N91-24331

PROBABILISTIC DESIGN ANALYSIS USING COMPOSITE LOADS SPECTRA (CLS) COUPLED WITH PROBABILISTIC STRUCTURAL ANALYSIS METHODOLOGIES (PSAM)*

S24-39 19881

J. F. NEWELL, K. R. RAJAGOPAL and H. HO
ROCKWELL INTERNATIONAL CORPORATION, ROCKETDYNE DIVISION

This paper discusses the application of the CLS to generate probabilistic loads for use in the PSAM nonlinear evaluation of stochastic structures under stress (NESSUS) finite element code. The CLS approach allows for quantifying loads as mean values and distributions around a central value rather than maximum or enveloped values typically used in deterministic analysis. NESSUS uses these loads to determine mean and perturbation responses. These results are probabilistically evaluated with the distributional information from CLS using a fast probabilistic integration (FPI) technique to define response distributions. The main example discussed describes a method of obtaining probabilistic (dependent) pressure, temperature and centrifugal steady state load descriptions and stress response of the second-stage turbine blade of the Space Shuttle main engine (SSME) high-pressure fuel turbopump (HPFTP). Additional information is presented on the on-going analysis of the high pressure oxidizer turbopump discharge duct (HPOTP) where probabilistic dynamic loads have been generated and are in the process of being used for dynamic analysis. Example comparisons of load analysis and engine data are furnished for partial verification and/or justification for the methodology.

Figure 1 depicts the component loading analysis. The description of the dependent random variables are obtained from a multilevel physical model that includes an engine system influence model and component load models of the turbine to describe the local conditions on the turbine blade. The independent loads are quantified at the appropriate model - engine or component - to best define the basic variables in the system, as well as maintain the required correlation between the dependent loads on the turbine blade. Both duty cycle and related probabilistic variations are accounted for in these models. The specific turbine blade model, Figure 2, is used both for part of the load modeling-thermal and pressure distribution - as well as the structural analysis. The structural model combines the loads with a probabilistic description of geometry, material property, and material orientations. The work herein discussed is an extension of the analysis performed under the PSAM contract where probabilistic loads were not considered.

Figure 3 is a cross section of the HPFTP turbine showing the overall configuration and the hot gas coolant network. The hot gas flow enters from the fuel preburner at 11 and discharges at 15. The second stage blade and rotor are between 14 and 15. Two geometric variations play a key role in the distribution of the coolant flow around the turbine blade, the interstage seal at 10 and the aft platform seal at 8.

The HPFTP turbine blade loads are dependent to the engine system level major component (turbine) dependent loads. The major component dependent loads are in turn dependent to a set of engine independent loads, including the engine operating parameter loads and the engine hardware parameter loads. A summary and categorization of these loads are listed in figure 4. The independent system level loads and hardware variations are in the first category listed. The major component dependent loads that are calculated in the engine model are the next level. The component level dependent loads are pressure, temperature and centrifugal. Additional local independent loads from the seals are internal to the turbine.

*Work performed under NASA Contract NAS3-24382

Probabilistic methods are built into these models and are described in the CLS discussion in this document. For this analysis, the Gaussian moment method was employed to illustrate the application of the probabilistic methodology. The pressure, temperature and centrifugal loads are correlated with higher level system independent loads. Theoretically, one could obtain correlation fields between pairs of the loads and then decompose them as part of the PSAM solution scheme. These fields are difficult to obtain and decompose. The marginal distribution method is used as a better solution to the load description and interface to the PSAM codes, Figure 5. Figure 6 outlines the process of generating the HPFTP turbine component loads marginal distribution.

At this time, validation of these loads is limited to the standard instrumentation available from engine tests. Pump speed and turbine discharge temperatures are regularly recorded as well as the independent loads at the pump interfaces. Figure 7 has typical plots of test data from a series of tests that can be used to estimate 2 sigma variations of independent loads. Figure 8 has typical dependent pump speed variations. A sample from a flight is also furnished of the 3 pump speeds at 104% power level. The variation in speeds are caused by a combination of hardware and duty cycle variations of primarily the low pressure oxidizer pump inlet pressure and the resulting cavitation of the HPOTP. Table 1 furnishes a correlation of calculated and measured variations of turbine speed and discharge temperature for both high pressure turbopumps. There is excellent correlation with speed and slightly poorer correlation with temperature. Part of the temperature error is attributed to instrumentation error that is not readily accounted for.

Table 2 summarizes the set of random variables, how they affect the structural model and their mean and standard deviation values. Figure 9 shows two points on the structural model where cumulative distributions of effective stress were calculated using NESSUS and FPI codes.

PSAM is performing a series of verification analysis on SSME hardware. CLS is being used to develop the loads for these analyses to furnish realistic input to PSAM and to demonstrate the integrated use of CLS and PSAM. Vibration loads for the HPOTP discharge duct, Figure 10, have been completed. This duct is attached to the HPOTP at two points, Zone G, and at the main injector (MI) at Zone A of the engine. The MI is part of a combustor that generates random vibrations. The pumps generate both random and sinusoidal loads. These vibration loads are dependent on power level of the engine and pump power and speed. The structure of the engine couples the responses of the components such that sinusoidals from the high pressure pumps are found throughout the engine at attenuated levels compared to the point where they are generated. Table 3 summarizes the 38 individual load components that are being applied to the duct. Figure 11 shows one of the six normalized PSD shapes used for the random loading. For this analysis, the random load composite has been modeled as a normalized shape that is scaled by G^2_{rms}. The sinusoids are depicted in Figure 12. The frequencies generated by a pump are correlated to the synchronous speed, 1N. The 1N, 2N and 3N response levels are typically caused by rotor unbalance and rubbing or nonlinear effects. The 4N is caused by fluid loads on the four primary blades of the inducer. The variations are based on engine test data. The sinusoid amplitude mean levels are correlated with pump speed, but the standard deviation magnitudes are uncorrelated. The sinusoid level distribution is modeled as lognormal, see Figure 13. The variations of the sinusoidal magnitudes have a coefficient of variation of .5 to over 1.0. The high variations are roughly equally caused by component hardware variations and test to test variations. Figure 14 is a recent study of random composite levels coefficients of variations for several environments on the SSME. This information will be used in the development of generic dynamic physical load models.

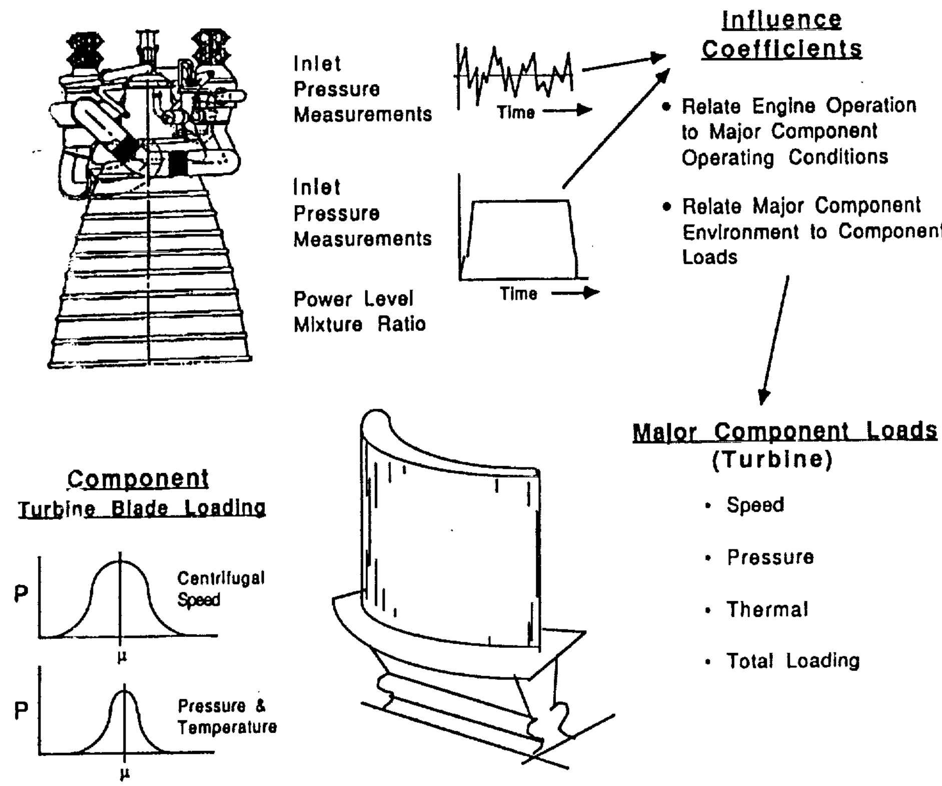


FIGURE 1. COMPONENT LOADS

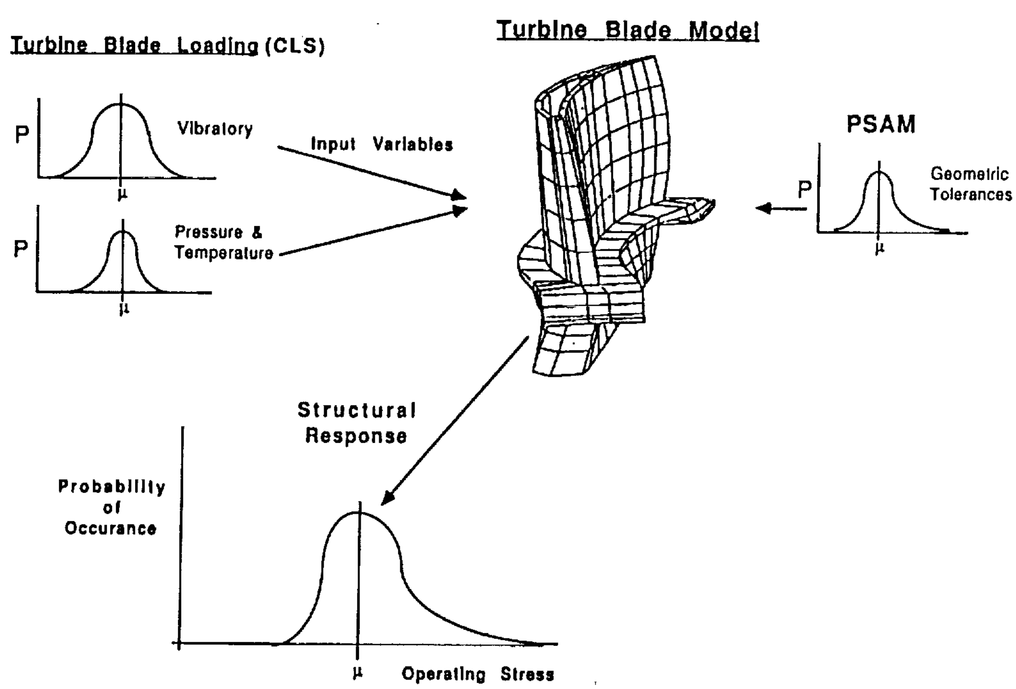


FIGURE 2. COMPONENT MODELS FOR LOADS AND STRUCTURAL ANALYSIS

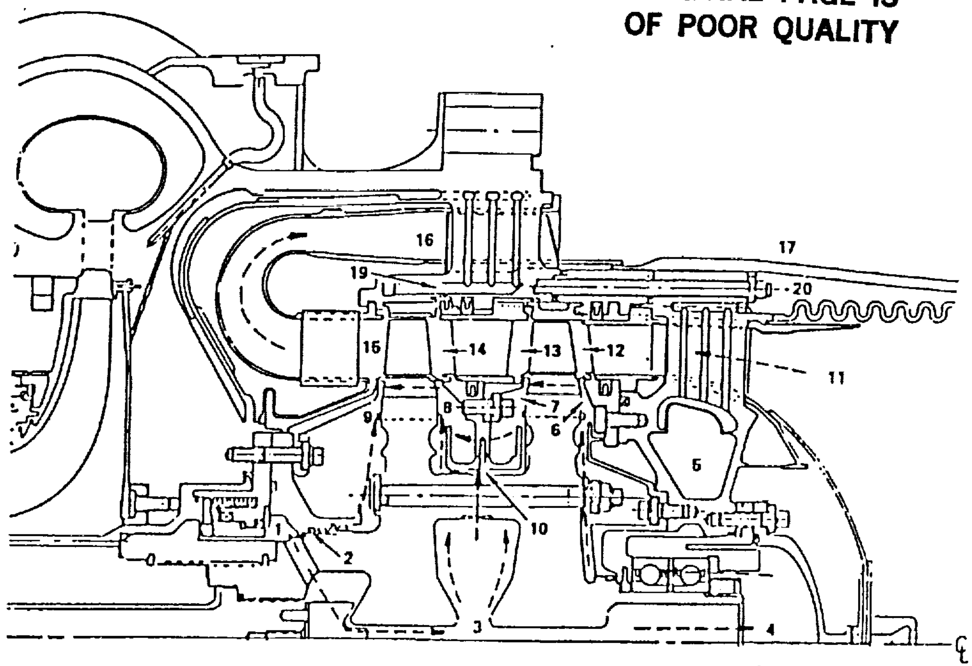


FIGURE 3. SSME HPFTP TURBINE HOT GAS AND COOLANT FLOW NETWORK

INDEPENDENT SYSTEM LOADS

- SYSTEM THRUST
- ENGINE OPERATING PARAMETERS
  MIXTURE RATIO
  FUEL INLET PRESSURE
  OXIDIZER INLET PRESSURE
  FUEL INLET TEMPERATURE
  OXIDIZER INLET TEMPERATURE
- ENGINE HARDWARE PARAMETERS
  HPFTP EFFICIENCY
  HPFTP HEAD COEFFICIENT

SYSTEM LEVEL MAJOR COMPONENT (TURBINE) DEPENDENT LOADS

- MAJOR COMPONENT LOAD (TURBINE)
  - HPFTP TURBINE INLET DISCHARGE PRESSURES
  - HPFTP TURBINE SPEED
  - HPFTP POWER

COMPONENT LEVEL (TURBINE BLADE) COMPOSITE LOADS

- COMPONENT LOADS
  - DEPENDENT
    HPFTP CENTRIFUGAL
    HPFTP TURBINE BLADE PRESSURE
    HPFTP TURBINE BLADE TEMPERATURE
  - LOCAL INDEPENDENT LOADS
    COOLANT SEAL LEAKAGE
    HOT GAS SEAL LEAKAGE

FIGURE 4. COMPOSITE LOADS OF THE HPFTP TURBINE BLADE FOR THE PROBABILISTIC STRUCTURAL ANALYSIS

- PURPOSE:
  - PREPARING COMPOSITE LOADS FOR STRUCTURAL ANALYSIS.
  - MARGINAL DISTRIBUTION LOADS USED DIRECTLY AS INPUT TO PROBABILISTIC STRUCTURAL ANALYSIS CODES, E.G. NESSUS & FPI.

- ADVANTAGES:
  - MUCH SIMPLER THAN CORRELATION FIELD APPROACH.
  - CORRELATIONS TO THE ENGINE INDEPENDENT LOAD LEVEL AS REQUIRED.
  - DIRECTLY USABLE FOR PERTURBATION LOADING IN PSAM.

- DEFINITION:
  - MARGINAL DISTRIBUTION FOR A COMPONENT LOAD IS A DISTRIBUTION FOR THE COMPONENT LOADS WITH ONLY ONE INDEPENDENT LOAD VARYING AND THE REST OF THE INDEPENDENT LOADS STAYING CONSTANT.
  - FOR A LINEAR SYSTEM

$$\Delta Y = \sum_I B_I \Delta X_I$$

$$\sigma^{MARGINAL}_{Y_I} = |B_I| \sigma_{X_I}$$

$$\frac{\partial Y}{\partial X_I} = B_I = \frac{B_I}{|B_I|} \frac{\sigma^{MARGINAL}_{Y_I}}{\sigma_{X_I}}$$

FIGURE 5. MARGINAL DISTRIBUTION METHOD

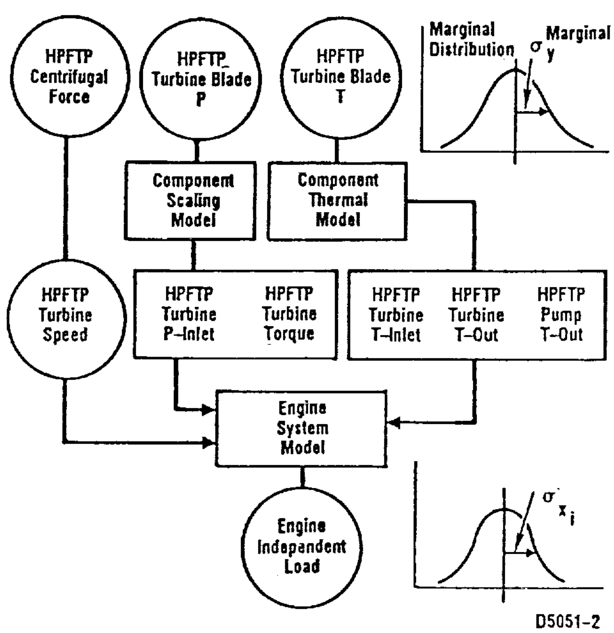
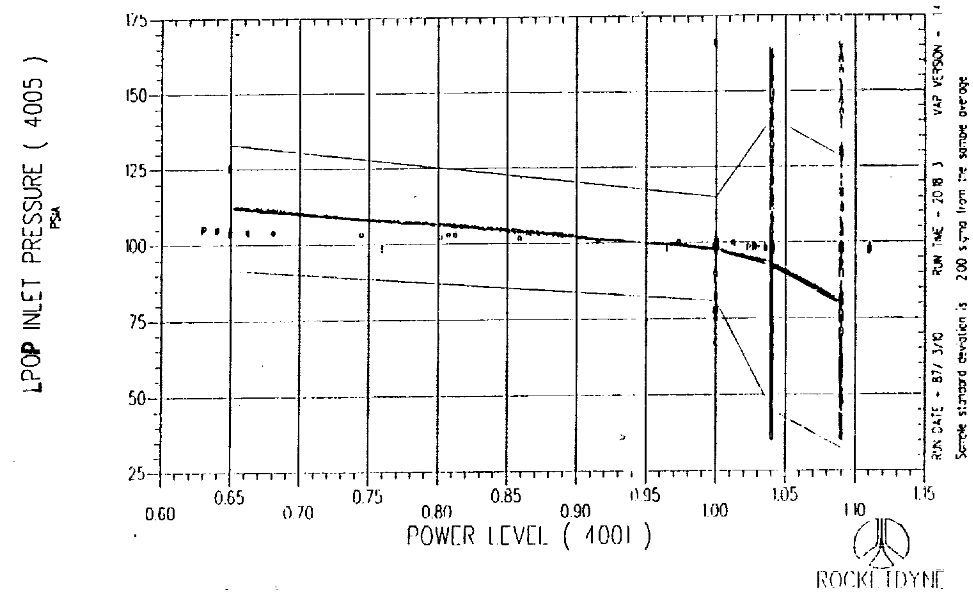
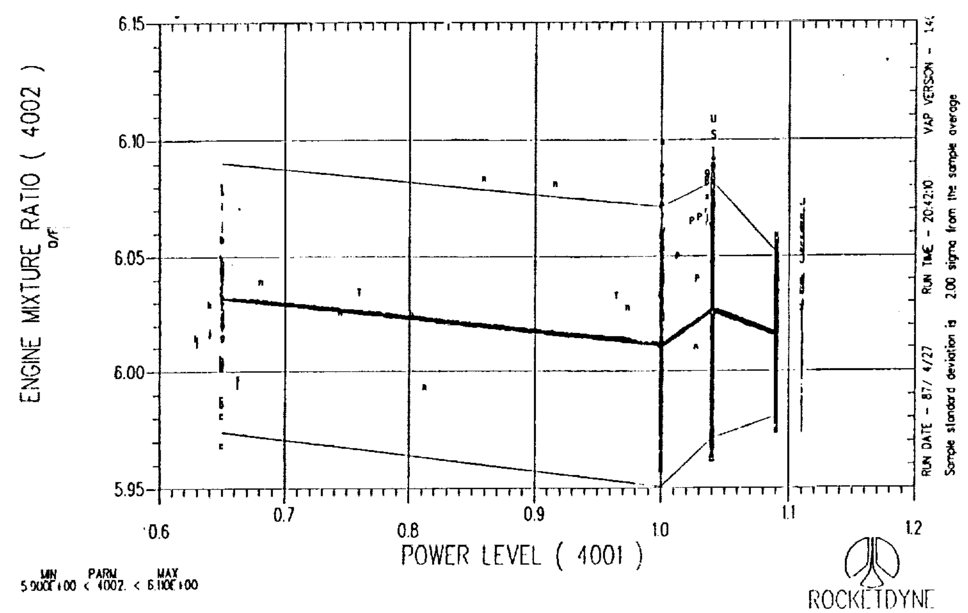


FIGURE 6. MARGINAL LOAD PROCESS

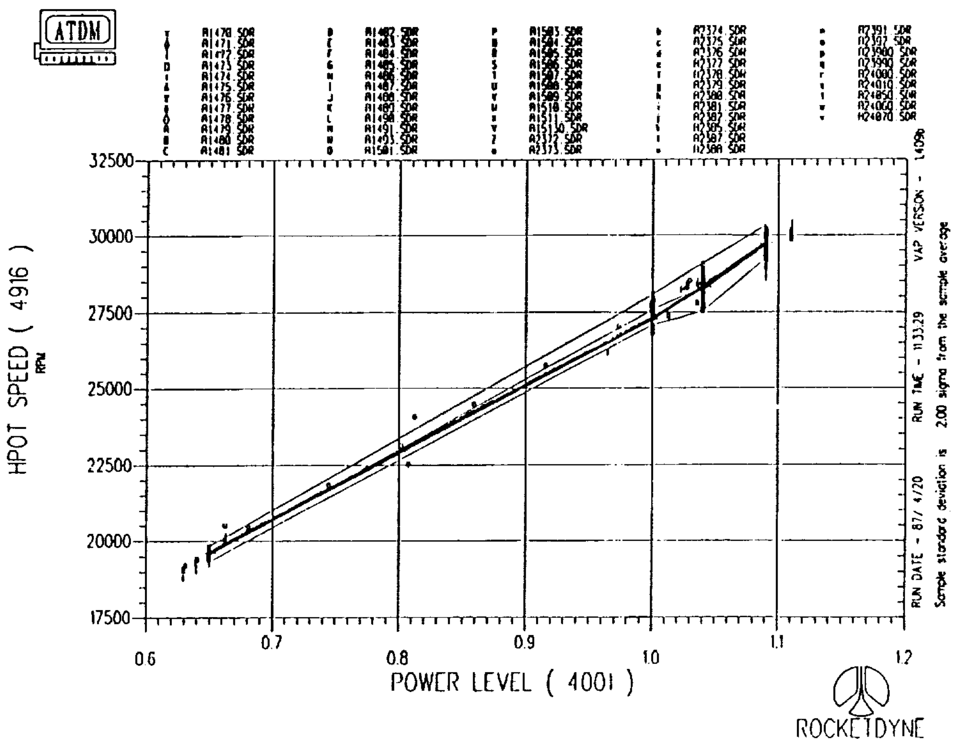




ORIGINAL PAGE IS OF POOR QUALITY

FIGURE 7. TYPICAL INDEPENDENT LOAD VARIATIONS FOR A PHASE II SSME SERIES OF TESTS

PHASE II TESTS



FLIGHT STS-27

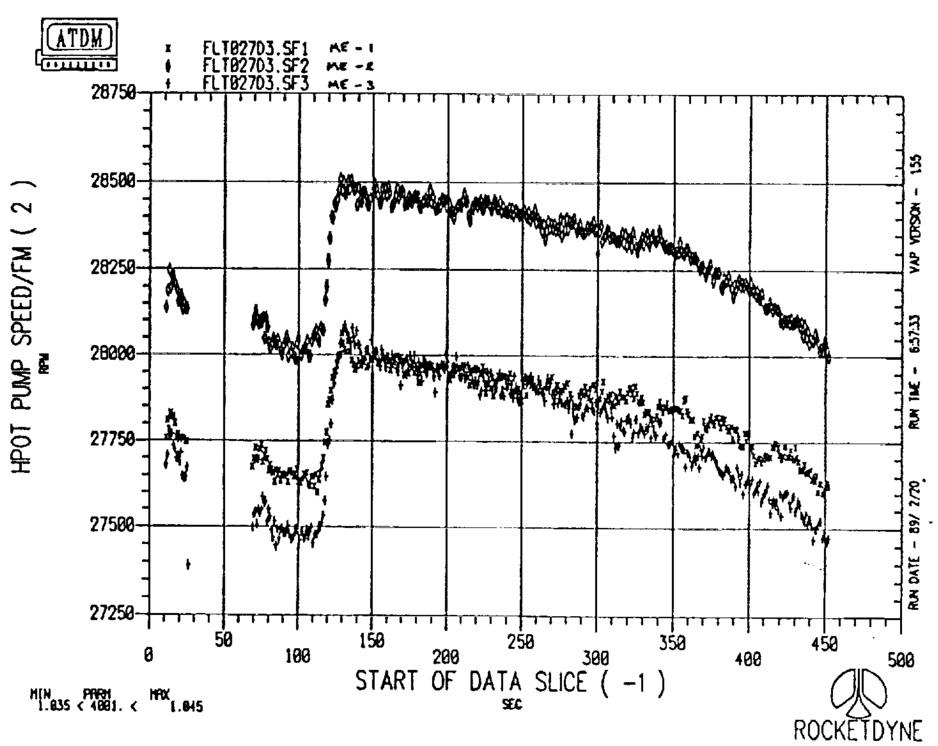


FIGURE 8. HIGH PRESSURE OXIDIZER TURBOPUMP SPEED

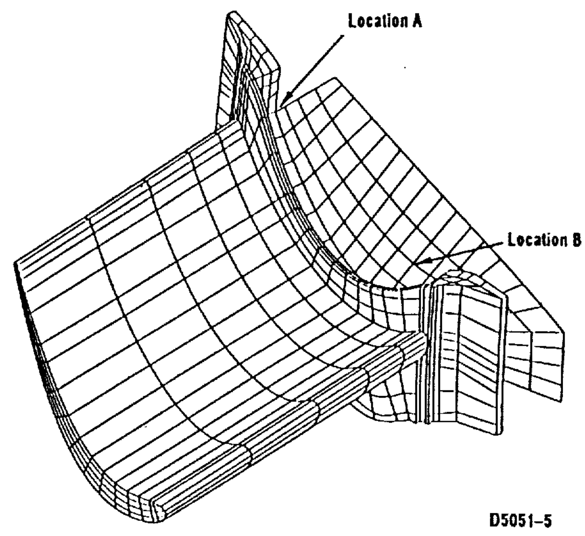
CONDITION	HPOTP SPEED CALC (RPM)	HPOTP SPEED MEASURED (RPM)	HPOTP TURBINE DISCHARGE TEMP CALC °R	HPOTP TURBINE DISCHARGE TEMP MEASURED °R	HPFTP SPEED CALC (RPM)	HPFTP SPEED MEASURED (RPM)	HPFTP TURBINE DISCHARGE TEMP CALC °R	HPFTP TURBINE DISCHARGE TEMP MEASURED °R
HARDWARE - 2σ RANDON	294	----	53	----	388	----	65	----
TEST - 2σ RANDOM	210	----	157	----	396	----	20	----
TOTAL RANDOM	360	----	165	----	554	----	70	----
LOW NPSP - DET.	620	----	225	----	56	----	52	----
HIGH NPSP - DET.	-317	----	-219	----	-94	----	-62	----
RANGE = RANDOM + DET.	1660	1500	475	400	1260	1000	114	150
MAX	29090	29000	1630	1650	35742	35750	1740	1760
NOM	28100	----	1374	----	35130	----	1688	----
MIN	27430	27500	1155	1250	34482	34750	1625	1610

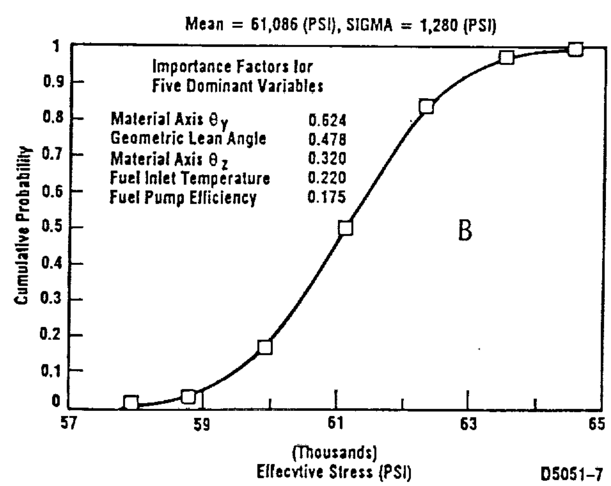
MEASURED -- MEASURED VARIATION FOR PHASE II TEST SET
HARDWARE -- VARIATIONS IN ENGINE HARDWARE
TEST -- INITIAL TEST CONDITIONS -- INLET TEMPERATURES AND MIXTURE RATIO
DET. -- DUTY CYCLE EFFECTS OF INLET PRESSURES PLUS CORRELATED 2σ VARIATIONS OF CAVITATION

TABLE 1. CALCULATED VS. MEASURED VARIATIONS IN PUMP SPEED AND TEMPERATURE

RANDOM VARIABLE NO	DESCRIPTION	TYPE	FEM QUANTITIES AFFECTED	MEAN	STANDARD DEVIATION
1	MATERIAL AXIS ABOUT Z	MATERIAL AXIS VARIATIONS	MATERIAL ORIENTATION ANGLES	-0.087266 RADIANS	0.067544 RADIANS
2	MATERIAL AXIS ABOUT Y			-0.034907 RADIANS	0.067544 RADIANS
3	MATERIAL AXIS ABOUT X			+0.052360 RADIANS	0.067544 RADIANS
4	ELASTIC MODULUS	ELASTIC PROPERTY VARIATIONS	ELASTIC CONSTANTS	18.38E6 KSI	0.4595E6 KSI
5	POISSON'S RATIO			0.386	0.00965
6	SHEAR MODULUS			18.63E6 KSI	0.46575E6 KSI
7	GEOMETRIC LEAN ANGLE ABOUT X	GEOMETRY VARIATIONS	NODAL COORDINATES	0.0	0.14 DEGREES
8	GEOMETRIC TILT ANGLE ABOUT Y			0.0	0.14 DEGREES
9	GEOMETRIC TWIST ANGLE ABOUT Z			0.0	0.30 DEGREES
10	MIXTURE RATIO LIQUID HYDROGEN/ LIQUID OXYGEN	INDEPENDENT LOAD VARIATIONS DEPENDENT LOADS ARE TURBINE BLADE PRESSURE TEMPERATURE AND SPEED	PRESSURE TEMPERATURE CENTRIFUGAL LOAD	6.00	0.02
11	FUEL INLET PRESSURE			30.00 psia	5.00
12	OXIDIZER INLET PRESSURE			100.00 psia	26.00
13	FUEL INLET TEMPERATURE			38.5° R	0.5
14	OXIDIZER INLET TEMPERATURE			167.0° R	1.33
15	HPFP EFFICIENCY			1.00	0.008
16	HPFP HEAD COEFFICIENT			1.0237	0.008
17	COOLANT SEAL LEAKAGE FACTOR	LOCAL GEOMETRY FACTORS	TEMPERATURE	1.00	0.1
18	HOT GAS SEAL LEAKAGE FACTOR			1.0	0.5

TABLE 2. LIST OF 2nd STAGE BLADE RANDOM VARIABLES





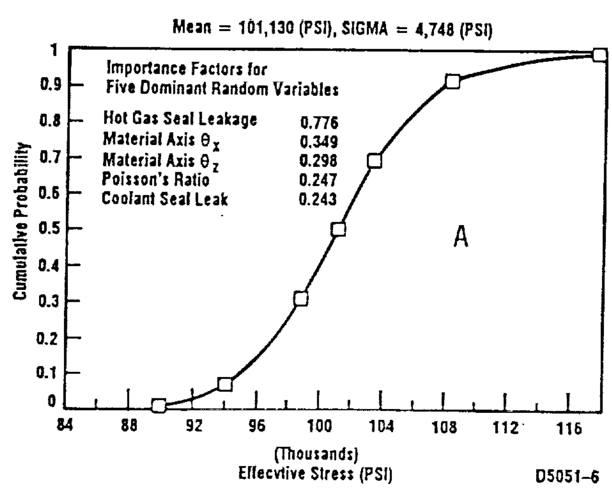


FIGURE 9. STRESS RESPONSE FOR HPFTP TURBINE BLADE

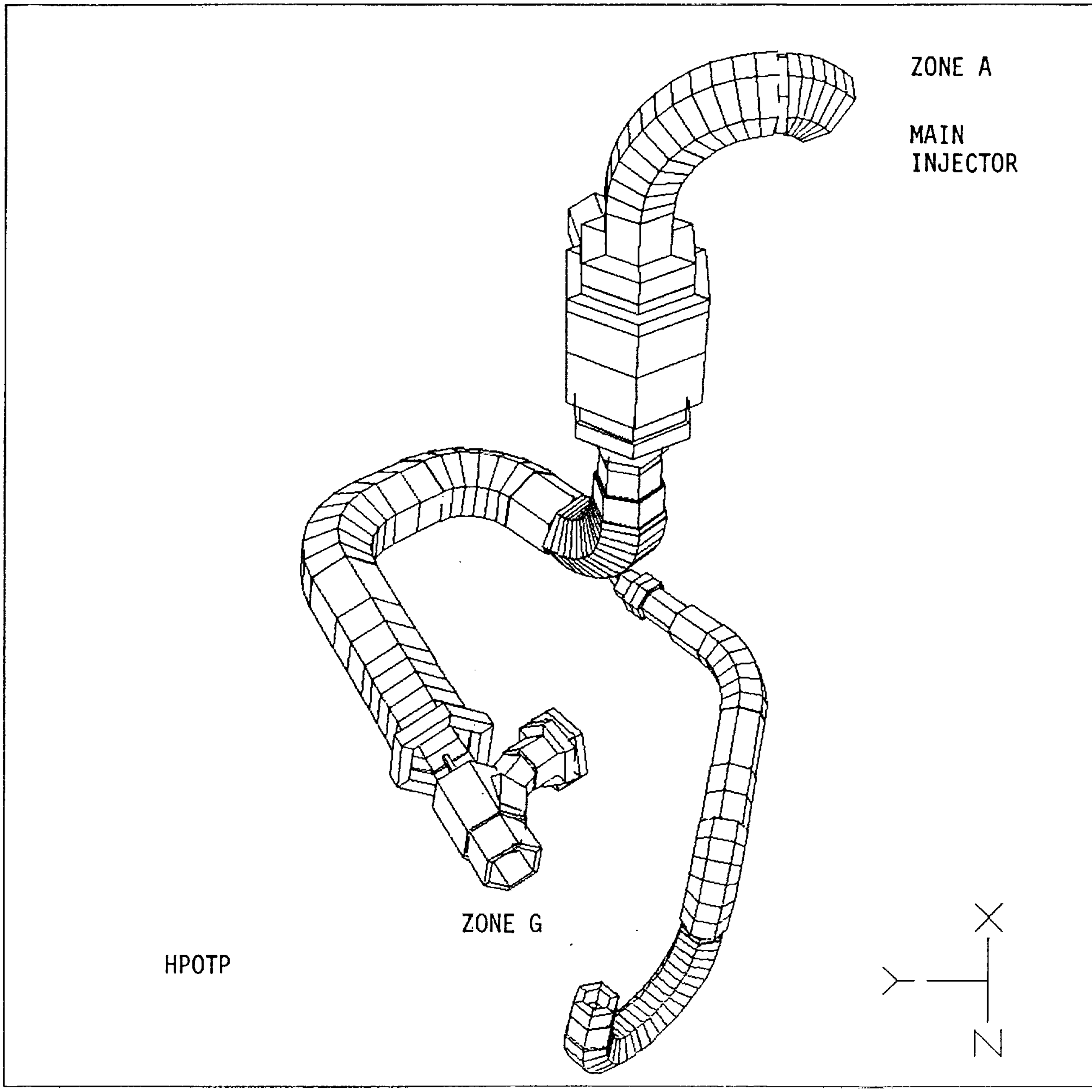


FIGURE 10. HPOTP DISCHARGE DUCT

SEQUENTIAL NO.	RANDOM VARIABLE DESCRIPTION		MEAN	ST. D.	COV
1)	ZONE G - X AXIS, PSD		222.0	163.0	0.73
2)	ZONE G - Y AXIS, PSD		73.5	59.4	0.808
3)	ZONE G - Z AXIS, PSD		73.5	59.4	0.808
4)	ZONE A - X AXIS, PSD		22.5	4.5	0.20
5)	ZONE A - Y AXIS, PSD		54.0	10.8	0.20
6)	ZONE A - Z AXIS, PSD		69.5	13.9	0.2
7)	OXIDIZER PUMP SPEED		2940.53	41.167	0.014
8)	FUEL PUMP SPEED		3707.08	37.07	0.01
9)	DAMPING		0.033	.005	0.15
	ZONE A OXIDIZER TURBOPUMP				
	OXIDIZER PUMP SINE AMPLITUDES				
10)	X DIRECTION	1N	.30	.120	0.4
11)		2N	0.30	.045	0.15
12)		4N	1.5	.45	0.3
13)	Y DIRECTION	1N	0.60	0.30	0.5
14)		2N	0.70	0.28	.40
15)		4N	2.6	.78	.3
16)	Z DIRECTION	1N	0.5	.225	0.45
17)		2N	0.70	.140	0.20
18)		4N	0.70	.140	.20
	FUEL PUMP SINE AMPLITUDES				
19)	X DIRECTION	1N	.35	1.050	.3
20)	Y DIRECTION	1N	0.80	0.280	0.35
21)	Z DIRECTION	1N	1.20	0.96	0.3
	ZONE G - MAIN INJECTOR				
	OXIDIZER TURBOPUMP				
	SINE AMPLITUDES				
22)	X DIRECTION	1N	1.35	1.35	1.0
23)		2N	1.50	0.75	0.5
24)		3N	1.10	0.495	0.45
25)		4N	11.0	2.75	0.25
26, 27)	X-Y DIRECTION	1N	1.9	1.71	0.9
28, 29)		2N	1.6	0.96	0.6
30, 31)		3N	0.75	.225	0.3
32, 33)		4N	5.5	3.30	0.6
	FUEL PUMP SINE AMPLITUDES				
34)	X DIRECTION	1N	0.65	0.2275	0.35
35, 36)	X-Y DIRECTION	1N	0.45	1.35	.3
37, 38)	Y-Z DIRECTION	2N	0.45	0.180	.4

Note:
1) P.S.D. units are in G^2
2) Pump Speed units are in Radians/SCE
3) Sinusoidal amplitude units are in GRMS

TABLE 3. BASIC RANDOM VARIABLES AND THEIR STATISTICS (INPUT)

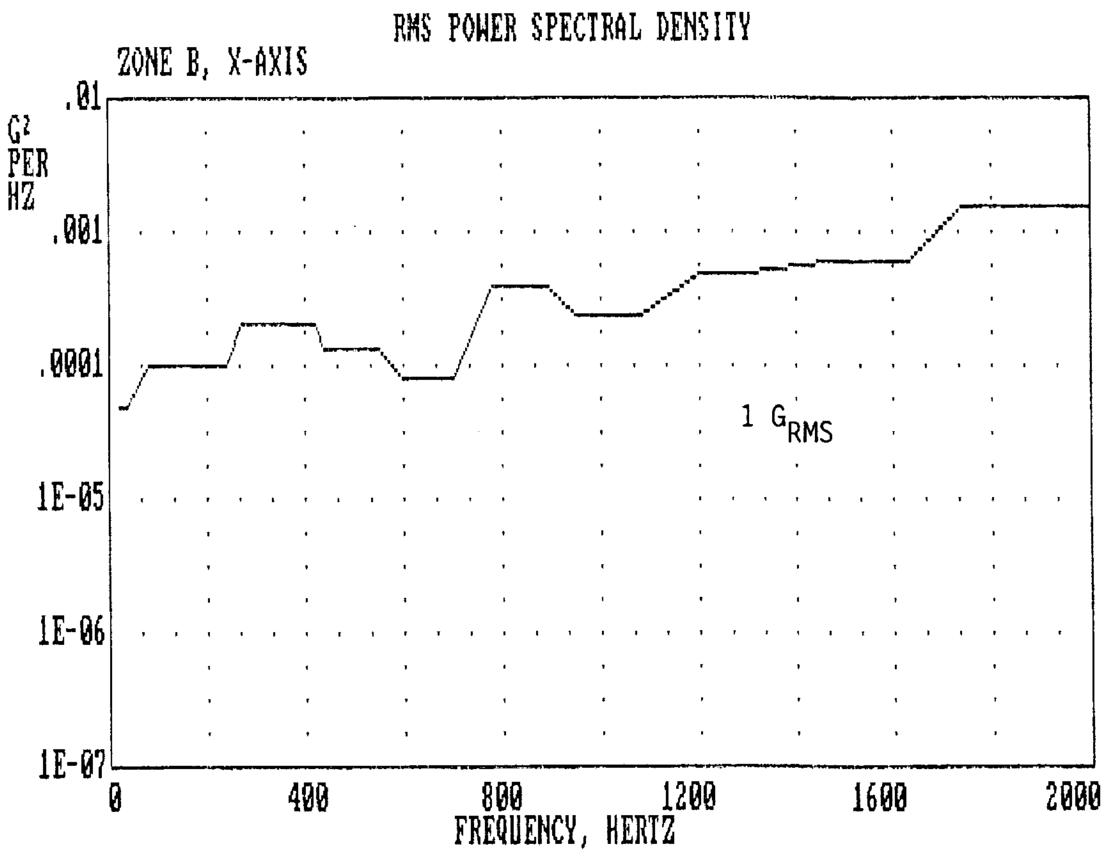


FIGURE 11. TYPICAL NORMALIZED PSD

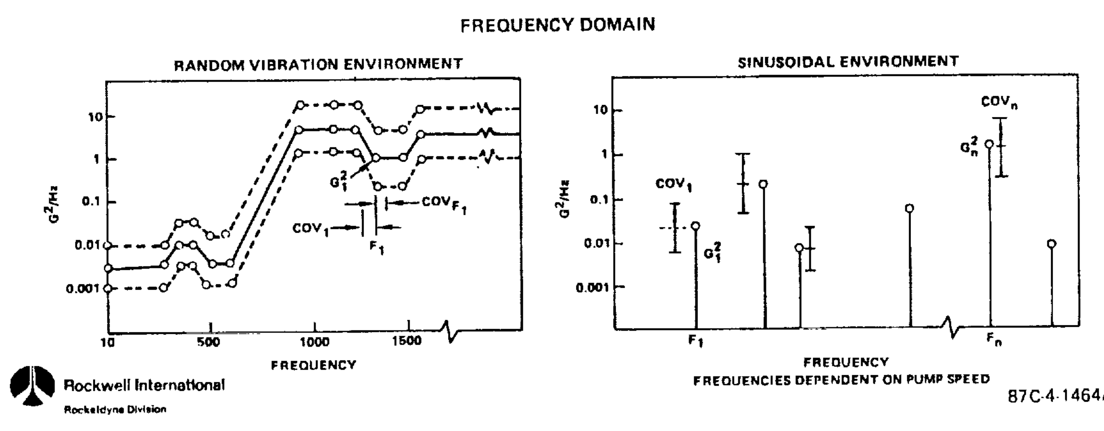


FIGURE 12. RANDOM AND SINUSOIDAL VIBRATION

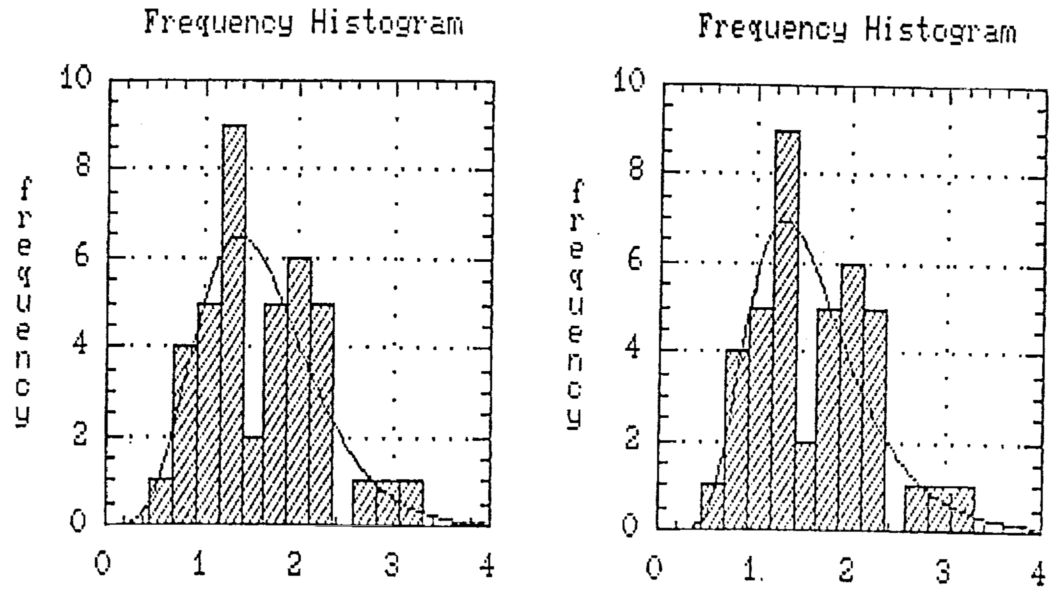


FIGURE 13. HPOTP SYNCHRONOUS MAGNITUDE DISTRIBUTION AT CONSTANT POWER

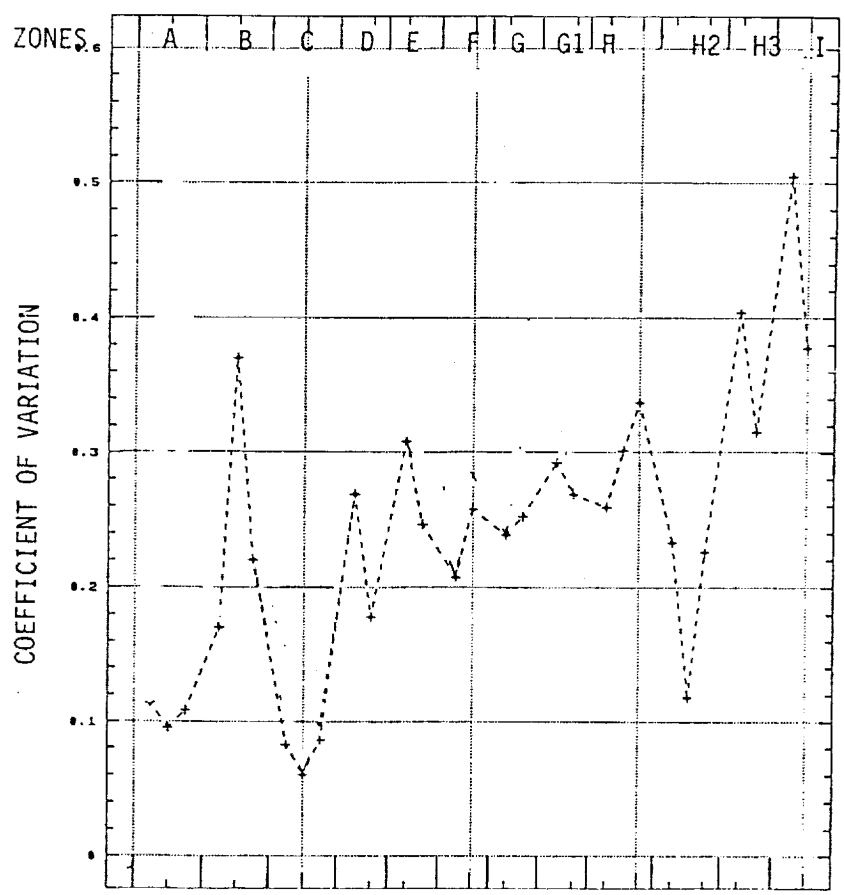


FIGURE 14. SSME ZONAL VIBRATION COMPOSITE GRMS COEFFICIENTS OF VARIATION