	1/24/85	0207	2209R1	9505R1		X			X
A1-467	1/30/85	0207	2209R1	9505R1		X			X
A1-468	02/04/85	0207	2209R2	9505R1		X			X
A1-470	2/25/85	2105	4004	2217		X		X	X
A1-471	02/27/85	2105	4004	2217		X			X
A1-472	03/04/85	2105	4004R1	2217		X		X	
A1-473	03/06/85	2105	4004R1	2217		X			X
A1-474	3/22/85	2105	4004R1	9808		X			X
A1-475	4/17/85	2105	4004R2	9808		X		X	
A1-476	5/21/85	2105	5102R1	9505R2		X			X
A1-477	05/24/85	2105	5102R1	9505R2		X		X	X
A1-478	06/01/85	2105	5102R1	9505R2		X			X
A1-479	6/5/85	2105	5102R1	9505R2		X			X
A1-480	6/7/85	2105	5102R1	9505R2		X			X
A1-481	6/10/85	2105	5102R1	9505R2		X		X	

Figure 13. Directory output format.

SSME LIFETIME ANALYSIS

HPFTP SERIAL # 5102R1

		>>>>>>>>>>>>>>>>>>>> RUN SECONDS AT <<<<<<<<<<<<<<<<<<<<										
TEST #	DUR.	63%	65%	90%	100%	102%	104%	106%	109%	111%	OTHER	RAMP
A1-476	70	0	0	0	9	0	0	0	30	0	0	31
A1-477	250	0	0	0	74	0	19	0	149	0	0	8
A1-478	503	0	0	0	99	0	0	0	380	0	0	24
A1-479	503	0	0	0	99	0	0	0	380	0	0	24
A1-480	503	0	0	0	99	0	0	0	380	0	0	24
A1-481	520	0	0	0	89	0	416	0	0	0	0	15
A1-482	520	0	0	0	87	0	416	0	0	0	0	17
A1-483	520	0	0	0	87	0	416	0	0	0	0	17
A1-484	603	0	0	0	11	0	0	0	586	0	0	6
A1-486	520	0	0	0	89	0	416	0	0	0	0	15
A1-487	503	0	0	0	27	0	124	0	330	0	0	22
A1-488	503	0	0	0	95	0	0	0	0	381	0	27
		---	---	---	---	---	---	---	---	---	---	---
TOTAL		0	0	0	864	0	1807	0	2235	381	0	231

TOTAL OPERATIONAL TIME = 5518 SECONDS

Figure 14. Component lifetime analysis.

HPOTP DATA COMPARISON *=early co

PUMP SERIAL #	4004R1	4004R1	4004R1	4004R1	4004R1	
TEST NUMBER	A1-492	A1-492	A1-493	A1-493	A1-493	
PWR LVL/SYNC FREQ	100%/459	109%/493	100%/458	104%/471	109%/489	
PUMP RAD (45)						
Composite	4.4	5.1	4.6	5.3	5.0	
Synchronous	2.5	2.4	2.2	2.7	2.2	
PUMP RAD (135-1)						
Composite						
Synchronous						
PUMP RAD (135-2)			(noisy)	(noisy)	(noisy)	
Composite	4.2	5.3	6.6	9.5	7.3	
Synchronous	1.2	1.8	1.2	1.3	1.4	
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite	4.6	6.2	4.4	5.2	5.6	
Synchronous	2.6	2.5	2.3	2.7	2.1	
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite	4.8	4.7	4.5	4.5	4.0	
Synchronous	2.9	2.5	2.6	2.8	2.1	
TURB. RAD (135)						
Composite	4.4	3.6	3.9	3.7	2.9	
Synchronous	2.7	2.1	2.3	2.1	1.6	

Figure 15. Summary sheet for HPOTP measurements.

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HPFTP DATA COMPARISON *=early co

PUMP SERIAL #	0307	0307	0307R1	0307R1	0307R1	
TEST NUMBER	A1-492	A1-492	A1-493	A1-493	A1-493	
PWR LVL/SYNC FREQ	100%/578	109%/608	100%/575	104%/588	109%/605	
PUMP RAD (0)						
Composite	2.8	4.2	2.4	2.3	3.2	
Synchronous	1.6	3.3	0.7	0.5	2.2	
PUMP RAD (90)						
Composite	6.2	7.6	5.6	5.0	6.0	
Synchronous	2.6	2.7	2.1	1.6	1.3	
PUMP RAD (174)						
Composite	4.8	6.4	5.3	4.9	4.7	
Synchronous	1.9	3.0	1.9	1.6	1.4	
PUMP RAD (186)						
Composite	5.2	6.3	4.7	5.8	6.0	
Synchronous	1.4	2.8	1.4	2.5	3.0	
TURB. RAD (90)						
Composite	7.8	7.4	7.9	8.4	6.9	
Synchronous	5.1	4.7	5.4	3.9	4.3	
TURBINE AXIAL						
Composite						
Synchronous						
TURB RAD (180)						
Composite	6.0	5.9	6.1	5.8	5.9	
Synchronous	3.5	3.5	3.0	2.2	3.6	
PUMP RAD (125)						
Composite						
Synchronous						

Figure 16. Summary sheet for HPFTP measurements.

Synchronous @100% Power Level

Test Stand	FUEL PUMP RAD 0 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 174 # Tests	$\bar{G}$ rms	Sig	Max G rms
A1	191	3.4	1.9	10.8	174	2.8	1.6	10.1	76	3.7	1.8	11.9
A2	82	2.7	1.7	7.9	76	1.9	1.1	6.9	47	2.6	1.3	6.2
A3	150	3.2	1.6	7.8	149	3.1	1.7	10.5	50	3.0	1.5	6.0
Combined	423	3.2	1.8	10.8	399	2.7	1.6	10.5	173	3.2	1.6	11.9

STATISTICAL SUMMARY OF SSME VIBRATION DATA 18-JUL-86 14:
37:52

Synchronous @100% Power Level

Test Stand	FUEL PUMP RAD 186 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB AXIAL # Tests	$\bar{G}$ rms	Sig	Max G rms
A1	163	3.9	2.1	13.9	128	2.7	1.6	10.4	107	2.5	1.5	8.5
A2	76	2.8	1.5	6.5	81	2.3	1.2	6.0	42	2.3	1.2	6.2
A3	137	3.5	1.8	11.0	124	3.9	2.2	10.4	76	3.3	1.5	8.2
Combined	376	3.5	1.9	13.9	333	3.1	1.9	10.4	225	2.7	1.5	8.5

TEST #'S A1183-489,A2221-374,A3064-259,

Figure 17. Statistical tabulation.

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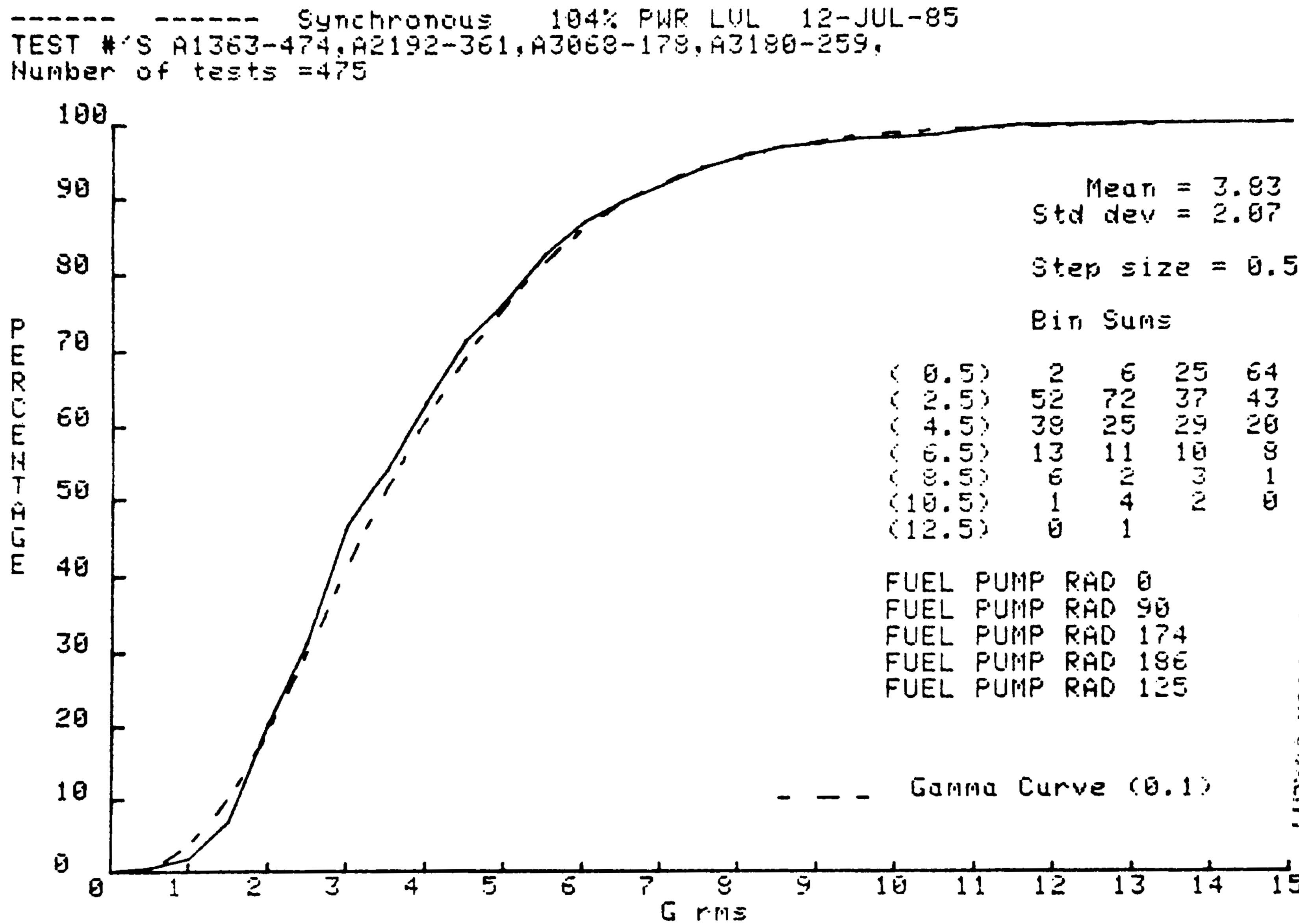

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Figure 18. Probability distribution.

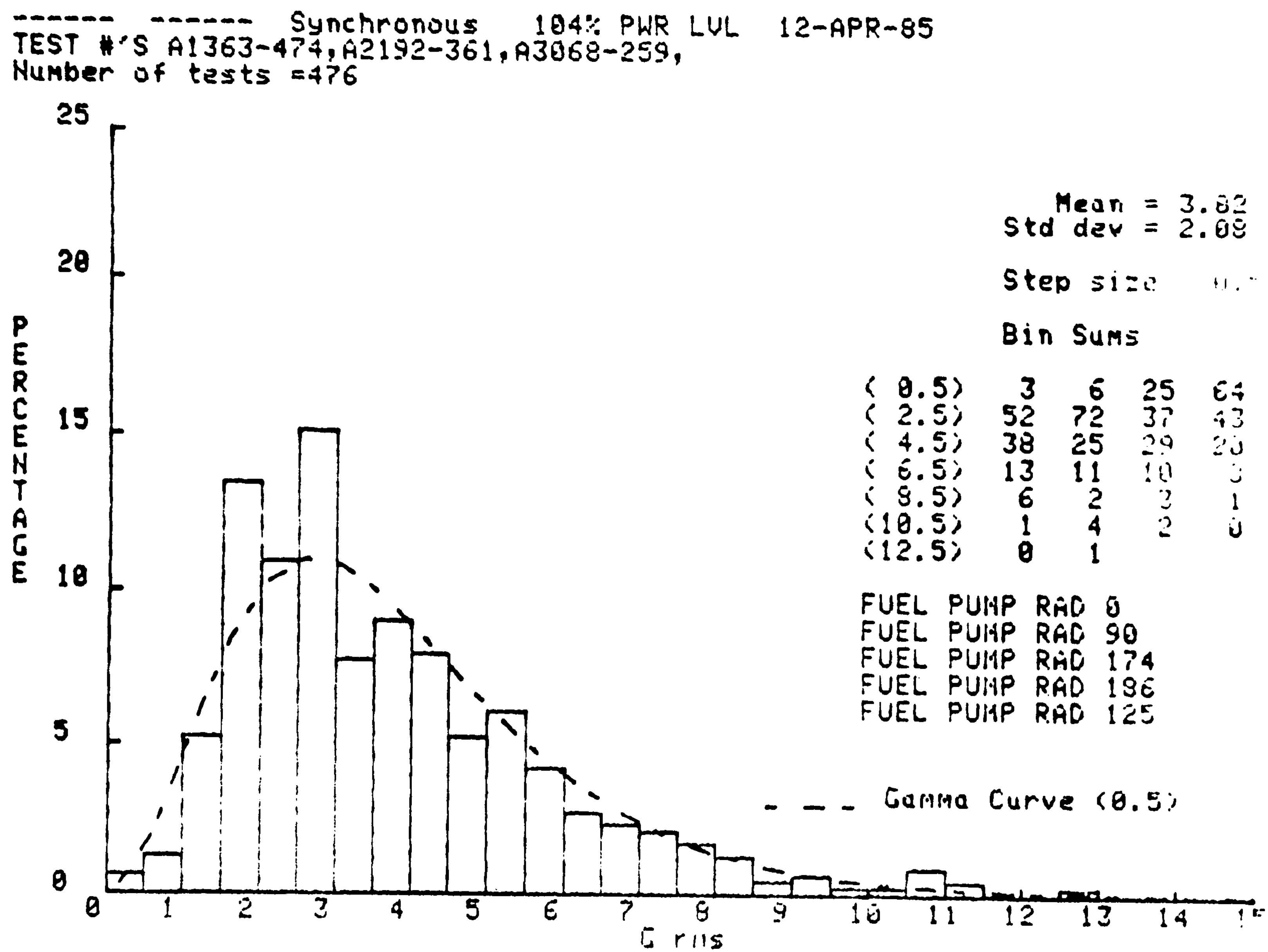

Figure 19. Probability density.

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of classical distributions is desirable to enhance data characterization since this permits continuous statistical definition and manipulation from discrete measurement observations. This routine has recently been enhanced to calculate the statistical parameters associated with the RMS level acquired by dividing synchronous by composite (Fig. 20).

DATA ACQUISITION PROCESS

The initial process in the SSME Vibration Data Base is the data reduction/conversion from continuous analog form to digital PSD form. To accomplish this task, an automated data reduction system was designed utilizing the equipment and manpower at the Slidell Computer Complex (SCC) Data Reduction Laboratory. This site was chosen due to its proximity to the single engine test stands at National Space Technology Laboratory (NSTL). SCC has not only the necessary data reduction facility, but also has the mainframe computer facilities required to house the massive amount of data.

The automated data reduction system has revolutionized single engine test and STS flight vibration data analysis. The previous data reduction system was located at MSFC and consisted of microprocessor based Fast Fourier Transform (FFT) analyzers and digital waveform analyzers. This equipment has no significant data storage capability; therefore, analog data had to be redigitized every time any new analysis was done. Another hindrance to this system was the inability to transport the analog tapes from NSTL to MSFC immediately following a test. In fact, the tapes would not arrive at MSFC until approximately 9:00 a.m. the following day. The new system is designed so that data reduction and display takes place during the late night and early morning hours following a test. This means that by the time analog tapes would arrive at MSFC under the old system, the new system has provided the engineers responsible for data review a complete data package consisting of three to four times the normal output of the old system.

The data processing flow for this system is defined as follows (Fig. 21):

1. Data are recorded at the test stand on analog magnetic tape. Following the test, the analog tapes are transported by automobile to Slidell Computer Complex (SCC).

2. The data are converted from analog to digital form and stored on disk in time domain. The sample rate is 5120 samples/second. It is important to note here that the data are contiguous, i.e., there are no gaps or missing samples within the data.

3. The data are recalled from disk in blocks of 2048 points. This is equivalent to 0.4 sec of time data.

4. Each block of 2048 points is then converted from time domain to frequency domain using the FFT and then converted to PSD form using equation (1). The factor of two is applied to account for negative fequencies. There is no window applied to the time data before conversion. From the above stated sample frequency, the resulting PSD bandwidth is 2.5 Hz. This yields a maximum frequency of 2560 Hz.

5. Each PSD, 1024 points, is then stored to digital magnetic tape. Consecutive PSD's are written to tape for the entire test duration.

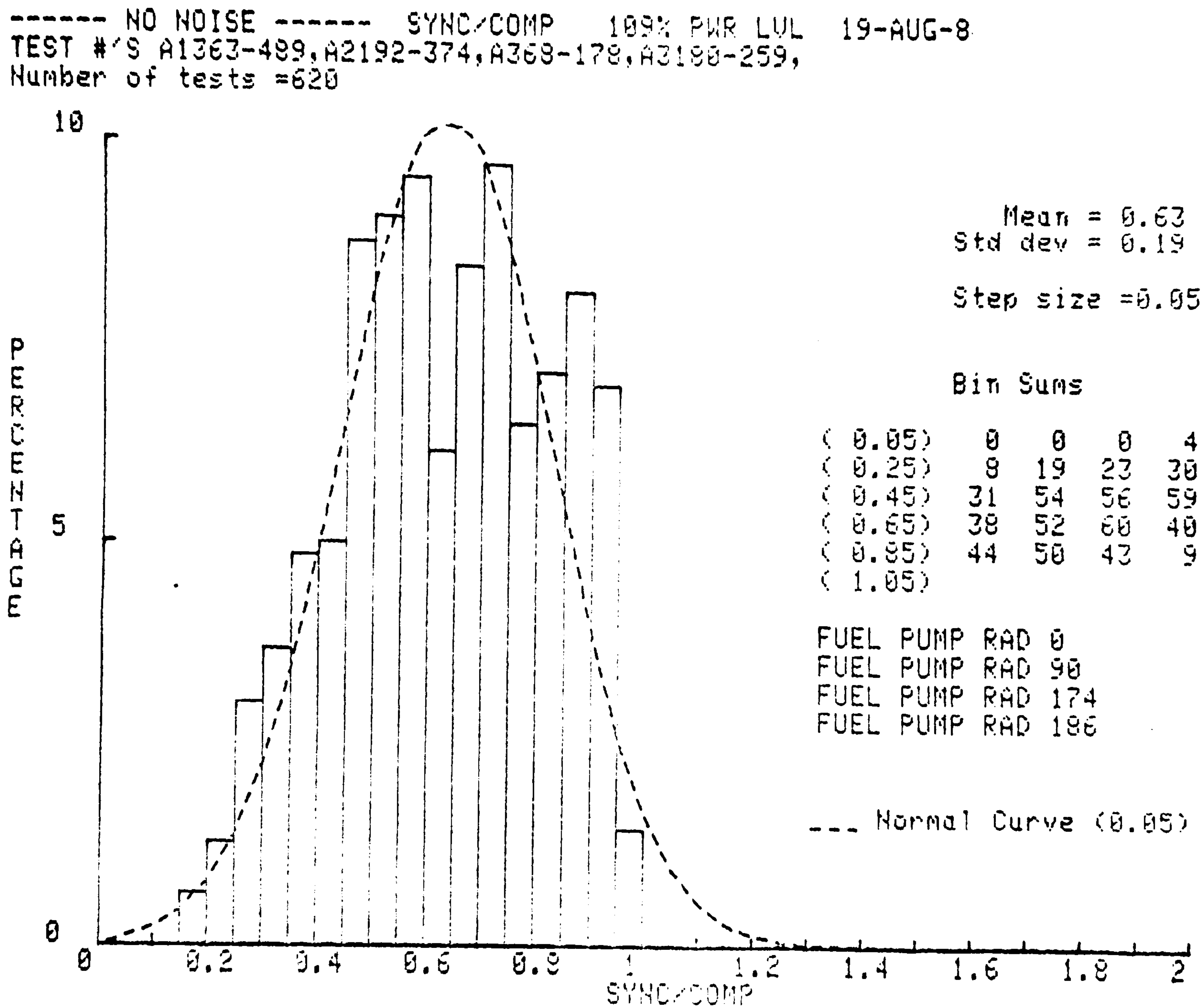

Figure 20. Sync RMS/composite RMS probability density.

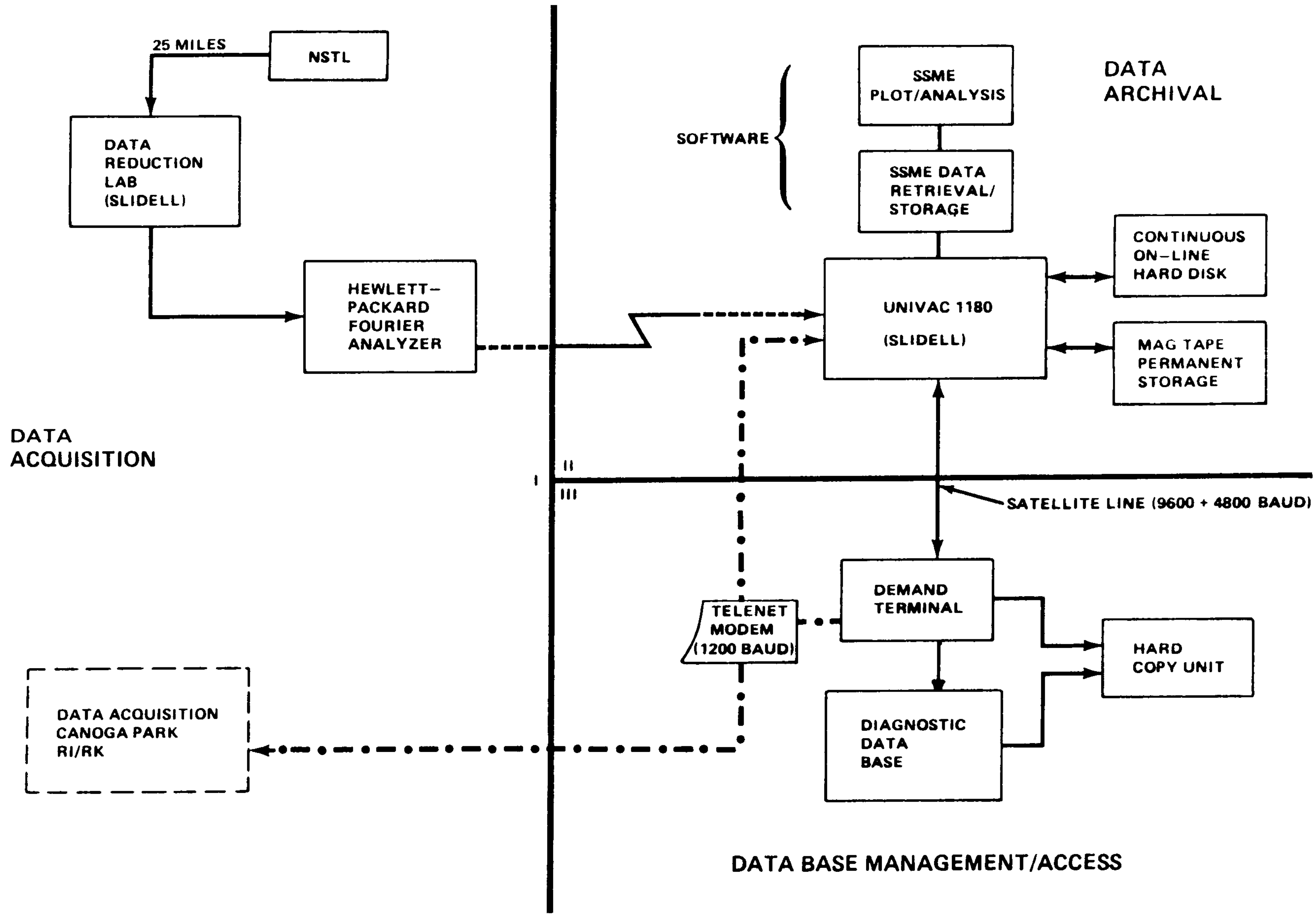

Figure 21. Data processing flow.

(Steps 1 through 5 are performed in the data reduction room at SCC using a Hewlett Packard 5451C Fourier Analyzer. Six measurements can be processed during a single pass through these steps. For a 500-sec test duration, this process takes approximately 3 hr for every six measurement pass.)

(The remaining steps take place on the UNIVAC 1100 computer.)

6. The PSD digital magnetic tapes are rolled in to the UNIVAC and made ready for processing.

7. Technicians at MSFC access the UNIVAC through satellite computer links and execute plot and analysis software from Tektronix graphic terminals. For a typical afternoon test firing, the first six measurements will be available for plotting at approximately 2:00 a.m. the following morning.

SOFTWARE DESCRIPTION

The following technical descriptions are provided for potential users of this software. All of the described code is written in ASCII FORTRAN on the UNIVAC 1100 system at SCC. All of the algorithms described can operate on up to six measurements at a time.

Synchronous Peak Detection

Before any pump speed related parameters can be computed, the synchronous speed has to be defined. This is a critical step in any turbomachinery vibration analysis process, particularly for the SSME turbomachinery because of the wide operating speed range; i.e., 20,000 to 37,000 RPM. The periodic (discrete) components present in the vibration data are directly related to the turbopump's operating speed. Subroutine "INTPSD" accomplishes this task. The algorithm consists of the following steps:

1. Search interval definition – MSFC engineers have developed equations using past history data that identify the approximate speed of a pump given the current power level (percent rated power level). The search range is from the predicted speed minus 25 Hz to the predicted speed plus 25 Hz. This range is adjusted for HPOTP data to detect the fourth harmonic of the synchronous peak by simply multiplying the limits by four (single engine test data only). Likewise, the low pressure oxidizer turbopump (LPOTP) is adjusted to detect the eighth harmonic.

2. Spatial average computation – The PSD for each measurement is summed together to obtain a single, spatial averaged PSD. This averaging reduces the noise level and enhances the periodic components.

3. Peak identification – Once the search interval is defined, the algorithm then locates the highest peak value within the search interval and saves its corresponding channel number.

Speed Estimation

Due to a fixed delta frequency of 2.5 Hz, the calculation of pump speed using only the discrete frequency peak is accurate within 150 RPM. To obtain a higher degree of pump speed computation accuracy, a routine was developed which will provide an estimate of the speed by using not only the discrete peak but its corresponding side bands as well. The side band information is necessary due to the leakage effect caused by the FFT. In other words, the pump speed will be exactly correct if and only if the discrete frequency is in the center of the analyzer spectral bandwidth.

The interpolation equation used to provide a measure of leakage uses a coefficient "R" defined as:

$$R = [(Ai - N)/(Aj - N)] \quad ,$$

where:

Ai = Maximum mean squared amplitude within speed search window

Aj = Mean squared amplitude of left or right side band of Ai (whichever is greater)

N = Background noise mean squared level.

This coefficient is then substituted into an empirical equation which provides an estimate of the frequency of the discrete signal as a function of percent of analyzer bandwidth. This equation has been verified experimentally as well as theoretically and is used to compute the channel correction factor (CCF). This equation is defined by:

```
CCF = (0.1878855/R ** 3) - (0.2290493/SQRT(R ** 5)) + (0.13210677/R **2)

      - (0.7820805/SQRT(R ** 3)) + (1.206314/R) - (0.01570345/SQRT(R))  .
```

The CCF is added or subtracted, depending on which side band is used (upper or lower), to the peak channel number, then multiplied by the delta frequency to obtain a more accurate estimation of the true speed.

Anomalous Frequency Detection

Any dominant or lingering discrete frequency which is not a multiple of the pump speed is termed an anomalous frequency. As described, this routine tracks these frequencies by rejecting the synchronous speed harmonics of all engine components and analyzing the remainder. The routine was developed as a spinoff to the synchronous speed detection scheme. In fact, the speed detection routine is executed prior to the anomalous frequency search. Once the synchronous speed is determined, the anomalous frequency routine searches for the maximum amplitude within the user defined frequency range. Any frequency point within two bandwidths either side of a synchronous harmonic is rejected. The recent development of the speed estimation routine has made it possible to include points closer to the synchronous harmonic due to the higher resolution speed computation.

Once the maximum amplitude is found, its RMS value is computed using a user defined number of side bands as well as the peak. This will provide an accurate estimate of the RMS value and is required because of leakage effects. Its frequency is then determined, and the ratio of the synchronous frequency to the anomalous frequency is calculated. These three values are saved for later plotting.

Standard Test Data Dump

For each single engine test or STS flight, there is a standard data package which is output by the isospectral software. This output consists of:

1. Selected PSD plots throughout test.
2. Composite RMS time history.
3. Synchronous RMS time history.
4. 2 * synchronous RMS time history.
5. 3 * synchronous RMS time history.
6. 4 * synchronous RMS time history.
7. Synchronous speed time history.

All of the above are executed for each measurement. Since these data are computed and displayed for every test, a routine was developed which calculates/displays all of the above automatically during one pass of the PSD data. Items 2 through 5 are calculated using two subroutines, "CSYNC" and "CRMS," while the first item is determined by interrogating the test power profile and automatically choosing desired plot slice times. At the end of the RMS plotting function, a summarized data computation is executed. Also executed for HPOTP data is a synchronous speed histogram plot routine.

FUTURE DEVELOPMENT

The main objective for single engine tests is to develop a system which will acquire all of the high frequency data real time. This system will be located at the test stand and will eliminate the time-consuming post-processing using six measurements per pass currently being done. Immediately after the test has been completed, the system will begin the task of recalling data and computing Fourier transforms. Once the entire set of data has been transformed, the Program Support Communications Network (PSCN) will be utilized to transfer the data to MSFC and Canoga Park, CA. All of the data digitized during a test will be available for plotting/analysis approximately 3 to 4 hr after a test. Development of this system has begun at MSFC using a MASSCOMP MC-5700 super microcomputer. This system utilizes separate processors for the CPU and data acquisition as well as an array processor. Further, the data will be retained in Fourier coefficient form (real/imaginary) rather than the current PSD format. This will greatly expand the diagnostic analysis techniques that the dynamicist can apply in the evaluation process.

CONCLUSION

The development of the SSME Vibration Data Base has greatly improved the quality (and quantity) of post-test vibration data reduction. The system has improved productivity immeasurably by digitizing and storing the entire test duration instead of very small time intervals. The development of sophisticated computation, tracking, and display software has provided engineers with deeper insight and more complete information as to the dynamic environment of engine components.

The development of the Diagnostic Data Base has made test-to-test comparisons more efficient by providing efficient search mechanisms along with tabulated, plotted, and statistical outputs. The Isospectral Data Base has been a significant aid in the evaluation of time, amplitude, and frequency trends within a test. With the development of a real time data acquisition system both for single engine tests and STS flights, the SSME Vibration Data Base will continue to develop into an extremely efficient and powerful data processing, evaluation, and diagnostic tool.

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APPROVAL

SPACE SHUTTLE MAIN ENGINE VIBRATION DATA BASE

By Pat Lewallen

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

G. F. McDONOUGH
Director, Systems Dynamics Laboratory

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