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Ashwin R. Shah
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

Richard D. Ball
Loral Aerosys
North Olmsted, Ohio

and

Christos C. Chamis
National Aeronautics and Space Administration
Lewis Research Center

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PROBABILISTIC ASSESSMENT OF SPACE NUCLEAR PROPULSION SYSTEM NOZZLE

Ashwin R. Shah
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

Richard D. Ball
Loral Aerosys
25111 Country Club Blvd./236
North Olmsted, Ohio 44070

and

Christos C. Chamis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

In assessing the reliability of a space nuclear propulsion system (SNPS) nozzle, uncertainties associated with the following design parameters were considered: geometry, boundary conditions, material behavior, and thermal and pressure loads. A preliminary assessment of the reliability was performed using NESSUS (Numerical Evaluation of Stochastic Structures Under Stress), a finite-element computer code developed at the NASA Lewis Research Center. The sensitivity of the nozzle reliability to the uncertainties in the random variables was quantified. With respect to the effective stress, preliminary results showed that the nozzle spatial geometry uncertainties have the most significant effect at low probabilities whereas the inner wall temperature has the most significant effect at higher probabilities.

INTRODUCTION

A space nuclear propulsion system (SNPS) nozzle was designed to generate the required thrust with the desired level of reliability. Nozzle system reliability is largely governed by structural integrity and behavior. Variables associated with the structural behavior are geometry, boundary conditions, material behavior, and incident loads. Manufacturing a large nozzle with accurate design dimensions is very difficult because of loose tolerances in the machinery. Therefore, there are always variations in the geometry and thickness of the material used. The nozzle is connected to the pressure vessel at the top; the difficulty in determining the degree of its fixity to the pressure vessel results in modeling variations. Thus, the boundary conditions at the attachment are not certain. Also, the grain structure of the material is never uniform because of variations in the material processing. Therefore, the behavior of the material is never certain either and has a scatter associated with it. Additional uncertainties are attributed to irregularities in the combustion reaction, variations in the fuel mixture ratio, in the gas temperature from time to time and from location to location, and, consequently, in the magnitude of the gas pressure on the nozzle.

All the variables governing the structural design of the nozzle have uncertainties associated with them as just described. The conventional deterministic design approach accounts for these variations in the form of an upper bound or a lower bound as the case may be. Because such an approach results in an overconservative or sometimes unconservative design, it is difficult to assess the degree of conservatism although the safety factor is known. Accurately quantifying the reliability and the associated risk with a given design is an impossible task for deterministic methods.

Probabilistic structural analysis is an approach that, in a rational way, accounts for the effects of uncertainties on the structural response. Furthermore, it determines the structural reliability and quantifies the risk. For more than a decade, the NASA Lewis Research Center has been engaged in developing probabilistic structural analysis methods. The methodology characterizes design variable uncertainties in the form of probability density functions. A finite-element structural analysis and reliability algorithms are used to perform a numerical integration of these probability density functions to evaluate the structural response distribution. The methodology developed to design propulsion system components probabilistically has been integrated into the computer code NESSUS (Numerical Evaluation of Stochastic Structures Under Stress). A brief description of NESSUS (ref. 1) is given herein.

The broad objective of this report is to give an overview of an SNPS nozzle, related problems, and an assessment of its reliability. One of the specific objectives is to demonstrate the effectiveness of this methodology when applied to the analysis of an SNPS nozzle and its extension (fig. 1). The design requirements for this nozzle are for very high pressures and thermal loads to achieve high thrust and good performance. Thus, another specific objective is to provide designers guidance and feedback in the following areas: uncertainties associated with pressure, temperature, geometry, and material behavior; the sensitivity of the nozzle reliability to the primitive random variables. Preliminary probabilistic stress and frequency analyses are performed to demonstrate the effectiveness of NESSUS.

NESSUS COMPUTER CODE

NESSUS (ref. 1) is a general purpose, integrated, probabilistic, finite-element-analysis computer code that performs static, dynamic, buckling, and nonlinear analyses. Several reliability-based probabilistic analysis algorithms, including fast Monte Carlo simulation techniques (ref. 2), are incorporated in the code. The structure of NESSUS is modular, which allows the user to perform an analysis in different stages. The input to solve any probabilistic structural analysis problem involves the identification of random variables, their probability distributions, structural geometry, loads, and boundary conditions.

Generally, uncertainties in a random variable can be gaussian or nongaussian. Also, if two or more random variables are affected by uncertainties in their common source (space or time), they become probabilistically correlated. For example, the modulus of elasticity E depends on the granular arrangement of the material and on the temperature T of the structure. If both the granular arrangement and the temperature are uncertain, then E and T would be probabilistically correlated. Thus, a gaussian or nongaussian random field can be correlated. NESSUS allows the user to define any gaussian-correlated random field at discrete finite-element nodes. Because probability algorithms in NESSUS require random variables to be uncorrelated and independent, they decompose the gaussian-correlated random field into a set of uncorrelated independent vectors by using a modal analysis (refs. 3 and 4).

A sensitivity evaluation of the structural response due to a variation in different uncorrelated random variables is performed by incorporating a perturbation analysis in the finite-element module. A modified

Newton's nonlinear algorithm (ref. 5) is used to perform the perturbation analysis. The discrete representation of the response surface required for the probabilistic analysis is obtained by perturbing independent random variables.

Several reliability algorithms, such as a fast Monte Carlo simulation, a fast probability integration (ref. 6), and first- and second-order reliability analyses (ref. 3), can be used to perform the probabilistic structural analysis. The fast probability integration methods are efficient and give accurate results, even in the lower and upper probability regions (tails). Using the perturbation analysis results, an explicit response function is developed. To obtain the cumulative distribution function of the structural response, the fast probability integration is performed by using the explicit response function and probability distributions of random variables. Also, the sensitivity of random variable uncertainties on the structural response uncertainties is quantified. The computed sensitivity information can be used to control the design process to achieve better reliability.

SNPS NOZZLE DETAILS

The nozzle is an important component of a space propulsion system because it is responsible for developing the required thrust. The nozzle is connected to a pressure vessel at the top and is free at the bottom. Hot gases burned in the pressure vessel are ejected under high pressure through a small-diameter throat where they expand downstream as the nozzle diameter increases. Gas pressure against the larger cross section provides the desired thrust. The magnitude of the thrust developed depends on the nozzle area ratio. Area ratios of 200 and higher are common in nuclear propulsion systems. However, the greater length required to obtain a higher area ratio is controlled by the limitation on weight. The temperature of the gases in the nozzle is as high as 2700 K, and the pressure as high as 7.09 MPa (ref. 7). Such high temperatures are beyond the melting point of available materials. Therefore, a cooling system is required to cool the material to less than the gas temperature. Liquid hydrogen, which is normally used as a coolant, is pumped through the coolant tubes laid along the interior circumference of the nozzle. After cooling the nozzle wall, the hot gaseous hydrogen is cycled back to the pressure vessel where it is used as fuel. The coolant pumping rate depends on the temperature levels desired in the nozzle wall material and is determined by performing a heat transfer analysis.

The design for an SNPS nozzle requires a reliability assessment and test verification. The engine nozzle is usually designed in segments so that an engine system ground test can be conducted: (1) the basic nozzle and (2) the nozzle extension. The area ratio (~10:1) of the basic nozzle considered herein was determined by the capacity of ground test facilities.

A preliminary probabilistic structural assessment of an SNPS nozzle (ref. 7) was performed and some preliminary results are presented herein. The nozzle (fig. 1) has an area ratio of 500 and a thrust level of 0.326 MN. The length of the nozzle is approximately 7.92 m; the radius at the throat is 0.091 m and at the exit, 2.0574 m. The proposed nozzle structure comprises the shell, vertical stringers, and circular frames. Vertical stringers and circular frames stiffen the shell to reduce the stress levels and vibration problems. The structure was discretized into 2100 nodes and 1305 shell elements. The thickness of the shell is assumed to be 5.1 mm. The vertical stringers and frames are 25.4 mm wide and 5.1 mm thick. For the purpose of the preliminary analysis, the nozzle was assumed to be fixed at the top. The proposed material is MAR–M247 and its material properties are given in reference 8.

DESIGN CRITERIA AND FAILURE MODES

For the SNPS nozzle, the structural design criteria for the avoidance of failure fall into two categories, global and local. The preliminary design criteria deal only with the global failure modes because the details for local analyses are usually unavailable during the early stages of design. A linear elastic analysis is commonly accepted for global design. The following global criteria are normally considered for a preliminary design: (1) the gross stress is less than the material strength; (2) the natural frequencies are not equal to the excitation frequencies; (3) loads are less than the critical buckling loads; and (4) displacements are less than the design allowables. To demonstrate the capabilities of NESSUS, we considered only the first two criteria.

To arrive at an overall reliability assessment of the nozzle, a systems approach considering all the possible failure modes has to be employed. The system reliability approach accounts for the simultaneous occurrence of different failure modes provided that deterministic failure modes exist. Also, to develop an economical design, a risk-cost analysis is performed, providing the risk associated for a given cost and the guidelines for the incremental cost involved to improve the reliability of the structure.

Preliminary evaluations showed that the nozzle needed vertical (stringer) and circumferential (frame) stiffeners to avoid severe vibrations due to fluctuating pressure. If the fundamental frequency of the nozzle is very close to that of the fluctuating pressure forces, its dynamic displacements could be excessive because of the resonance, and the thrust generation capability of the nozzle could be impaired, which may induce fatigue failures. Hence, a reliability assessment for probable resonance problems is appropriate. Nozzle buckling is another structural design criterion. Global buckling could lead to a catastrophic failure. Therefore, the reliability assessment for probable buckling is also appropriate. Other local structural failures should also be investigated. For example, local crippling of coolant tubes is one of the major local failure modes; it impairs the cooling process and leads to hot spots, the melting of metal, and, subsequently, global structural failure.

RESULTS AND DISCUSSION

A preliminary linear elastic probabilistic structural assessment of the nozzle includes uncertainties in the geometry, material behavior and properties, temperature, pressure, and thermal loads. The estimated assumed probability distributions of the random variables associated with these uncertainties are listed in table I. The deterministic mean state fields from both the thermal and the pressure loads are given in figures 2 and 3, respectively. These figures show that the loads are predominant in the upper part of the nozzle. The probabilistic assessment results for uncertainties in terms of the cumulative distribution functions (CDF) for stress and frequency were obtained and are now presented.

Figure 4(a) shows the cumulative probability distribution function of the effective (Von Mises) stress in the shell at a location near the throat in the upper portion of the nozzle; figure 4(b) shows the sensitivity of the effective stress to the random variables. The mean value of the effective stress is 352 MPa and the standard deviation is 79 MPa (19 percent). It is seen from figure 4(b) that the effective stress is most sensitive to uncertainties in the nozzle length and the temperature on the inner wall surface at probability levels of 0.01 and 0.999. Thus, the uncertainties in these variables should be controlled to reduce the scatter in effective stress, thereby achieving higher reliability.

Figure 5(a) shows the CDF of effective stress in the stiffener at a typical location in the upper portion of the nozzle; figure 5(b) shows the sensitivity of the effective stress to the random variables. The mean effective stress at this location is 655.0 MPa and the uncertainty range is 20 percent. The stresses in stiffeners are high because of higher thermal gradients across their widths. The stresses in the stiffeners are sensitive to the nozzle radius (X- and Y-coordinates), the length, the temperature, and the modulus of elasticity at both 0.01- and 0.999-probability levels (fig. 5(b)). Evident from these figures is that the large scatter in the stresses is the result of their sensitivity to temperature loads which were assumed to have large scatter. Also, the probability of effective stresses has long tails; that is, the stress values far from the mean have a low probability of occurrence. These cumulative distribution functions can be used to compute the reliability of failure modes caused by exceeding the yield strength.

Because the stresses in both the shell and stiffener are highly sensitive to the uncertainties in the temperature on the inner wall, the variations in the combustion irregularities should be controlled more effectively. Also, a tighter manufacturing tolerance should be implemented to reduce uncertainties in the nozzle shell geometry. Scatter in the material properties can be reduced by controlling the material processing variables.

The reliability of the nozzle, with respect to shell and stiffener failures, was evaluated for a mean strength of 827 MPa. The reliability to prevent yield stress for the shell was 0.99995 and for the stiffener, 0.941. The reliability for the stiffener is unacceptably low. Therefore, the stiffener design should be revised to increase the nozzle reliability.

The first two fundamental mode shapes of the nozzle are plotted in figures 6 and 7. The mean natural frequency of the first mode is 65.566 Hz, which is a bending mode of vibration. However, the second mode of vibration is a breathing mode with a mean frequency of 198.63 Hz. The CDF of the first natural frequency is shown in figure 8(a), and the sensitivity of the natural frequency to the random variable uncertainties is shown in figure 8(b). Figure 8(b) shows that the uncertainties in the modulus of elasticity govern the frequency at a cumulative probability level of 0.001 whereas uncertainties in the thickness of the shell govern the frequency at a cumulative probability level of 0.999. The probabilistic frequency analysis results (fig. 8(a)) show that the scatter in the frequency is small because this scatter is controlled by variations in the thickness, modulus of elasticity, and mass density (fig. 8(b)), which all have a small range of uncertainty (table I). To achieve a reliability of 0.999 and avoid resonance, the frequency of the excitation force should be higher than 66.7 Hz or lower than 64 Hz.

CONCLUSION

A reliability assessment of a space nuclear propulsion system (SNPS) nozzle was performed and the preliminary results obtained demonstrated that the NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) computer code could be used to perform a probabilistic structural analysis of these types of structures. The sensitivity of the structural response and its respective reliability was quantified and its role in the design process was discussed. The results showed that the stresses in the stiffener are higher than those in the shell because of the higher thermal gradient in the stiffeners. The stresses at lower probability levels are governed by the uncertainties in the nozzle geometry whereas those at the higher probability levels are governed by the temperature on the inner wall surface. The scatter of the natural frequency of the nozzle is small and is dominated by the uncertainties in the thickness of the shell at high probability levels.

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TABLE 1.—UNCERTAINTIES IN RANDOM

VARIABLES OF SPACE NUCLEAR PROPULSION SYSTEM NOZZLE

Random variable	Range of uncertainty	Distribution
Pressure	5	Normal
Geometry		
X-coordinate (radius)	0.3	Normal
Y-coordinate (radius)	.3	Normal
Z-coordinate (length)	.3	Lognormal
Thickness	2.5	Normal
Temperature gradient		↓
Inside surface	5	↓
Layer 2	↓	↓
Layer 3	↓	↓
Layer 4	↓	↓
Outside surface	↓	↓
Modulus of elasticity	↓	Weibull
Coefficient of thermal expansion	2.5	Normal
Strength	4	Weibull

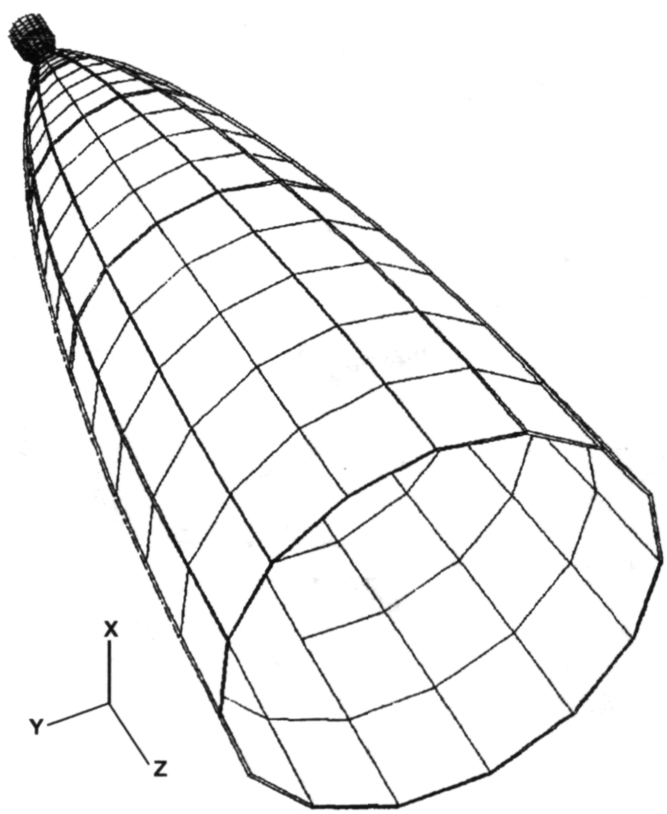

Figure 1.—Finite-element model of space nuclear propulsion system (SNPS) nozzle.

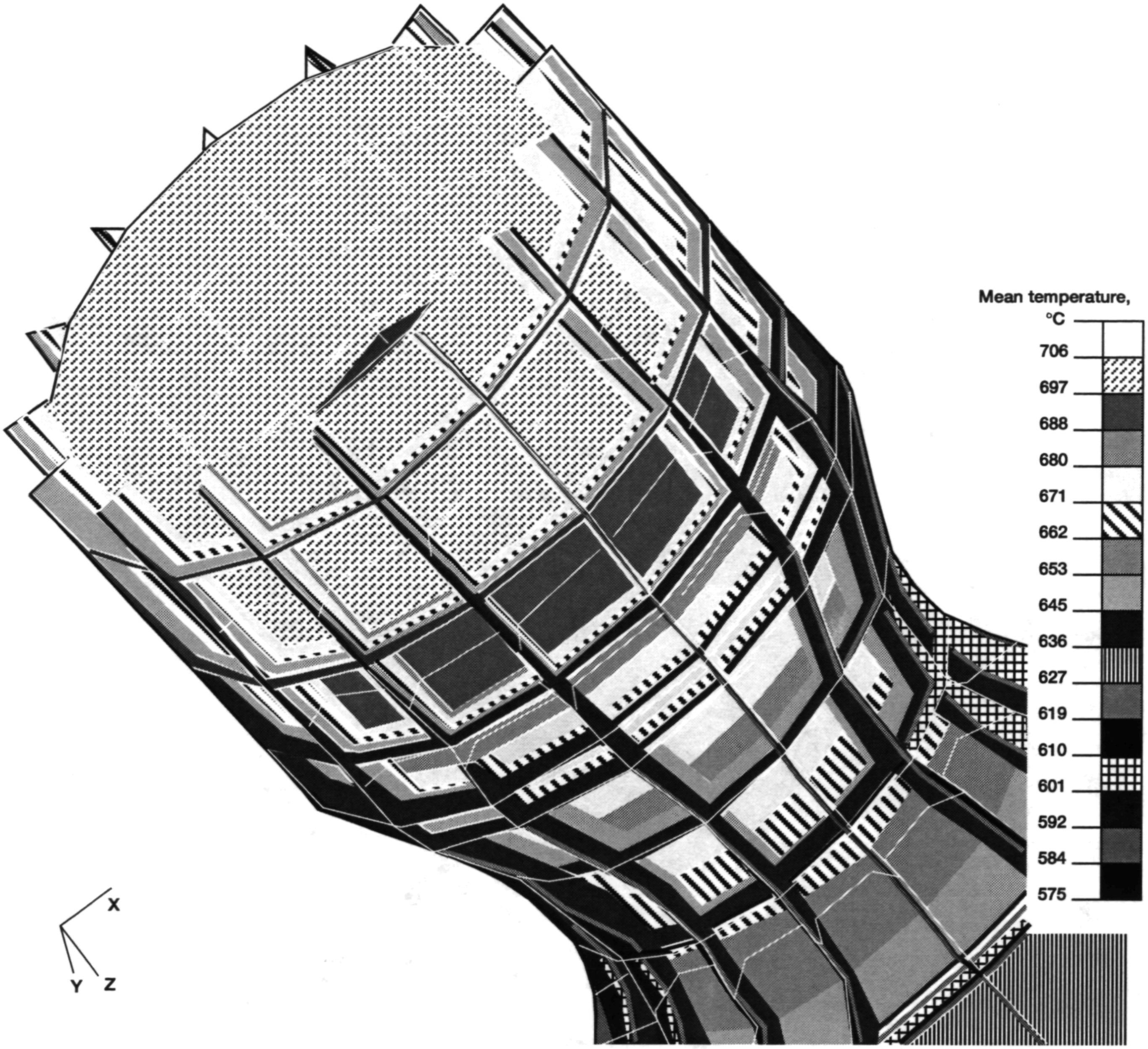

Figure 2.—Temperature distribution in SNPS nozzle.

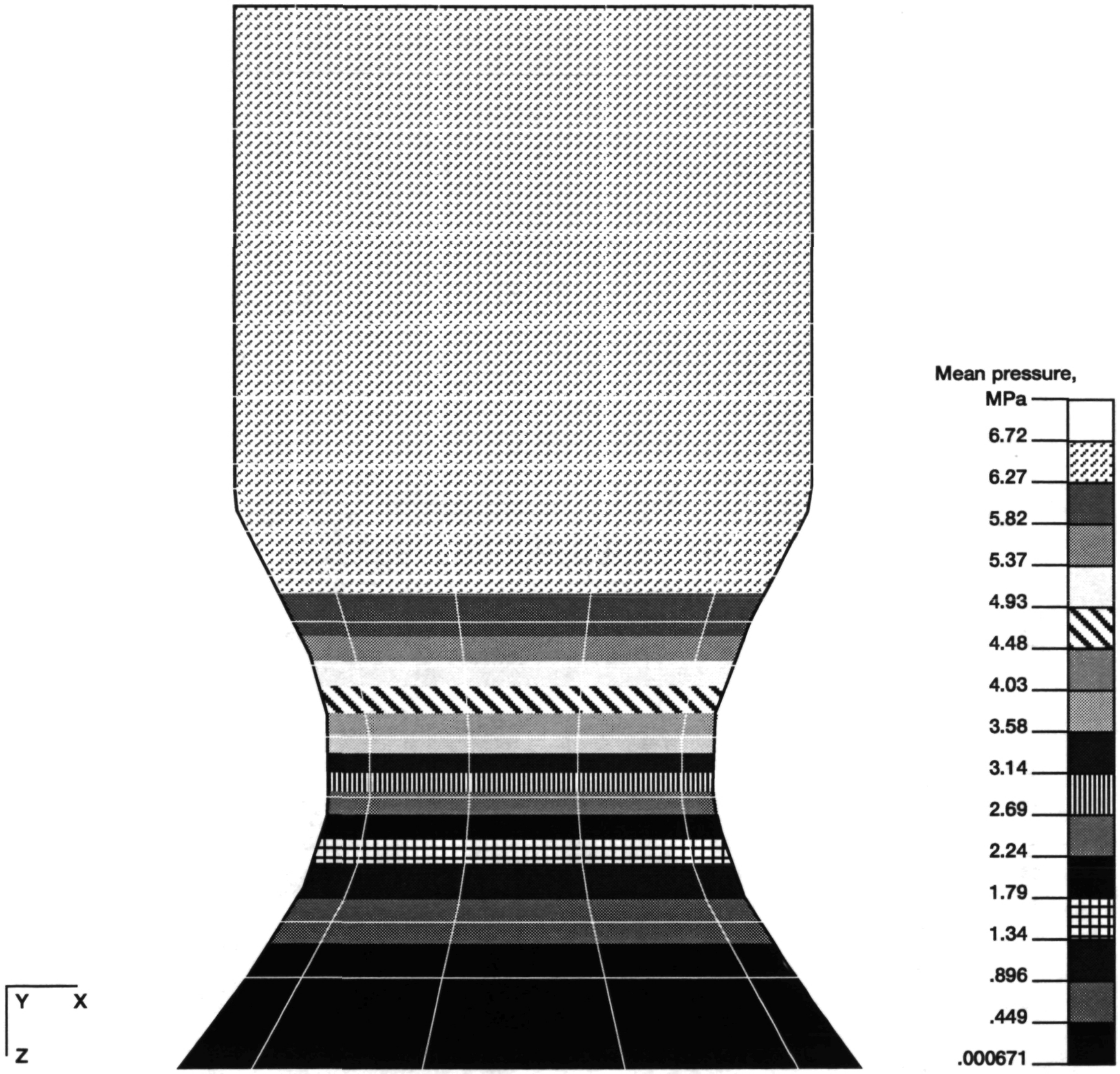

Figure 3.—Pressure distribution in SNPS nozzle.

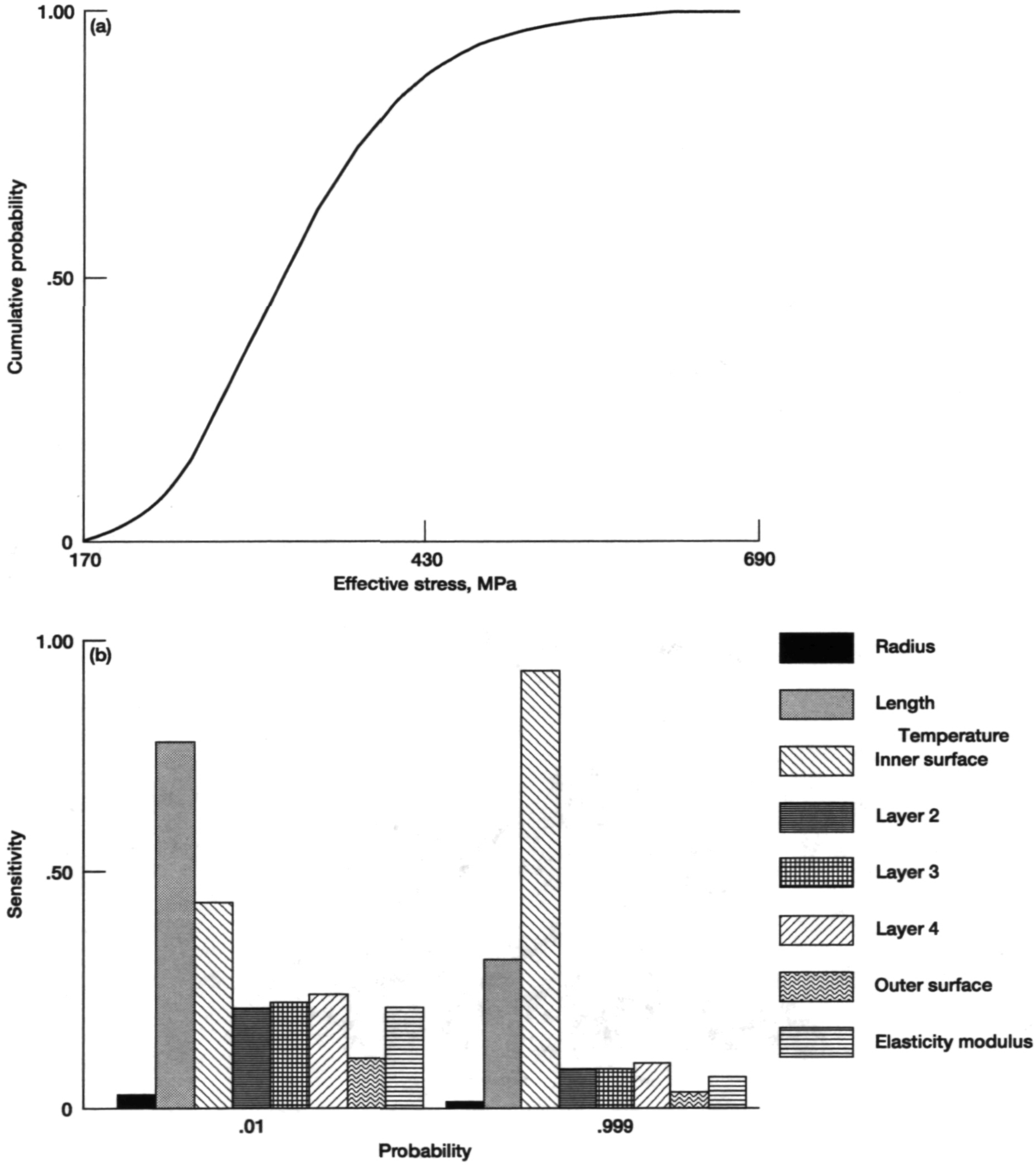

Figure 4.—Results of probabilistic assessment in shell. (a) Effective stress in shell. (b) Sensitivity of effective stress.

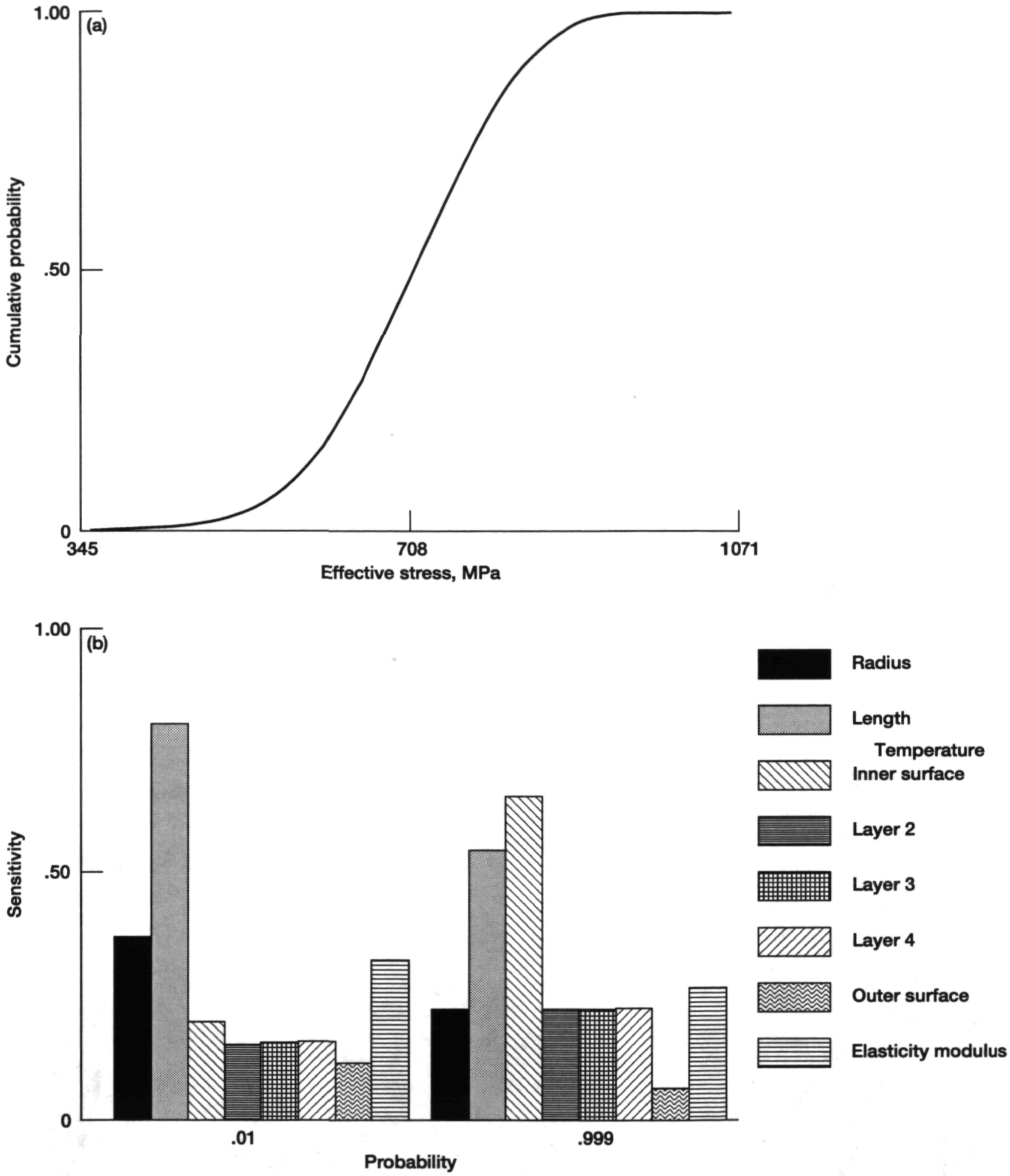

Figure 5.—Results of probabilistic assessment in stiffeners. (a) Effective stress in stiffener. (b) Sensitivity of effective stress.

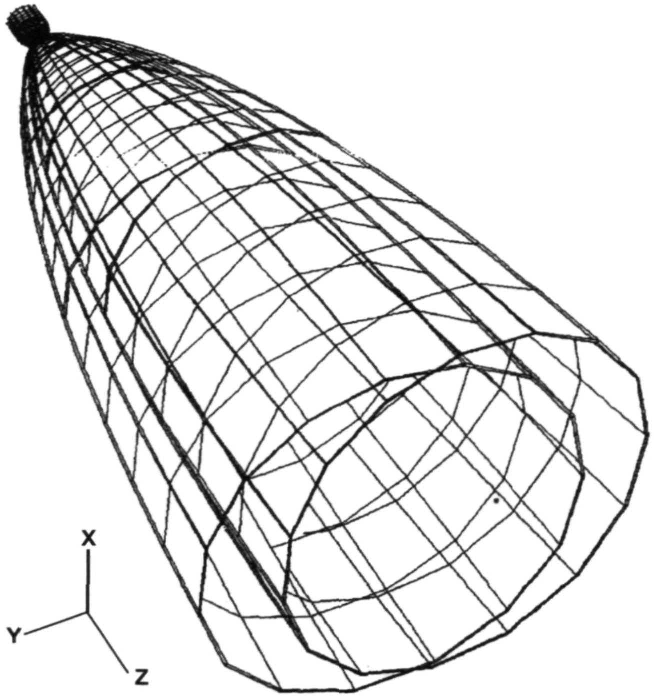

Figure 6.—SNPS nozzle first mode of vibration (frequency, 65.566 Hz).

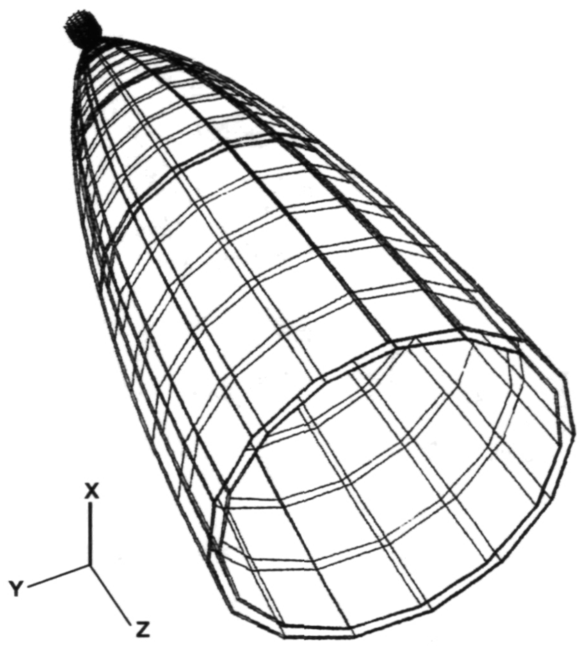

Figure 7.—SNPS nozzle second mode of vibration (frequency, 198.63 Hz).

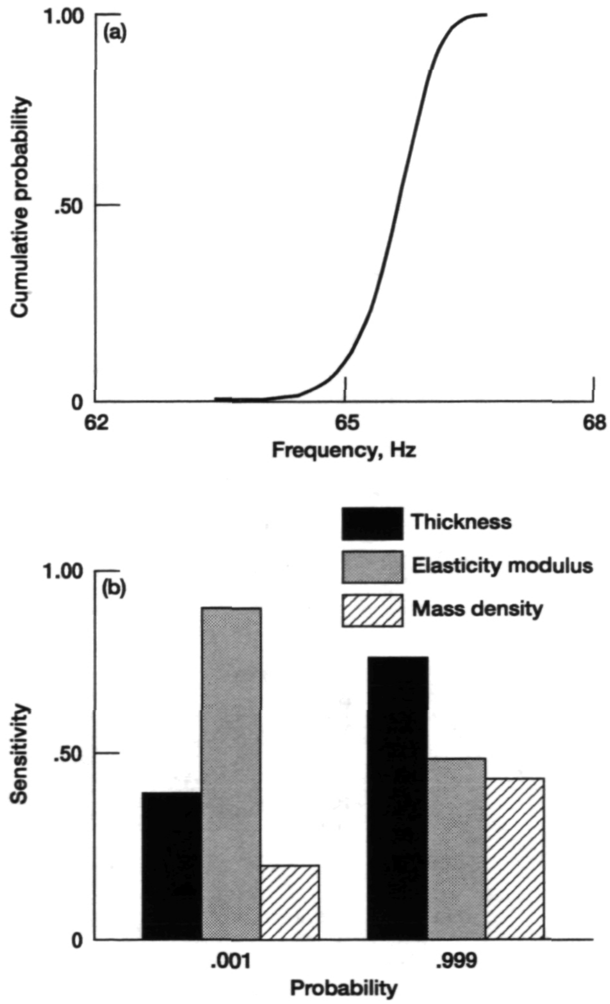

Figure 8.—Results of probabilistic assessment of nozzle. (a) First natural frequency. (b) Sensitivity of first natural frequency.

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Lewis Research Center
Cleveland, Ohio 44135–3191

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13. ABSTRACT ***(Maximum 200 words)***
In assessing the reliability of a space nuclear propulsion system (SNPS) nozzle, uncertainties associated with the following design parameters were considered: geometry, boundary conditions, material behavior, and thermal and pressure loads. A preliminary assessment of the reliability was performed using NESSUS (Numerical Evaluation of Stochastic Structures Under Stress), a finite-element computer code developed at the NASA Lewis Research Center. The sensitivity of the nozzle reliability to the uncertainties in the random variables was quantified. With respect to the effective stress, preliminary results showed that the nozzle spatial geometry uncertainties have the most significant effect at low probabilities whereas the inner wall temperature has the most significant effect at higher probabilities.

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