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PROBABILISTIC EVALUATION OF SSME STRUCTURAL COMPONENTS

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INTRODUCTION

This paper describes the application of CLS and NESSUS family of computer codes to the probabilistic structural analysis of four SSME space propulsion system components. These components are subjected to environments that are influenced by many random variables. The applications consider a wide breadth of uncertainities encountered in practice,while simultaneously covering a wide area of structural mechnics. This has been done consistant with the primary design requirement for each component. This paper dicusses the probabilistic application studies using finite element models that have been typically used in the past in deterministic analysis studies.

PROBABILISTIC TURBINE BLADE STATIC AND MODAL ANALYSIS

A high pressure fuel turbopump turbine blade was considered in this study (Figure 1). A total of ninteen random variables were considered in the analysis (Table 1) covering a wide range of parameters encountered in a practical production situation. Results of the analysis predicting expected variation in effective stress response at two different locations is shown Figure 2 and Figure 3 along with the sensitivity factors which are different at each loaction.This application demonstrates that large scale probabilistic static analysis is feasible and provides valuable information in the form of sensitivities that can help in designing more durable components.(Reference 1).

A knowledge of the variations in the frequencies of the first few modes of a turbine blade is of importance to avoid resonance conditions. Knowing the distribution of the frequencies and speed ranges it is possible to obtain quantitative probability estimates of interference with engine orders. The first ten variables listed in Table 1 were used in this probabilistic analysis.

The results from a mean value first order and the more accurate advanced mean value first order results are shown in Figure 4 for mode 1. It points out the unsymmetrical nature of the distribution and the capability of the probabilistic tools in predicting it. The computed coefficient of variation of the natural frequencies is consistant with the actual experience. If the frequency range is a criteria for acceptance or rejection of blades this analysis technics can then be used to calculate a [redacted] target design point that will reduce the rejection rate (Reference 2).

VIBRATION ANALYSIS OF DUCTS SUBJECTED TO UNCERTAIN LOADS

The high pressure oxidizer turbopump discharge duct is used in this study (Figure 5). The duct has three attach points subjected to both random and sinusoidal vibration, a multisupport excitation problem. The variation in the vibratory loads is attributed to engine system duty cycle operation, engine system hardware variations, and local component variations within the turbopump or combustors. A total of thirty eight random variables were used in this analysis (Table 2). A typical result obtained in the form of a cumulative distribution function at a typical node for bending moment in the y direction is shown in Figure 6. The analysis points to a way of designing structures subjected to a large number of excitation sources without exercizing undue conservatism (Reference 3).

PROBABILISTIC MATERIAL NONLINEAR ANALYSIS OF LOX POST

A main injector element of SSME is used in this study (Figure 7). The response variable of interest is the cyclic strain range (including the elastic and plastic portions of the stress strain curve). This response quantity is one of the primary drivers in determining Low Cycle Fatigue life of the component. The dominant loading on the component is the differential wall temperature across the Lox Post wall of approximately 1000 degrees rankine. It was the only loading considered in this analysis.

The random variables that affect the local temperature field are shown in Table 3. The probabilistic analysis involved a full two duty cycle incremental nonlinear analysis and constructiing a response surface linking effective strain range to random variables. The probabilistic analysis results based on the response surfaces at several locations are shown in Table 4 and the corresponding sensitivity factors in Table 5. The analysis demonstrates a methodology of linking global system variables to local response variables that can eventually be extended to calculate damage, all in a probabilistic domain (Reference 4).

PROBABILISTIC BUCKLING LOAD ANALYSIS

The structural liner in the SSME two duct hot gas manifold design was the subject of this study. The shell is doubly curved with five distinct zones of thicknesses (Figure 8). One of the primary design requirement for the liner is to have adequate margin against buckling failure. Unlike the previous examples cited above this application deals with estimation of the strength variable. As a first step in this process a probabilistic linear buckling analysis was conducted. A more rigorous material and geometric probabilistic collapse load analysis would be more accurate but the computational effort will also be significantly larger.

In this study the thickness in the five zones of the shell were considered as independent random variables but within each zone, the thickness variation was considered to be fully correlated. The probabilistic analysis method used is a response surface approach. The resulting computed cumulative distribution function is shown in Figure 9. Thus knowing the distribution of the buckling strength and the distribution of differential pressure the probability of buckling failure based on the linear eigen value analysis can easily be calculated.

SUMMARY

Application of the probabilistic analysis tools developed in CLS AND PSAM contracts to a select SSME components has been successfully demonstrated. The scope and size of the application prove the viability and usefulness of the tools and methods developed to practical design in terms of designing more durable components.

REFERENCES

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2. Southwest Research Institute, University of Arizona, Rocketdyne, and Joao B.Dias, " Probabilistic Structural Analysis For Select Space Propulsion System Components ", 4th Annual Report, October 1988.

3. DebChaudhury,A., Rajagopal.K.R., Ho.H., and Newell.J.F., "A Probabilistic Approach to the Dynamic Analysis of Ducts Subjected to Multibase Harmonic and Random Excitation", 31st AIAA structures, Structural Dynamics, and Materials Conference, LongBeach, California, April 1990.

4. Newell,J.F., Rajagopal,K.R., Ho.H., and Cunniff.J.M., "Probabilistic Structural Analysis of Space Propulsion System Lox Post", 31st AIAA Structures, Structural Dynamics, and Materials Conference, LongBeach,California, April 1990.

5. Southwest Research Institute, University Of Arizona, Rocketdyne, and Joao B.Dias, " Probabilistic Structural Analysis Methods For Select Space Propulsion System Components", 5th Annual Report, October 1989.

TABLE I
LIST OF RANDOM VARIABLES USED IN
TURBINE BLADE ANALYSIS

NO	RANDOM VARIABLE 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 PSI (126.22E9 Pa)	0.4595E6 PSI (3.168E9 Pa)
5	POISSON'S RATIO			0.386	0.00965
6	SHEAR MODULUS			18.63E6 PSI (128.45E9 Pa)	0.46575E6 PSI (3.223E9 Pa)
7	MASS DENSITY	MASS VARIATIONS	MASS	0.805E-3	0.493E-5
8	GEOMETRIC LEAN ANGLE ABOUT X	GEOMETRY VARIATIONS	NODAL COORDINATES	0.0	0.14 DEGREES
9	GEOMETRIC TILT ANGLE ABOUT Y			0.0	0.14 DEGREES
10	GEOMETRIC TWIST ANGLE ABOUT Z			0.0	0.30 DEGREES
11	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
12	FUEL INLET PRESSURE			30.00 PSI (2.068E5 Pa)	5.00 PSI (.344E5 Pa)
13	OXIDIZER INLET PRESSURE			100.00 PSI (6.894E5 Pa)	26.00 PSI (1.793E5 Pa)
14	FUEL INLET TEMPERATURE			38.5° R (21.39° K)	0.5° R (0.278° K)
15	OXIDIZER INLET TEMPERATURE			167.0° R (92.78° K)	1.33° R (0.739° K)
16	HPFP EFFICIENCY			1.00	0.008
17	HPFP HEAD COEFFICIENT			1.0237	0.008
18	COOLANT SEAL LEAKAGE FACTOR	LOCAL GEOMETRY FACTORS	TEMPERATURE	1.00	0.1
19	HOT GAS SEAL LEAKAGE FACTOR			1.0	0.5

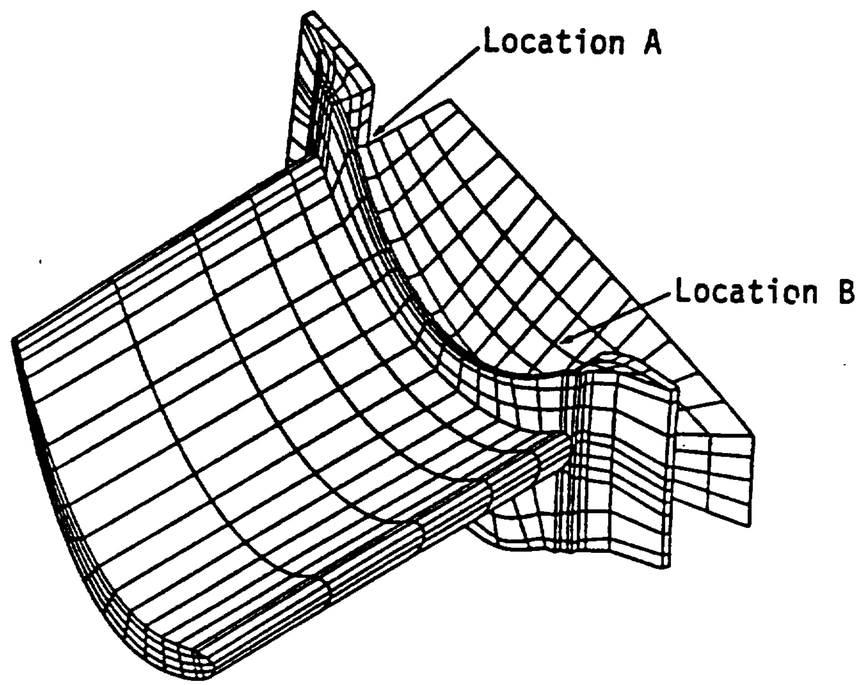

Figure 1. Turbine Blade Finite Element Model

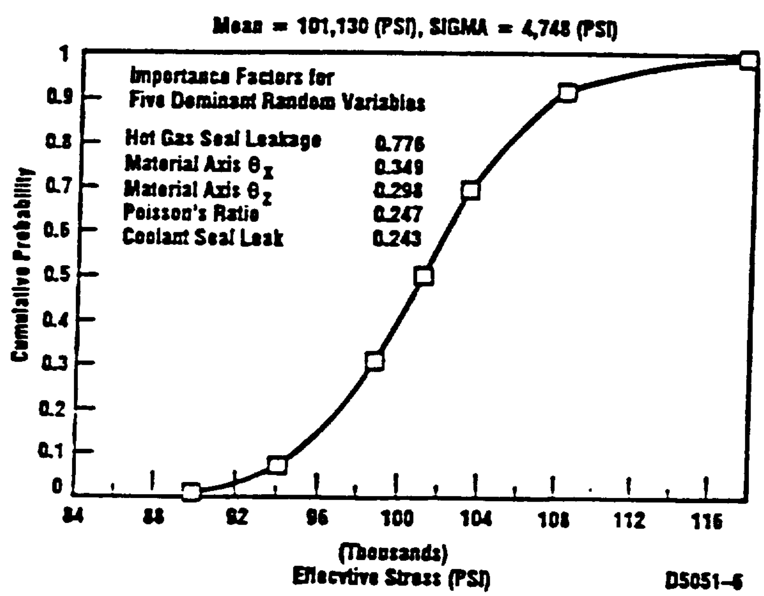

Figure 2. CDF For Effective Stress at Location A

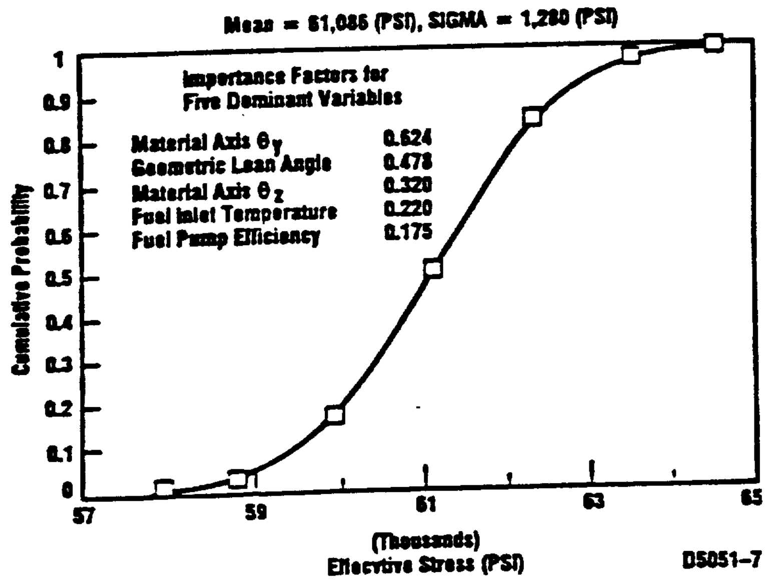

Figure 3. CDF For Effective Stress at Location B

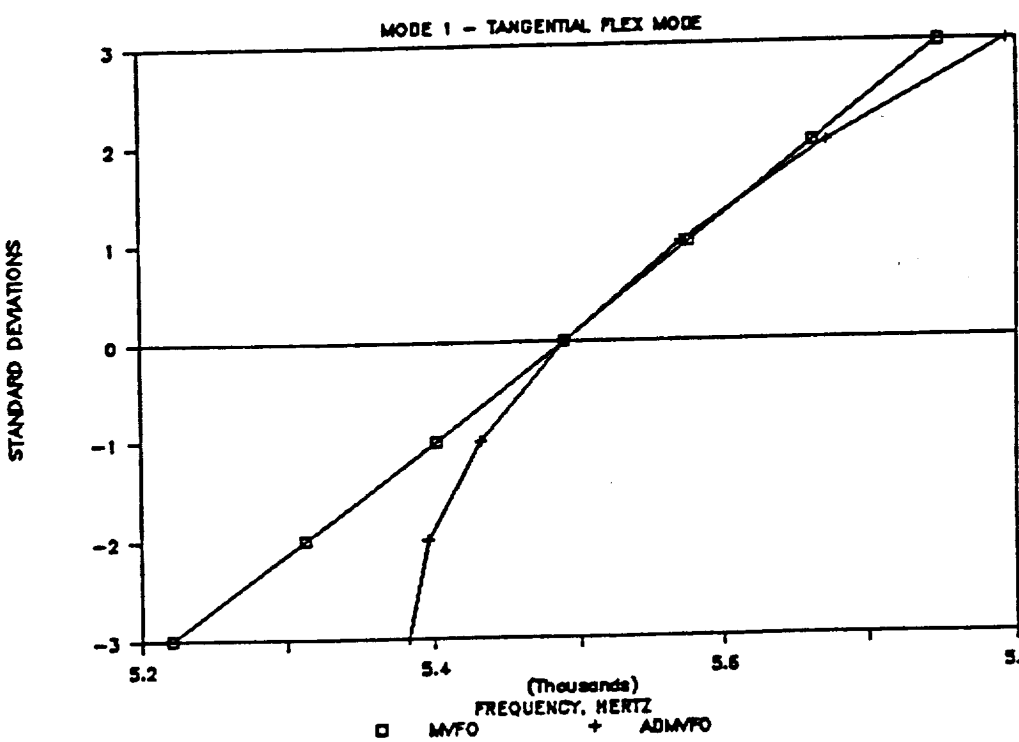

Figure 4. CDF For Mode 1 Frequency Using MVFO and ADMVFO

Table 2. HPOTP Discharge Duct Analysis Random Variable Statistics

Sequence No.	Random Variable Description		Mean	CV	Dist. Type
1)	Zone G - X axis, PSD power		222.0	0.73	Log Normal
2)	Zone G - Y axis, PSD		73.5	0.808	Log Normal
3)	Zone G - Z axis, PSD		73.5	0.808	Log Normal
4)	Zone A - X axis, PSD		22.5	0.20	Log Normal
5)	Zone A - Y axis, PSD		54.0	0.20	Log Normal
6)	Zone A - Z axis, PSD		69.5	0.2	Log Normal
7)	Oxidizer Pump Speed		2940.53	0.014	Log Normal
8)	Fuel Pump Speed		3707.08	0.01	Log Normal
9)	Damping		0.033	0.15	Normal
	Zone A Main Injector				
	Oxidizer Pump Sine Amplitudes				
10)	X direction	1N	0.30	0.4	Log Normal
11)		2N	0.30	0.15	Log Normal
12)		4N	1.5	0.3	Log Normal
13)	Y direction	1N	0.60	0.5	Log Normal
14)		2N	0.70	0.40	Log Normal
15)		4N	2.6	0.3	Log Normal
16)	Z direction	1N	0.5	0.45	Log Normal
17)		2N	0.70	0.20	Log Normal
18)		4N	0.70	0.20	Log Normal
	Fuel Pump Sine Amplitudes				
19)	X Direction	1N	0.35	0.3	Log Normal
20)	Y Direction	1N	0.80	0.35	Log Normal
21)	Z Direction	1N	1.20	0.3	Log Normal
	Zone G - Oxidizer Turbopump				
	Oxidizer Pump Sine Amplitudes				
22)	X Direction	1N	1.35	1.0	Log Normal
23)		2N	1.50	0.5	Log Normal
24)		3N	1.10	0.45	Log Normal
25)		4N	11.0	0.25	Log Normal
26, 27)	Y&Z Direction	1N	1.9	0.9	Log Normal
28, 29)		2N	1.6	0.6	Log Normal
30, 31)		3N	0.75	0.3	Log Normal
32, 33)		4N	5.5	0.6	Log Normal
	Fuel Pump Sine Amplitudes				
34)	X Direction	1N	0.65	0.35	Log Normal
35, 36)	Y&Z Direction	1N	0.45	0.4	Log Normal
37, 38)	Y&Z Direction	2N	0.45	0.4	Log Normal

Note: 1) Power units are in g^2
2) Pump speed units are in radians/second
3) Sinusoidal amplitude units are in g

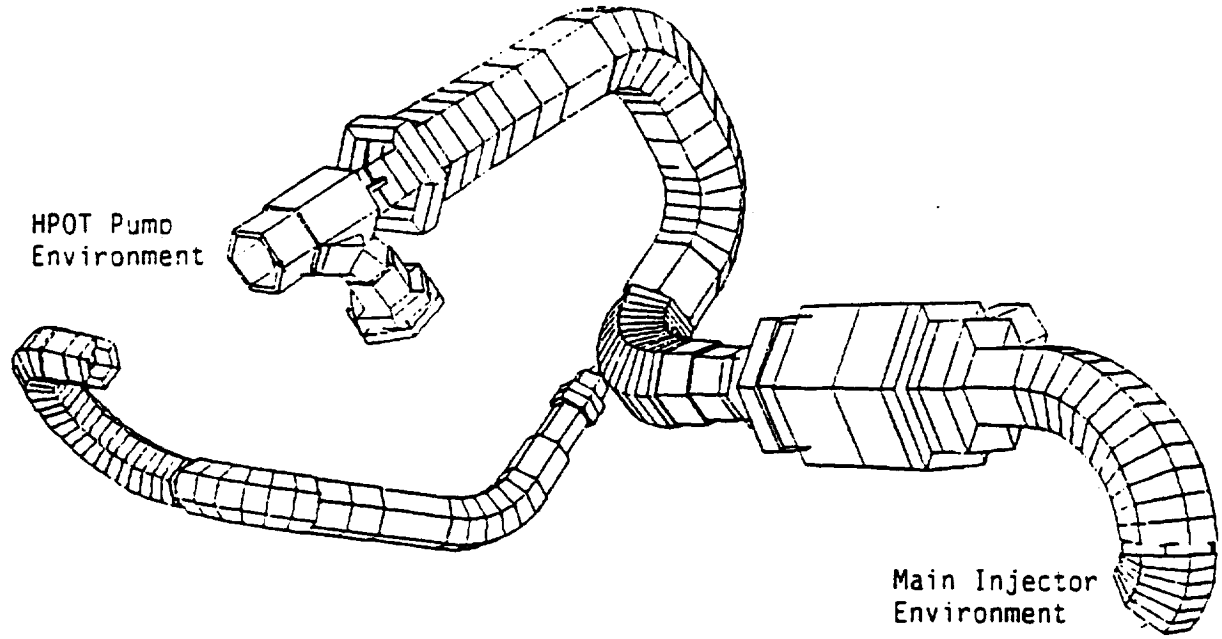

FIGURE 5. DUCT MODEL WITH ELBOWS, VALVES, ATTACHMENTS AND SECONDARY LINES.

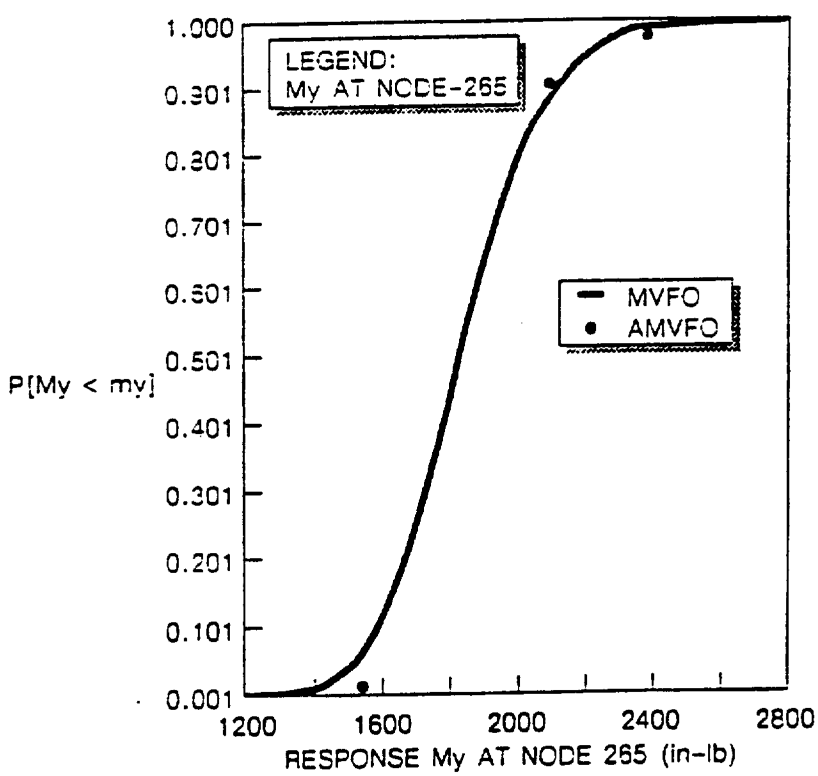

FIGURE 6. CDF OF A RESPONSE BASED ON MVFO AND AMVFO METHODS.

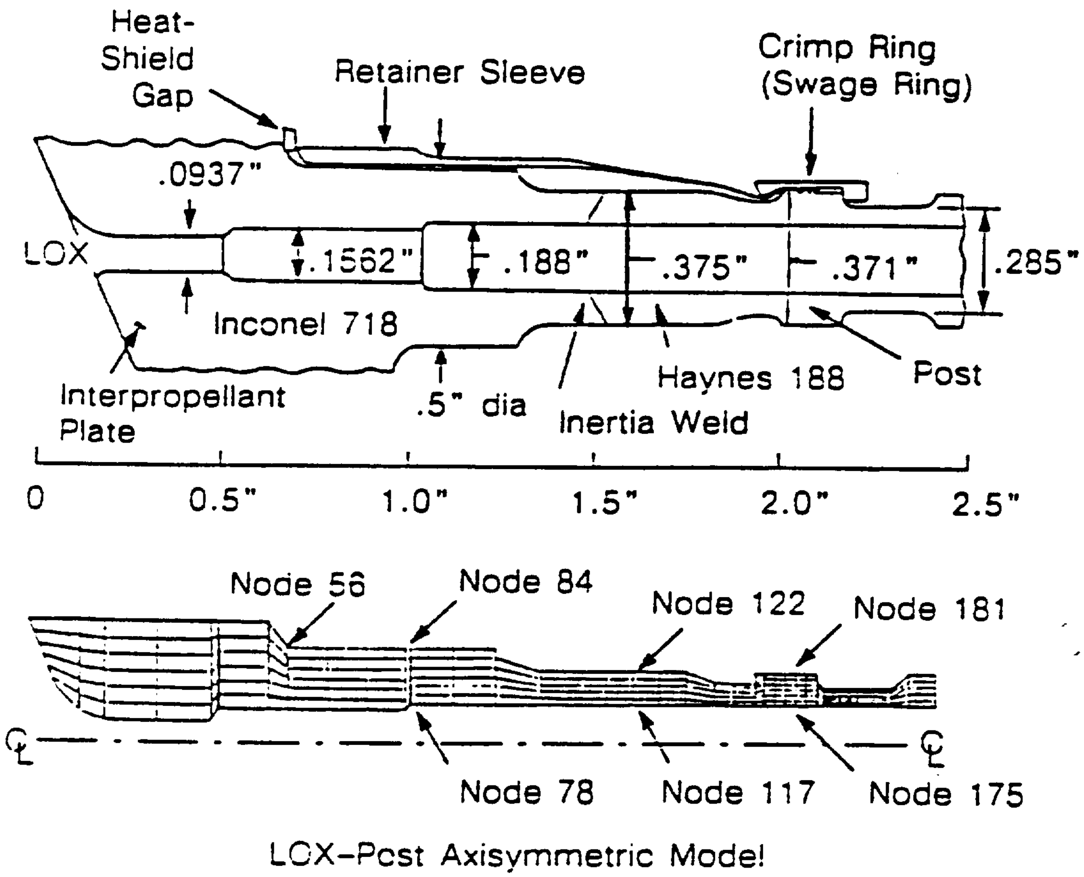

FIGURE 7. LOX POST AND ITS AXISYMMETRIC FINITE ELEMENT MODEL.

TABLE 3
RANDOM VARIABLES USED IN LOX-POST ANALYSIS

Random Variable	Mean	Standard Deviation	Distribution
Material yield stress (ksi)	175.0	8.75	Normal
Hot-gas temperature (R)	1654.70	26.6407	Normal
Coolant temperature (R)	191.643	4.21019	Normal
Hot-gas flowrate (lbm/sec)	167.249	1.0928	Normal
Coolant flowrate (lbm/sec)	929.918	4.31211	Normal
Mixture ratio	0.948012	0.0184211	Normal
Heat-shield-gap factor	0.47	0.235	Lognormal
Hot-gas film coefficient	1.0	0.1	Normal
Coolant film coefficient	1.0	0.08	Normal

TABLE 4
SUMMARY STATISTICS FOR EFFECTIVE STRAIN RANGE
FOR THE LOX POST

Node	Median	Mean	Standard Deviation	Coefficient of Variation
56	0.004143	0.004821	0.0002613	0.054
78	0.006759	0.008360	0.0002275	0.027
84	0.002114	0.004175	0.0001661	0.040
117	0.002990	0.004757	0.0001454	0.031
122	0.001186	0.003831	0.0001473	0.038
175	0.002949	0.005135	0.0001430	0.028
181	0.002296	0.002401	0.00006408	0.027

TABLE 5
SENSITIVITY* FACTORS FOR THE EFFECTIVE
STRAIN RANGE FOR THE LOX POST

Random Variable	Node 56	Node 78	Node 84	Node 117	Node 122	Node 175	Node 181
Hot-gas temperature	0.455	0.796	0.771	0.802	0.793	0.860	0.786
Coolant temperature	0.014	0.026	0.024	0.023	0.023	0.019	0.022
Hot-gas flowrate	0.062	0.075	0.111	0.070	0.074	0.045	0.108
Coolant flowrate	0.000	0.003	0.002	0.002	0.002	0.001	0.003
Mixture ratio	0.022	0.034	0.034	0.035	0.034	0.028	0.031
Shield-gap factor	0.793	0.115	0.071	0.028	0.003	0.011	0.017
Hot-gas film coefficient	0.399	0.587	0.620	0.590	0.603	0.507	0.605
Coolant film coefficient	0.002	0.031	0.042	0.024	0.026	0.005	0.052

*Range between 0 and 1. Larger values indicate a greater influence of the random variable on the response.

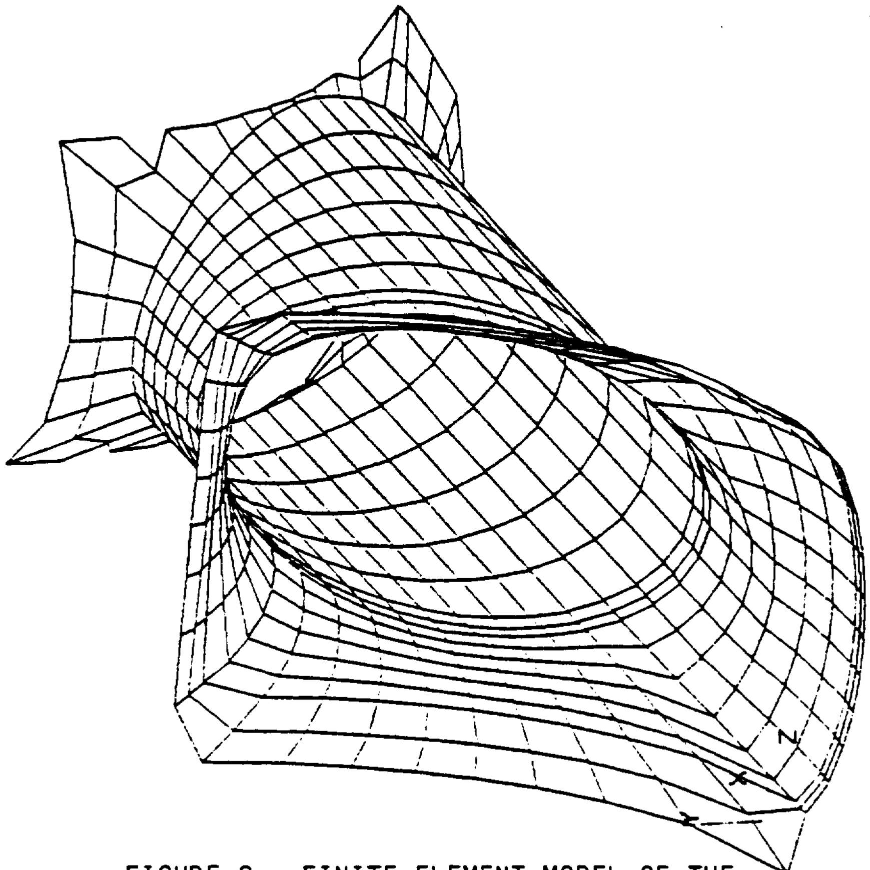

FIGURE 8. FINITE ELEMENT MODEL OF THE STRUCTURAL LINER.

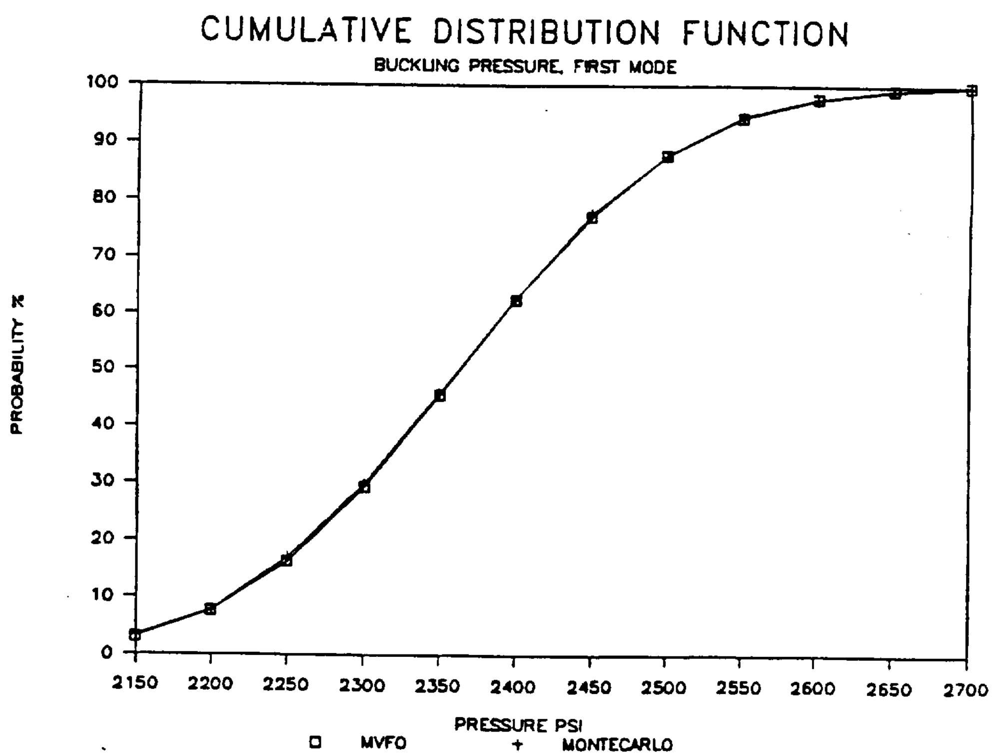

FIGURE 9. CDF OF THE FIRST BUCKLING MODE PRESSURE.